Spread of smoke and fire gases via the ventilation system.

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1997

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Department of Building Science
Report TABK--97/1011

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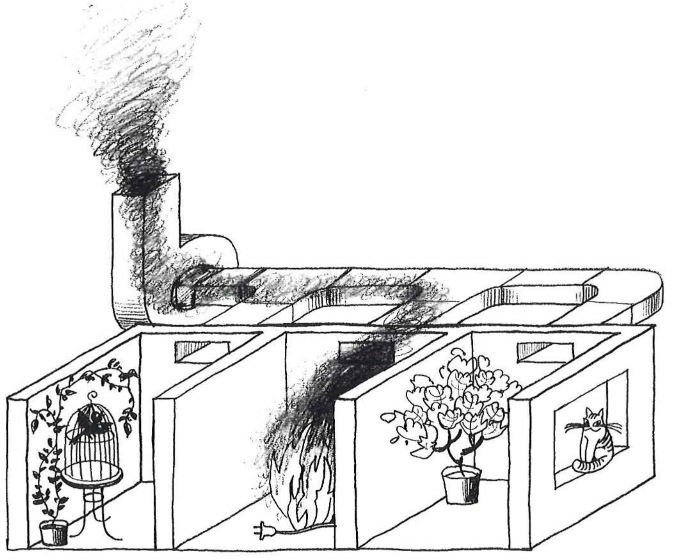

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Building Services

Lund University

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- moisture research

Spread of smoke and fire gases via the ventilation system

Polina Gordonova

This report relates to Research Grant No 050-942 from the Swedish Fire Research Board to the Department of Building Science, Lund University, Lund Institute of Technology, Lund, Sweden.

Keywords

Compartment fires, fire flow, fire pressure, fire simulation, smoke spread, ventilation ducts.

The English language corrected by L. J. Gruber BSc(Eng) MICE MIStructE

Printed by KFS AB, Lund 1998

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Abstract

Ventilation ducts provide possible routes for smoke spread between adjacent rooms in case of a compartment fire. However, the probability of this and the conditions which lead to such a phenomenon have not been fully examined yet. According to the recommendations in the building regulations/ codes of different countries, the only way smoke spread can be prevented is to install different kinds of dampers or smoke barriers and to shut down the ventilation system in the event of fire, or to rely only on shutting down the ventilation system. In order to improve the fire safety of ventilation systems, an investigation has been made in this project whether it is possible to make use of the ordinary existing ventilation system to remove hot smoky gases from the compartment, without spreading them to adjacent rooms. A method by which the smoke spread via the ventilation system can be prevented by running the fans is presented in this thesis.

Smoke spread is determined by the rate of heat release by the fire, the airtightness of the building or room, and the layout of the ventilation system. The heat released by the fire results partly in a volumetric expansion which can be interpreted as a flow. The project which focuses on four different types of rooms uses data based on measured heat release rate-time curves and the chosen characteristics of the room, in order to predict fire behaviour and its consequences with the help of the computer simulation program CFAST (HAZARD1). The airtightness (leakage of spaces), and the durability of windows during the fire, have been investigated.

The results obtained from simulations have been used to predict the largest fire flow produced by the expansion, and with the help of the computer program PFS which treats arbitrary flow systems, this has been compared to the "boundary" safe flow.

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Preface and acknowledgements

Work on this thesis began in 1995 at the Department of Building Science, Lund Institute of Technology, Lund University.

I would like to express my sincere thanks to my supervisor Lars Jensen, the head of the Department Bertil Fredlund, Håkan Håkansson, and to the staff of the Department of Building Science.

In particular, I want to thank Sven Eric Magnusson, Göran Holmstedt, Björn Karlsson, Håkan Franzich, Lars Göran Bengtsson and the staff of the Department of Fire Safety Engineering for their support, good ideas and help in supplying data and information. Guest researcher Yan Zhenghua is especially acknowledged for field model program fire simulation.

I would like to express my sincere thanks to Tor Aurell, the consultant, who helped me in searching through certain databases.

I would also like to address my warmest thanks to the members of the reference group: Staffan Bengtsson, Sven Palmkvist, Claes Malmqvist och Hauker Ingasson for their support and long-term interest.

This work was funded by the Swedish Fire Research Board, which is gratefully acknowledged.

Summary

The following study examines the problem of smoke spread via ventilation ducts to adjacent room(s) in case of a compartment fire. Although the problem is well known, the probability of this and the conditions which lead to such a phenomenon have not been fully examined yet. The main goal of this study is to examine the possibility of operating the fans during different fires in four types of buildings (compartment, hospitals, offices and hotels) and to estimate the risk of smoke spread in different conditions.

Whether or not smoke spread will occur is determined by the energy released by fire, the airtighteness of buildings and the layout and properties of ventilation systems.

In this connection it is extremely significant to assess the relationship between typical fires in the above types of buildings, the airtightness of the construction and the layout of the ventilation system, and to give recommendations on good practice to diminish or even eliminate the risk of smoke spread through ventilation ducts to the adjacent rooms.

For the purpose of this study the following subjects were evaluated:

most typical fire cases for chosen types of buildings,
internal and external airtightness of the chosen rooms,
window breakage,
peak fire flows,
fire compartment groups,
ventilation system design (principle features),
real ventilation system design,
measures for prevention of smoke spread via ducts,
toxicity of spread dilute smoke,
visibility of spread dilute smoke,
cold ventilation flows vs. real temperatures of ventilation flows.

According to statistical estimation of the principal dangers and damage caused by fire, presented in different sources, the most probable items in which fires initiate in the chosen rooms are: sofa [6] and bed [7] in dwelling houses, bed [9] in hospitals, equipment and furnishing [10] in offices and bed [6] in hotels. "Real" fire growth curves, based on measured heat release rate vs. time during full-scale burning tests of these items, are chosen to simulate fires in spaces. The fires analysed are single-room fires, limited to the item in which the fire started.

The objective of airtighteness evaluation is to summarise knowledge about the real magnitude of leakage in relation to the whole building envelope including interior building constructions, for the studied types of enclosures, built at different times. For the purpose of this study, air leakage in accordance with the Swedish Building Regulations, BBR 94, applied to the whole buildings envelope, can be accepted as a suitable and probable value.

Different computer programs are used to simulate fire progress in chosen rooms and the parameters obtained with these are compared. CFAST (Consolidated Model of Fire Growth and Smoke Transport), which is part of the computer program HAZARD1, is a basic tool of fire simulations in the presented study. Two other programs: DSLAYV and SMAFS (Smoke Movement and Flame Spread) are also used for fire simulations in order to compare predicted parameters. Both programs, CFAST and DSLAYV, use a two-layer model of fire, while SMAFS is a field model program. Comparison of parameters predicted by CFAST with those obtained with DSLAYV and SMAFS shows that the order of magnitude of values is reasonable.

One of the most important issues is to estimate the characteristic parameters/features that are produced by certain fires, and to assess their influence on the pressure/flow ratio in the ventilation system. Peak mass flows, peak temperatures and peak pressures, predicted by computer simulations, are analysed and compared to each other. Results are presented in the form of a table and show peak values for temperature, exceeding 340°C in certain cases, and peak values for pressure which vary widely between 30 and 2100 Pa.

In this connection, evaluation of both the time at which the window breaks and the temperature in the fire room at which this occurs is of great importance. An analysis is made in order to summarise present knowledge concerning the behaviour of glazing in fire. In addition, a simple window breakage model is presented for the evaluation of the time of breakage and temperature differences in the glass. Analysis shows that glass cracks due to thermal stress if the temperature difference in the glass itself varies between 58°C and 100°C. The corresponding temperature in the fire room varies between 200°C and 400°C.

Volume fire flows, predicted by computer simulations for different fires in studied rooms of different geometry, are analysed for each type of room. A regression analysis of the largest predicted fire flows is made with the statistical programs Minitab and EXCEL. Several theoretical models for the assessment of fire flows as a function of heat released in assumed fires are also presented. Comparison of flows predicted in such a way with those predicted by CFAST leads to the generalisation of peak fire flows for each type of room as a function of room volume.

Characteristic flow curves baced on the equations made with the computer program EXCEL for the chosen buildings, of volumes ranging from 30 m^3 to 240 m^3, are presented. These volumes are assumed to be those most usual for the described types of buildings.

For the purpose of comparison, both the presented flows and flows obtained with DSLAYV for t^2 - fires are plotted in the same diagram.

A search has been made through research publications in different databases in science and technology and via several search program in Internet to ascertain the present state of knowledge regarding ordinary mechanical ventilation systems during compartment fires. Current publications on this subject in different scientific and technical periodicals were also followed, and an attempt was also made to discuss the subject with researches via Network's scientific news groups. The author was unsuccessful in getting information on corresponding research with regard to the operation of ventilation systems during a fire or, at least, in discussing its possibilities.

For the purpose of evaluating smoke spread through ducts, a computer program PFS, which treats arbitrary flow systems, was used. The "boundary" safe flows assessed with PFS has been compared with the predicted largest fire flows obtained in this study.

The boundary case for smoke spread via ventilation ducts can be described by zero airflux in the adjacent room(s) and also zero pressure in the connecting junction between the fire room and the main duct. All flows and pressure exceeding the "boundary" values cause smoke spread.

A description of basic principles and theoretical model of exhaust, supply-exhaust (open and closed) mechanical ventilation systems serving two rooms, which determine boundary conditions of smoke spread through ventilation ducts, are presented in the report.

The most typical ventilation systems used in the studied types of buildings and fire compartments in these are discussed in the report. The analysis focuses on

-exhaust ventilation system with one exhaust fan and a distribution system consisting of one or two main ducts with branches to each compartment,

-supply-exhaust ventilation system with supply and relief fans and distribution ductwork to each compartment,

-supply-exhaust ventilation system with a "zero"-duct. This means that supply air is distributed via terminals directly to the compartments, while relief (exhaust) air collects in corridors ("zero"-ducts) and is removed via relief dampers by the exhaust ventilation system.

In all types of ventilation systems the plenum can be both vertical and horizontal. These ventilation systems can include different variations of system layouts, and the degrees of complexity of these systems can be widely different.

The report presents an evaluation of boundary conditions for smoke spread in the types of ventilation systems discussed above with four branches, general measures for the prevention of smoke spread via ventilation ducts, and a brief description of PFS-elements and layout.

PFS provides the opportunity to describe resistance properties of wyes and junctions in two different ways: as a quadratic function and with the help of empirical equations. Both types are tested. As this study is interested in "abnormal" flow behaviour, i.e. changes in flow directions and the consequent decrease in flow in certain parts of junctions to zero value, it is not obvious how wyes would respond. Higher flows cause higher velocities in ducts, and, as a result, higher Reynolds numbers. Along with increasing flow, turbulence increases pressure field described as quadratic function. For these reasons, the resistance properties of wyes and junctions described as a quadratic function is used in further analysis.

Different solutions are analysed for the prevention of the smoke spread to the adjacent room(s) via ventilation systems with four branches. There are

shutting down the fan(s),

doubling the speed of rotation of the fan(s),

converting the supply fan into exhaust fan,

bypassing support plenum to the exhaust plenum

and a combination of these measures with ordinary fan function and with each other.

Fire flow exceeding boundary fire flow, obtained in previous calculations, is used as default flow. The studied cases do not cover all possible measures for the prevention of smoke spread through ventilation ducts, but they show method of evaluating the danger due to this.

The "real case" study examines the risk of smoke spread through the chosen ventilation systems in buildings of higher degree of complexity. Ordinary design air flows are assessed in the examined buildings. Different cases are studied in order to estimate boundary fire flows and corresponding pressures in different rooms. This problem is very numerically complex for such ventilation systems with numerous branches, because the flow in the boundary room must be equal to zero, while other flows and pressures are much higher then normal. Because of this, fire flows obtained from fire simulations are used in smoke spread evaluation in the studied ventilation systems. "Fires" are placed in different rooms and the resulting smoke spread to the adjacent room(s), as well as different measures of preventing this phenomenon, are studied.

The problem of evaluation the toxicity of spread diluted smoke is discussed in the report. This evaluation regarding the concentration of CO is made step by step for an exhaust ventilation system with a shut-down fan. An assessment of

the total volume of smoke spread,

relative smoke spread to a single room, including evaluation of the proportion of

smoke reaching one of n rooms

the concentration of CO in a single room is presented in the study. All rooms are assumed to be identical.

The concentration of CO, together with the duration of exposure and the type of activity during which exposure takes place, determines the CO-doze and toxic effects. Different recommendations about acceptable and dangerous CO-concentrations and also CO-dozes are discussed. An evaluation of CO-concentrations in ppm, corresponding to the IDLH (immediately dangerous to life and health) CO level, limited to 1500 ppm during 30 min, which reaches one of the n rooms is also presented.

Analogously with the evaluation of the toxicity of the diluted spread smoke, evaluation of the visibility of this is discussed in the report. The expressions presented give mean values of assessed visibility in the space.

The whole study assumes that the examined flows, including fire flows, have ambient parameters, "cold" flows. It is well known and also as shown by compartment fire simulations that fire flow temperatures can exceed 300°C - 340°C. This means that the assessed smoke spread via ventilation ducts can differ from that in reality. Evaluation of friction pressure drop in straight ducts shows that it decreases to approximately one half as the temperature in K doubles. The pressure drop in wyes and junctions is more difficult to evaluate. At the same time, along with smoke dilution and heat loss downstream from the main duct, flow temperatures decrease and "cold" flows become default ones.

One more method for the evaluation of possible smoke spread via exhaust ducts is presented in the study. The "Alexander" method is a method for manual calculations, based on the" cut-off" principle. The "cut-off" principle means, that a branch(es) at the boundary conditions with zero pressure is cut off and the rest of ventilation system is calculated once more regarding the new pressure/flow conditions.

The problem examined in the present study appears complex, and the assumptions, made with a certain lack of knowledge and a paucity of empirical data, cannot diminish the uncertainty of the results obtained. The results should not therefore be interpreted as some sort of total solution to the elimination of smoke spread, but should be considered as a guidance in such types of analysis.

Sammanfattning

Projektet undersöker rökspridning via ventilationskanaler till andra närliggande rum vid händelse av en brand. Trots att problemet är välkänt, är sannolikheten av att fenomenet inträffar och villkor som leder till detta inte utforskat än. Projektets syfte är att studera möjligheter för att utnyttja fläktar i drift vid händelse av en brand i små lokaler i bostäder, sjukhus, kontor och hotell; samt att uppskatta risken för rökspridning via ventilationssystem i dessa byggnader.

Risk för rökspridning beror på utvecklad värmeeffekt, byggnadens läckage och ventilationssystemets egenskaper.

I detta sammanhang är det viktigt att uppskatta ett samband mellan de mest typiska bränderna för ovan presenterade typer av byggnader, byggnadens täthet och utformning av ventilationssystem; samt att ge rekommendationer för minskning eller uteslutning av risk för rökspridning via ventilationssystem.

För detta syfte är följande parametrar uppskattade:
de mest typiska bränderna för de utvalda typerna av lokaler,
yttre och inre täthet hos brandceller,
fönstersprängning,
maximallt brand-flöde,
brandcellsindelning,
förenklade ventilationssystem (principiella lösningar),
"verkliga" förgrenade ventilationssystem,
åtgärder mot rökspridning via ventilationskanaler,
giftighet av utspädd rök,
siktbarhet av utspädd rök,
"kallt fall" kontra "hett fall".

Enligt statistisk data för brandskador av såväl personer som egendom, är de mest sannolika brandföremålen i de analyserade lokalerna: soffa och säng i bostäder, säng i sjukhus, kontorsin-

redning i kontor och säng i hotell. ”Verkliga” brandkurvor (värmeeffekt-tid samband) vilka erhållits vid fullständig förbränning av ovan presenterade föremål ligger till grund för rumsbrandssimuleringar. Bränder antas vara begränsade till ett rum samt till det föremål, branden började i.

För att uppskatta yttre och inre täthet av analyserade lokaler har en sammanställning av kunskap beträffande hus byggda vid olika tider genomförts. BBR 94:s krav på hur stor en byggnads otäthet högst får vara, tillämpad på hela omslutande skalet inklusive inre konstruktioner, antas dimensionerande för det här projektet.

För att uppskatta brandförlopp i en lokal har olika simuleringsprogram använts och resultatparametrar har jämförts. CFAST (Consolidated Model of Fire Growth and Smoke Transport) som ingår i dataprogrammet HAZARD1 är ett huvudsimuleringsprogram i det här projektet. Två andra simuleringsprogram: DSLAYV och SMAFS (Smoke Movement and Flame Spread) används också för att kunna jämföra resultaten. Både CFAST och DSLAYV är program baserade på tvåzonsbrandmodeller. SMAFS är ett fältmodelsprogram. Jämförelse mellan resultatparametrar erhållna med CFAST med motsvarande parametrar erhållna med DSLAYV och SMAFS visar värden inom samma storleksordning.

Maximalt brandmassflöde, maximal temperaturer och maximalt brandtryck erhållna med hjälp av simuleringarna har analyserats och jämförts med varandra. De maximala temperaturerna överskrider i vissa fall 340°C och maximalt brandtryck verierar avsevärt mellan 30 och 2100 Pa.

I detta sammanhang verkar det viktigt att kunna uppskatta tidpunkt och temperaturer i ett brandrum då fönster går sönder. Sammanställning av kunskap om brandpåverkan på fönster är gjord. Dessutom presenteras en enkel modell för uppskattning av tidpunkt och temperaturskillnad i själva fönsterglaset då det går sönder. Analysen visar att glaset spricker p.g.a. termisk spänning vid temperaturskillnader i glaset av 58°C - 100°C. Motsvarande temperaturer i brandrum varierar mellan 200°C och 400°C .

Brandvolymflöde erhållna med hjälp av simuleringar för olika bränder i de undersökta typer av byggnaderna med varierande lokalgeometri analyseras i projektet för varje typ av lokaler var för sig. Regressionsanalys av de maximala flödena är gjord med hjälp av statistiskt program Minitab och EXCEL. Dessutom presenteras några teoretiska modeller skapade för denna analys. Modeller syftar på att uppskatta brandflöde som funktion av brandeffekt, utvecklad i de studerade rummen. Generalisering av de på ovannämnda sätt uppskattade brandflödena efter jämförelse av dessa med brandflödena från CFAST simuleringarna resulterar i beskrivning av brandflöde som funktion av rumsvolym. Ekvationer erhållna med hjälp av dataprogrammet EXCEL visar bra överensstämmelse och kan användas för brandflödesuppskattning i de studerade byggnadstyperna. Motsvarande brandflöde - rumsvolym kurvor för rumsvolym mellan 30 m^3 och 240 m^3 presenteras i rapporten. Dessa rumsvolymer antas vara de vanligaste i de studerade byggnaderna. Ett kombinerade brandflöde - rumsvolym diagram till innehållande kurvor ritade enligt både beskriven metod och för traditionella αt^2 bränder presenteras i rapporten.

Olika databaser i vetenskap och teknologi genomsöktes, vetenskapliga artiklar har genomlästs samt olika sökprogram i Internet har använts för att skaffa information om kunskaper berörande behandling av ventilationssystem vid händelse av en brand. Dessutom har vetenskapliga och tekniska tidskrifter inom aktuellt ämnesområde följts. Ett försök har också gjorts för att diskutera problemet med forskare via Network motsvarande vetenskapliga nyhetsgrupper.

Risk för rökspridning via ventilationskanaler är uppskattat med hjälp av datorprogram för godtyckliga flödessystem PFS. Gränsbrandflöde, uppskattat med PFS jämföras med maximalt brandflöde enligt brandsimuleringar. Gränsfallet för rökspridning via F-system innebär att frånluftsflödet är noll vid alla rum räknat uppströms från där brandrummet ansluter. Gränsfallet för rökspridning via TF-system innebär att tilluftsflödet till brandrum är noll. Rökspridningen sker när dessa tilluftsflöde vänder och till alla rum räknat nerströms från där brandrummet ansluter.

Grundläggande principer och teoretiska modeller för uppskattning av gränsbrandflöde för tvårums F- och TF-ventilationssystem (öppet och stängt) presenteras i rapporten.

De mest typiska ventilationssystemen i de undersökta byggnaderna samt brandcellsindelning i dessa diskuteras.

Följande typer av ventilationssystem analyseras:

-F-system med en fläkt och kanalsystem bestående av en eller två huvudkanaler,

-TF-system med två fläktar och kanalsystem med grenar till varje brandcell,

-TF-system med ”noll” -kanal. Detta innebär att tilluft förs genom tilluftsdon till varje brandcell, medan frånluft samlas i korridor (”noll”-kanal) och sedan förs bort därifrån via frånluftsdon med hjälp av frånluftsfläkt.

Den här undersökningen är begränsad till principiell analys av risk för rökspridning via ventilationssystem av ovan presenterade typer med fyra grenar, och till motsvarande analys för rökspridning via ”verkliga” förgrenade ventilationssystem med samma grenar.

Uppskattning av gränsfall för rökspridning via ventilationssystem i de studerade typerna av ventilationssystem med fyra grenar, åtgärder mot rökspridning och en kort beskrivning av dataprogrammet PFS presenteras i rapporten.

Det finns två olika sätt att beskriva tryckfallsfunktioner för T- och X-stycken i PFS. Båda sätten har provas. Projektet undersöker en ”onormal” flödesriktning i T- och X-stycken, d.v.s. en omvänd flödesriktning i en av delarna och flödesminskning till nollflöde i vissa delar av formstycke som följd. Hur blir tryckfallsförhållandet i formstycke i det här fallet är inte känt. Högre flöde resulterar i högre hastighet i ventilationskanaler och högre Reynoldstal. Ökande flödesturbulens resulterar i sin tur i säkrare sätt att beskriva tryck som kvadratisk funktion. Beskrivning av T- och X-stycken i PFS som kvadratiska funktioner antas dimensionerande i detta sammanhang.

Olika åtgärder mot rökspridning via ventilationssystem analyseras i projektet:

avstängda fläkt(ar),

fläkt(ar), som varvas upp till dubbla varvtalet,

tilluftsfläkt konverterad till frånluftsfläkt,

bypass från tilluft- till frånluftkanal,

kombination av ovan presenterade åtgärder tillsammans med normal fläkt och med varandra.

Brandflöde som överskrider gränsfallets flöde från tidigare beräkningar används i denna analys. De undersökta fallen omfattar ej alla möjliga åtgärder mot rökspridning via ventilationssystem, men den presenterade metoden kan användas för uppskattning av risk för sådan.

"Verkliga" fall analyserar risk för rökspridning via mer komplicerade ventilationssystem typiska för de studerade byggnadstyperna. Gränsbrandflöde och gränsbrandtryck uppskattas för olika ventilationssystem. Uppskattningen av gränsfallet för rökspridning är beräkningstekniskt svårt för förgrenade ventilationssystem eftersom ett flöde skall vara noll i en av grenar samtidigt som andra flöde och tryck ligger långt utöver de normala värdena. Brandflödena för respektive byggnadstyper uppskattade och presenterade i form av diagram i detta projekt används för undersökning av rökspridningsrisk via ventilationssystem. "Bränder" placeras i olika rum och rökspridning till de närliggande rummen samt olika åtgärder mot det fenomenet undersöks.

Uppskattning av giftighet av utspädd rök diskuteras i rapporten. CO-nivån och CO-dosen kan uppskattas uppåt med några enkla beräkningssteg för ett F-system med avstängd fläkt. Uppskattningen av

total rökvolym som sprids,

andel av rök som sprids till ett enskilt rum, inklusive andel av rök till ett utav *n* rum,

CO-nivå i ett enskilt rum presenteras i rapporten. Alla rum antas vara lika stora. CO-nivå tillsammans med exponeringstid och typ av aktivitet bestämmer CO-dosen och förgiftningseffekter. Olika rekommendationer angående acceptabla och farliga CO-nivåer och CO-doser diskuteras här. Uppskattning av CO-nivån i ppm motsvarande IDLH (immediately dangerous to life and health) begränsat till 1500 ppm under 30 min vistelse, som når ett av *n* rum också presenteras.

Uppskattning av medelsiktbarhet av rök är analog med uppskattningen av CO-förgiftningsrisken. Presenterade ekvationer ger medelvärde för siktbarhet.

Undersökningen är gjord under förutsättningen att alla de examinerade flödena, inklusive brandflödena har normala temperaturer, d.v.s. "kalla" flödena. Samtidigt är det välkänt att temperaturer är högre än de normala temperaturerna och simuleringsresultat i denna rapport visar att brandflödestemperaturer kan överskrida 300°C - 340°C. Detta innebär att förväntad rökspridning via ventilationssystem enligt den presenterade analysen kan skilja sig från den i verkligheten. Uppskattningen av friktionstryckfall i raka ventilationskanaler visar att detta minskar c:a två gånger samtidigt som lufttemperaturen i K ökar två gånger. Tryckfall i motstycke är svårare att uppskatta. Ett överslag visar att klarar man det kalla fallet, klarar man även det heta fallet. Så småningom tack vare rökutspädning och värmeförluster i ventilationskanaler, sjunker flödestemperaturerna och de "kalla" flödena blir dimensionerande.

Ytterligare en metod för uppskattningen av eventuell rökspridning via F-system presenteras i rapporten. Den s.k. "Alexandermetoden" är en förenklad metod för handberäkningar baserad på "borthuggningsprincip". "Borthuggningsprincipen" innebär att den del av kanalsystem som kan utsättas för rökspridning huggas bort och resten av ventilationssystemet räknas om med hänsyn till de nya tryck/flöde förhållandena.

Problemet som undersöks i denna rapport verkar komplicerad och antaganden, gjorda med viss kunskapsbrist och brist av empiriska data, kan inte minska osäkerheten av resultat. Resultaten kan, alltså, inte tolkas som en slags generell lösning för uteslutning av rökspridning via ventilationssystem, utan skall betraktas som en hjälp vid analyser inom detta område.

List of symbols and definitions

Symbols

Unless otherwise started, the following symbols are used throughout this document:

A	area, [m^2]
b	width, [m]
c	specific heat of incompressible substance, [J/kg K]
C	flow coefficient, [-]
d	diameter, [m]
D	optical density per meter, [m^{-1}]
E_y	elastic (Young's) modulus, [N/m^2]
E	energy, [J]
f	coefficient of volumetric expansion, [(m^3/s)/MW]
h	heat transfer coefficient, [W/m^{2}K]
l	length, [m]
m_b	mass flow rate, [kg/s]
p	pressure, [Pa]
q	volume flow rate, [m^3/s]
Q	heat rate, [kW]
R	resistance, [-]
s	visibility range, [m]
t	time, [s]
T	temperature, [°C (K)]
v	velocity, [m/s]
V	volume, [m^3]
z	height, [m]
Re	Reynolds number, [-]
ΔM	mass loss of sample, [g]

Greek letters

α	characteristic value for a certain fire progress, [kW/s^2]
β	thermal expansion,{K^{-1}]
η	viscosity, [N s/m^2]
λ	thermal conductivity, [W/mK]
ν	kinematic viscosity, [m^2/s]
ρ	density, [kg/m^3]
σ	thermal stress, [N/m^2]
Δ	increment of

Definitions

For the purpose of this dissertation, [5] and [6] were used as the main material to describe research in this domain. Nevertheless, some other terms has been used in order to express more recent concepts. The definitions of this dissertation are as follows:

Air leakage:
The uncontrolled flow of air through a component of the building, or the building envelope itself, when a pressure difference is applied across the compartment.

Airtighteness:
A general descriptive term for the air permeability resistance of a building.

Building envelope:
The inside of the exterior surfaces of the building.

Buoyant flow:
A gas flow which is caused directly or indirectly by gravity.

Compartment fire:
Fire in enclosed spaces, which are commonly thought as rooms in a building.

Constrained fire:
The availability of both fuel and oxygen are considered.

Fire flow:
Fire gas flow caused by temperature expansion of the heated gas in the fire room in the case of fire.

Fire plume:
The generally turbulent buoyant flow, which includes any flames.

Forced (mechanical) ventilation:
Ventilation by means of fans.

Natural ventilation:
Ventilation using only natural driving forces such as differences in air temperature and density, wind pressure.

Overflash:
The transition from a growing fire to a developed fire in which all combustible items in the compartment are involved in fire.

Ventilation:
The process of supplying and removing air intentionally by natural or forced (mechanical) means to and from any space.

Unconstrained fire:
Fuel is burned without regard for oxygen availability.

1 Introduction

The problem of smoke spread via ventilation ducts in case of fire has been examined in this work. Fire releases a large amount of heat which causes the room air and smoke produced by combustion to expand. The expansion produced by a room fire drives some of the gas out of the room via all types of openings and leaks. Apart from doors and windows, the most probable openings through which the gas can flow out are ventilation terminals and systems. A room can have all its doors and windows closed, but if the ventilation ducts are open, the gas will leak through the ventilation system and the fire gases can spread to the adjacent rooms.

However, the probability of this and the conditions which lead to such a phenomenon have not yet been fully examined. The main purpose of this study was to examine the possibility of operating the fans during different fires in four types of buildings (compartment, hospitals, offices and hotels) and to estimate the risk of smoke spread in different conditions.

1.1 Background

According to the building regulations and codes in Sweden and in other countries, until recently the only recommended way to prevent the spread of smoke was to install different kinds of dampers and smoke barriers and to shut down the ventilation system in the event of fire, or to rely only on shutting down the ventilation system designed accordingly to given pressure drop relations. The disadvantage of this second method is that some fire gases will always spread to adjacent rooms through the ventilation system.

The first attempt to analyse the problem was made in 1988 by Lars Jensen. He presented the results of the analysis in [1]. The main principles of this analysis will be discussed later in Section 2. Further studies in the field, made by Tobias Hielscher and Björn Warelius, under the supervision of Lars Jensen, resulted in dissertation [2] in 1992. The next work which expanded the principal ideas of the above reports was published in 1993 [3]. In 1994 the Swedish Board of Housing, Building and Planning, Boverket, published a report on this issue [19]. A handbook which summarised up-to-date experiences on the subject was published in 1996, [16]. The results and theoretical bases of all these works will be discussed in Section 2.

1.2 Objective and limitations

After certain theoretical studies and practical tests in order to solve the problems associated with the use of fans during a fire, in order to reduce and in certain cases to eliminate the risk of fire gas spread through ventilation ducts, the main principles and methods are now known. Application of these basic principles largely depends on the characteristic parameters, estimated for different fires in different types of buildings. The main building types chosen for this work are

- dwelling houses
- hospitals
- offices
- hotels.

The main objective is to assess the relationship between typical fires in the above types of buildings, the airtightness of the construction and the layout of the ventilation system, and to give recommendations on good practice to diminish or even eliminate the risk of smoke spread through ventilation ducts to the adjacent rooms. In this connection, one of the most important issues to estimate are the characteristic parameters/features that are produced by certain fires, and to assess their influence on the pressure/flow ratio in the ventilation system.

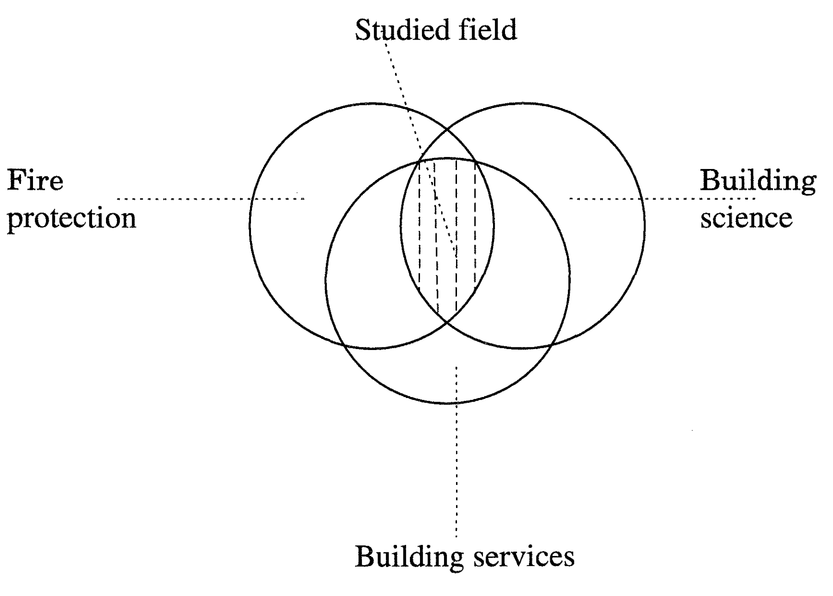
The aim of this study is to clarify the following:

design fire case
design fire spread requirement in relation to flashover
design internal and external airtightness of the chosen rooms
durability of the ventilation system in case of fire
method for assessing what measures are adequate against fire gas spread
proposal for Swedish Building Codes concerning fire gas spread.

This report to some extend can also be used as a textbook in teaching in this field.

1.3 Comprised fields of knowledge

The study is interdisciplinary in nature and comprises different fields of engineering knowledge: fire protection engineering, building science, and building services. It can be illustrated with the following schematic figure:



The whole study is divided into two sections, one of which examines fire behaviour and estimates characteristic parameters in the chosen types of enclosures, and the other one examines the ability of the ventilation system to spread smoke and fire gases via ducts.

Section 1 Analysis of fire behaviour in single spaces

2 Fire behaviour in single spaces

2.1 Statistical estimation

In order to evaluate the principal dangers and damage caused by fire in the chosen types of enclosures, and to assess the most probable items in which fire starts, the following analysis was made.

This Subsection discusses injuries to persons and damage to property caused by fire. It deals both with the cause and the magnitude of this damage. There are large gaps in the information regarding the probability of the outbreak of fire in relation to e.g. the area of the space and the number of people. Thus, it appears to be impossible to analyse this risk, but some data for its assessment are given in this section.

The number of deaths in fire in Sweden varies from 100 to 150 persons per year. The majority of all fatalities occur in dwelling houses (76%). The most usual cause of such fatal fires is obviously smoking.

The danger is also associated with remaining in the burning space for a certain time. Table 2.1 sets out the risk assessment according to English statistical sources for death and property damage for each hour of remaining in the burning space in different types of buildings.

Table 2.1 Risk of death and property damage in case of fire in different types of premises [4].

Type of building	Damage per person 10^8 exposed hours	Deaths per person 10^8 exposed hours
Dwelling house	0.9	0.9
Hospital	0.55	0.29
Office	0.55	0.05
Hotel	20	3.6

It is seen from Table 2.1 that the most dangerous fires, regarding both injuries and the risk of death while remaining in the burning space for a certain time, are those in hotels, but the danger in other types of buildings cannot be ignored. At the same time it is much more difficult to evaluate the number of injures than deaths and to define the type of injury. SRV 1993 reports about 530 injures in 1992.

To evaluate the most probable fire behaviour in the examined cases, it is important to assess the objects which can cause ignition.

Table 2.2 provides information about the objects which cause fatal fires in dwelling houses.

Table 2.2 Objects which cause fatal fires in dwelling houses [4].

Object	%
Bedclothes	36
Sofa, armchair	14
Clothes (old people, handicapped)	11
Flammable liquid (suicide)	6
Food	3
Building construction (electrical fault, defective fireplace etc.)	6
Other	4
Cannot be identified	20

As seen from Table 2.2, the most probable objects which cause fatal fires in dwelling houses are bedclothes and sofas. Table 2.3 presents data regarding the probability of fire hazard annually in different types of buildings.

Table 2.3 Probability of fire hazard in different types of buildings [4].

Type of building	Probability function of one fire per year	Probability of fire per year at A = 1500 m^2
Hospital	$0.0007\ A^{0.75}$	0.17
Office	$0.000059\ A^{0.9}$	0.042
Hotel	$0.00008\ A^{1.0}$	0.12

It is seen from Table 2.3 that the most probable fires are those in hospitals and the least probable are fires in offices. In order to predict the fire behaviour in the building, it is significant to assess the flashover phenomenon. Table 2.4 gives some data on limitations of fire hazard to the object in which the fire started and to the room in which it started.

Table 2.4 Fire behaviour related to the spread of fire from the object in the room of fire origin and spread of the compartment fire to another room [4].

Type of building	Total numbe r of fires	Limited to the object in which the fire started, %	Spread to other objects in the room of fire ori-gin, %	Spread out-side the room of fire origin, %
Dwelling house	52024	46	46	8
Hospital	2243	73	26	1
Hotel	5244	36	53	11
Other	20502	25	63	11

As can be seen from Table 2.4, the majority of all fires remain in the room of fire origin. At the same time, there is the risk of fire spread to the other objects in the same room.

All the data on the statistical evaluation of fire behaviour in chosen rooms is taken from [4].

To sum up the statistical data in this part regarding the danger of fire in the analysed buildings, the most probable fire behaviour is limited to the room of fire origin, and the most probable objects where the fire starts are bedclothes and sofas in dwelling houses.

These data are very important in predicting fire behaviour in buildings, which will be discussed in this section.

2.2 Estimation of basic parameters in compartment fires

The ability to predict different parameters such as pressure, heat release rate, temperature, gas flow through openings, in compartment fires is of great significance for the prediction of fire gas spread. In this section, the fundamental principles underlying the prediction of compartment fire parameters will be summarised along with a number of solution methods.

2.2.1 The stages of fire growth

Compartment fires are often discussed in terms of growth stages. Figure 2.1 shows a theoretical curve of temperature vs. time along with the growth stages.

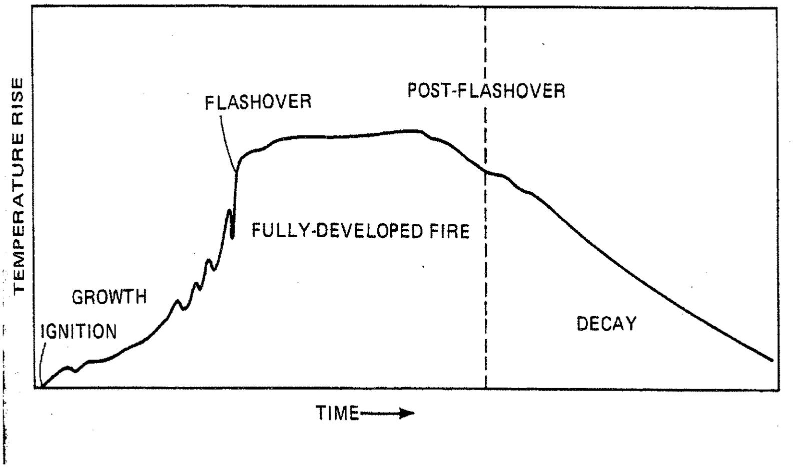


Figure 2.1 *General description of theoretical compartment fire (in absence of fire control) [7].*

The growth stages can be defined as follows:

Ignition
Growth
Flashover

Fully developed fire
Decay.

Ignition stage: The period during which the fire begins.

Growth stage: The stage during which the fire grows. At the beginning of this stage the growth of fire is not influenced by the compartment. The fire can be described in terms of its rate of energy and combustion product generation. If sufficient fuel and oxygen are available (fuel-controlled fire), the fire will continue to grow, causing the temperature and rate of heat release to rise, until it changes into a ventilation-controlled fire.

Flashover: The stage characterised by the total involvement of all combustible items. The flashover stage can be described in terms of the temperature at which the radiation from the hot gases in the compartment will ignite all the combustible items in the room. Gas temperatures of 500-600°C are common. This gas temperature is equal to a radiation intensity of 12.5 - 20 kW/m^2 floor.

Fully developed fire: The stage during which the heat release rate is the greatest. During this stage the fire is said to be strictly ventilation-controlled. If there are some openings in the compartment, the unburned fuel will leave the compartment with the gas flow, mix with oxygen and burn outside the compartment.

Decay stage: The stage during which the heat release rate declines and the fuel is consumed. The fire changes from ventilation to fuel controlled.

While many fires will not conform to this idealisation, it provides a useful framework for the discussion of compartment fires. All fires include the ignition stage; beyond that they may fail to grow, or they may be affected by different activities before passing through all the stages listed above. It can be extremely important to differentiate between well ventilated fires (fuel-controlled) and ventilation-controlled fires. All fires consume oxygen. A period when fire growth depends only on the amount of fuel, i.e. when there is sufficient air and oxygen, is called well-ventilated or fuel-controlled fire. The stage of fire when its growth depends on the amount of air (oxygen), i.e. when there is insufficient air, is called ventilation-controlled fire stage. These processes can play a decisive role in fire growth stages, particularly in compartment fires.

In small compartments of the analysed types, real fires can be different from the above case.

2.2.2 t^2 fire growth

The curves in Figure 2.2 give a schematised picture of fire growth during complete burning of combustibles (samples) in terms of temperature as a function of time. It will typically be found that there are limited experimental data available regarding the burning rate of a specific burning item. Nevertheless, there are different ways in which fire progress can be described. One of these, the simplified method, is based on the assumption that the growth phase of many fires can be characterised as a function of the square of time. This idealised fire energy release rate is described by

$$Q = \alpha t^2 \qquad \text{(kW)} \qquad (2.1)$$

where Q is in kW and t in seconds. α is in kW/s^2 and has a characteristic value for a certain fire progress. Its value for four types of fires as well as time to reach 1MW heat release is presented in Table 2.5.

Table 2.5 Fire growth parameter and time to reach 1 MW heat release for different types of idealised fires.

Type of fires	α, kW/s^2	Time to reach 1 MW, s
Slow	0.00293	584
Medium	0.01172	292
Fast	0.0469	146
Ultrafast	0.1876	73

Note that each α value is four times as high as the previous one and time to reach 1 MW heat release is two times as high as the previous one.

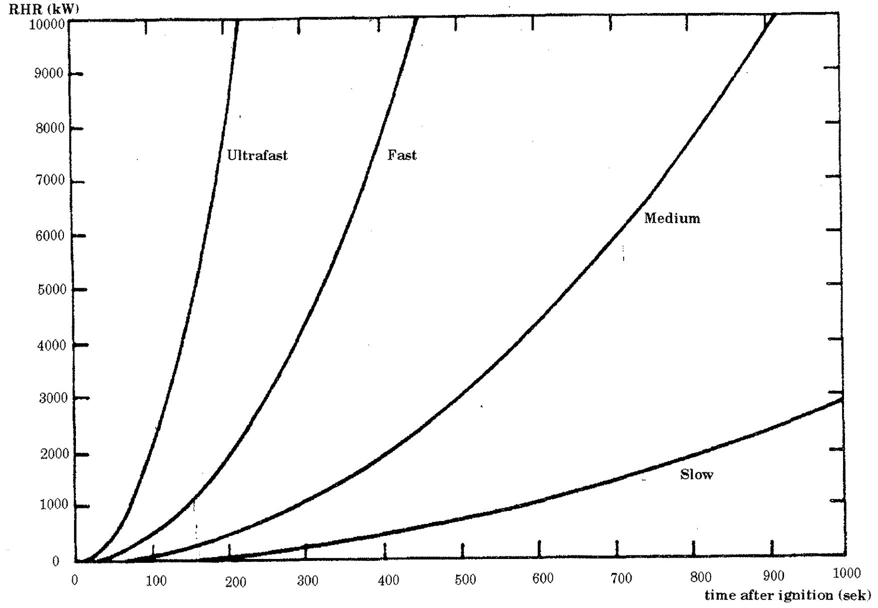


Figure 2.2 Four types of fire progress [30].

This method of evaluating fire growth is used especially for industrial buildings and warehouses. Owing to its simplicity, sufficient agreement with test results and lack of available data, this method can be applied to some other types of fires. However, this description of fire progress can be questioned when fire behaviour is more precisely defined.

2.2.3 Measured heat release fires

In order to evaluate fire behaviour more precise, another type of fire growth curve is widely used. These type of data are based on the results of full-scale tests in which different items were burnt in the laboratory and heat release rate as a function of time was measured.

According to the results in Subsection 2.1, the following items were assumed to initiate fires:

- in dwelling houses sofa [6] and bed [7]
- in hospitals bed [9]
- in offices equipment and furnishing [10]

- in hotels bed [6].

Figures 2.3 - 2.7 present fire growth curves for these items.

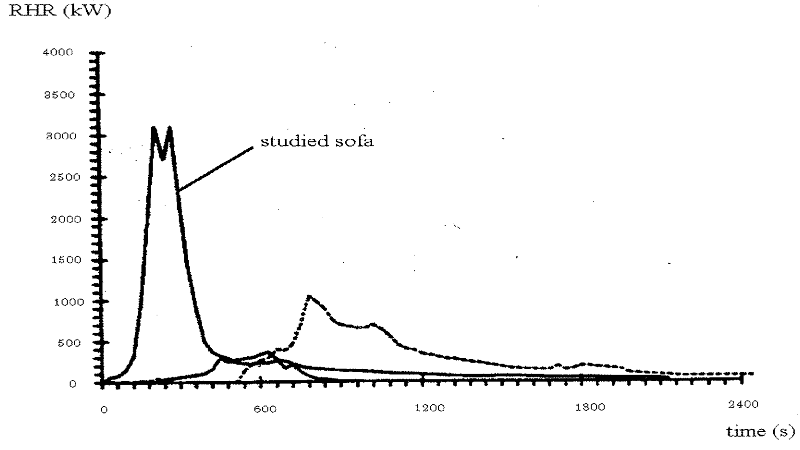


Figure 2.3 Heat release rate / time for burning sofa [6].

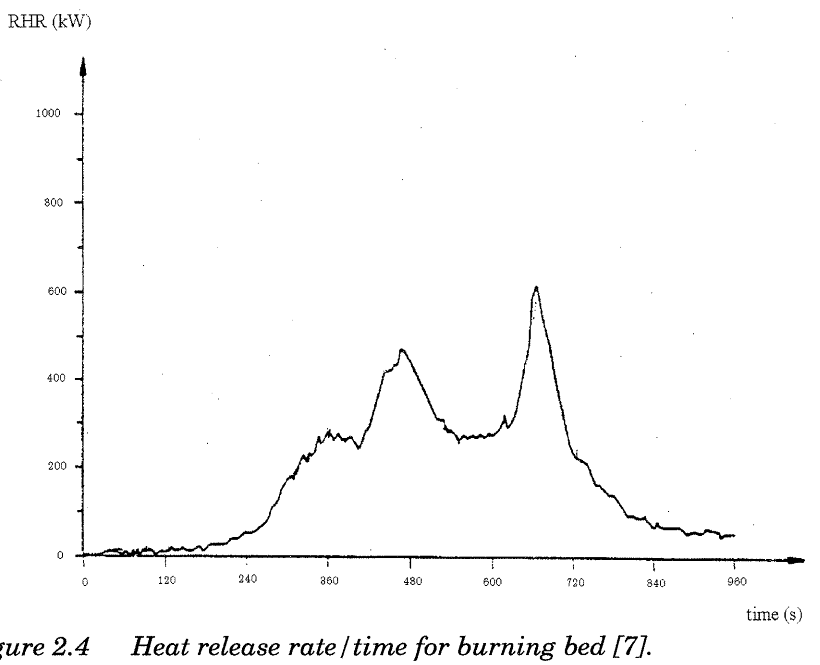


Figure 2.4 Heat release rate / time for burning bed [7].

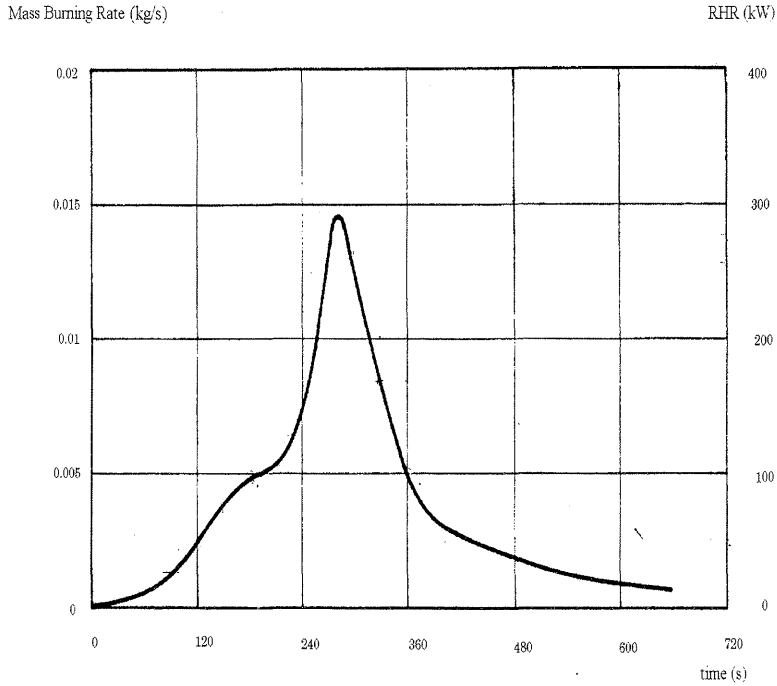


Figure 2.5 *Heat release rate / time for burning hospital bed [9].*

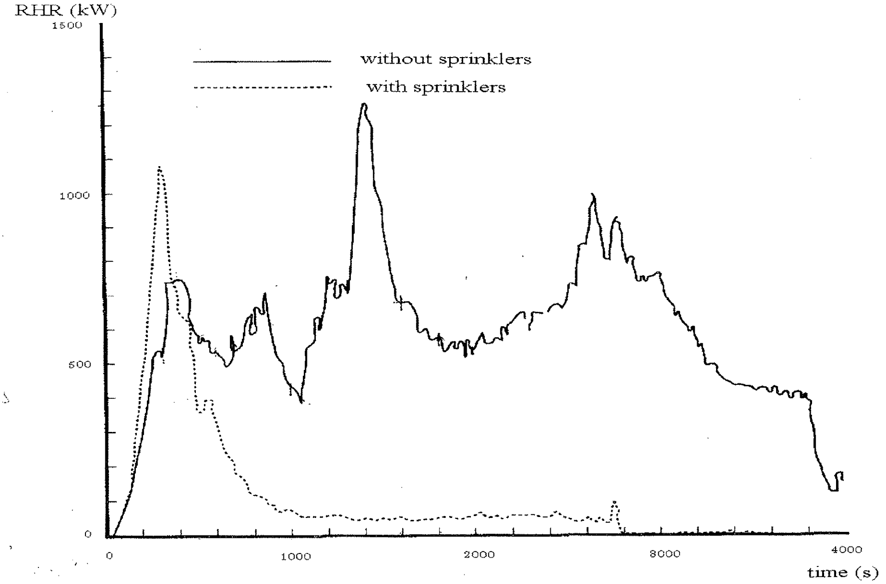


Figure 2.6 *Heat release rate / time for burning equipment and furniture in office [10].*

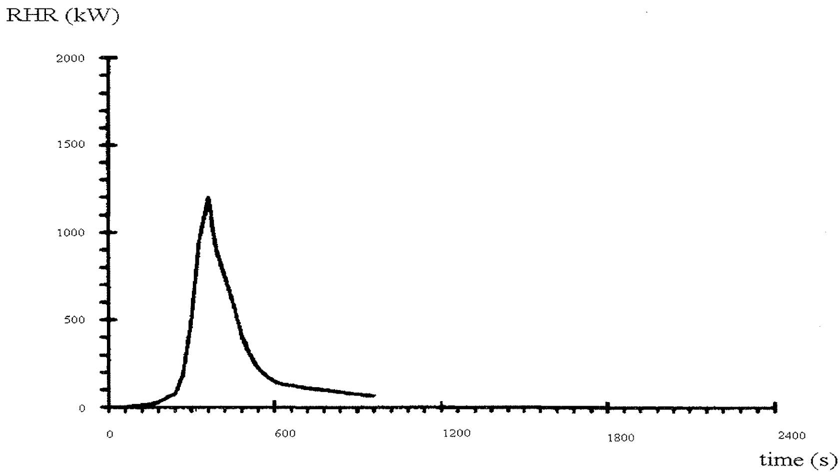


Figure 2.7 Heat release rate / time for burning bed [6].

The ability to predict different parameters in compartment fires is of great significance for this project and for fire protection engineering.

2.2.4 Compartment fire model

In order to calculate or predict parameters generated by a compartment fire, a description or model of the fire phenomenon must be created. Such a model is also an idealisation of real hazards. Different models divide the room into different numbers of control volumes depending on the desired level of accuracy. The most common fire model is the zone model. It generally uses two volumes to describe the room - an upper layer and a lower layer.

An arbitrary fire, which starts at some point below the ceiling, releases energy and products of combustion. These are time dependent variables. The hot products of combustion form a plume which rises to the ceiling due to its buoyancy. While rising, the plume draws in ambient air from within the compartment. This decreases the temperature of the plume and, at the same time, increases the volume flow rate. After reaching the ceiling, the plume spreads out and forms a hot gas layer which descends as gases continue to flow into it. Hot gases collect at the ceiling and fill the room from the top. As the hot gas layer descends and reaches openings in the compartment, hot gas flows out and the ambient “cool“ air flows in through the openings. This description of compartment fire is referred to as a two-layer or zone model. This two-layer model has evolved from observation of such layering in real-scale fire experiments. While these experiments show some variation in conditions within the layer, these are small compared with the differences between the layers. These two-layer models can thus provide a fairly realistic simulation under most conditions. This model assumes that the predicted parameters such as temperature, pressure, smoke and gas concentration, and layer height above the floor, are uniform at any time within this volume which is referred to as the control volume.

There are different mathematical models based on different assumptions, which describe the two-layer fire model with the help of differential equations. The detailed analysis of such mathematical models is beyond this study, but it can be interesting to emphasise that two of them, constructed by Zukoski and McCafrey respectively, are used in different computer programs, discussed further.

Other types of models include field models. These models divide the room into thousands or even hundreds of thousands of grid points. Such models can predict the variation in conditions within layers. They are used when highly detailed calculations are essential.

The main compartment fire phenomenon is illustrated schematically in Figure 2.7.

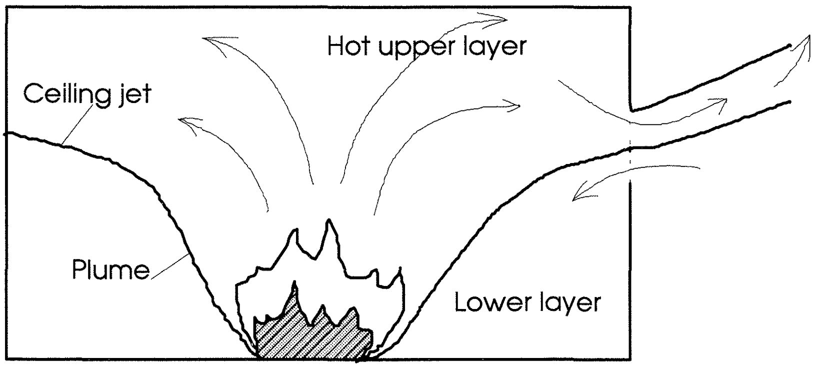


Figure 2.8 Two-layer model.

2.3 Computer methods for predicting compartment fires

Very complicated processes of fire development which are described with the help of a large number of mathematical expressions necessitate the use of a computer program. There are different computer programs which simulate hazard phenomena. These simulations provide estimates of different elements of hazard development, such as fire growth, smoke generation, temperature rise, species production, layer descent. Some programs are confined to the room of fire origin, others can estimate processes in multiple rooms. This study is limited to single-room compartment fires. The programs described below were chosen to simulate hazard development for the types of fires analysed in this study.

2.3.1 CFAST (HAZARD1)

CFAST (Consolidated Model of Fire Growth and Smoke Transport), which is part of the computer program HAZARD1 [15], predicts the conditions within a structure, resulting from a user-specified fire. The program is developed and written at the Center for Fire Research, the National Institute of Standards and Technology, USA. The program uses the two-layer model described in Subsection 2.2.4 in order to calculate the distribution of evolving smoke, fire gases and temperature throughout a building during a fire. In CFAST, each room is divided into two layers, all parameters in which are assumed to be exactly the same at every point. Since these layers represent the upper and lower parts of the room, conditions within the room vary only vertically, from floor to ceiling, and not horizontally. CFAST is based on solving a set of equations that predict state variables (pressure, temperature, heat release, species, etc.) based on the enthalpy and mass flux over small periods of time. These equations are derived from the conservation equations for energy, mass and momentum, and the ideal gas law. The fire model involves an interdisciplinary consideration of physics, chemistry, fluid mechanics and heat transfer. The model is particularly well suited for predicting parameters and for studies of changes, both subtle and large, within a single room. The necessary approximations required by operational practicality result in the introduction of uncertainties in the results. The fire plume model description follows McCafrey's plume model.

Limitations:

- an important limitation of CFAST is the absence of a fire growth model. The program utilises a user specified fire,
- the two zone model involves a mixture of established theory, approximations and empirical correlation,
- burning is constrained by the available oxygen. An oxygen co bustion chemistry scheme is employed only in constrained (ventilation-controlled) fires. Predictions of concentrations of chemical products are based on user-specified hydrocarbon r tios,
- some coefficients, used in the equations, are empirically de termined values.

The only mechanisms provided in zone models to move enthalpy and mass into the upper layer of a room are two types of plumes: those formed by the burning item in the room of fire origin, and those formed by the jet of upper layer gases escaping through an opening.

2.3.2 DSLAYV

DSLAYV is a computer program which predicts the conditions within a single space, resulting from a user-specified fire. The program uses the two-layer model described in Subsection 2.2.4 in order to calculate the smoke filling process, temperature throughout a space during a fire, pressure rise and other parameters. A steep thermal gradient separates the two layers. For a given fire size, specified in terms of heat release rate, the conservation equations of mass and heat are solved for the layers, yielding the smoke layer height, temperature and the radiant heat conditions in the room of fire origin as a function of time. The fire plume model description follows Zukoski's plume model. Only incombustible linings are allowed for in the model. The surfaces enclosing the lower layer are heated, but the air layer is considered to be at ambient temperature. DSLAYV is an interactive program. A dialogue between the user and the program is governed by commands adapted to the concepts of the user. The program is developed and written by Bengt Hägglund at the National Swedish Defence Research Institute, and is presented in [18].

2.3.3 SMAFS

SMAFS (Smoke Movement and Flame Spread) is a field model program which is designed to simulate the fluid flow and combustion processes in a general sense, especially those involved in fire. The program is used at the Department of Fire Safety Engineering, LTH, and simulations are made by guest researcher Yan Zhenghua, which is gratefully acknowledged.

The simulation is based on the simultaneous solution of a large number of differential equations. Consideration is mainly given to the following physical and chemical processes:
1. turbulent fluid flow,
2. radiation,
3. combustion,
4. heat transfer inside wall boundaries, and
5. pyrolysis of solid combustible materials.

The purpose of developing this package is to have a theoretical tool to predict turbulent flow and turbulent combustion which are of great interest to industry and safety design. It includes the following models: turbulence model, combustion model, radiation model, solid material pyrolysis model, heat transfer wall function, etc. The limitation is determined by the accuracy and validity of the incorporated models.

With the support of its pre-processor and post-processor, the package is quite easy to use. The computer power requirement is mainly dependent on the complexity of the problem under study.

In this study CFAST was chosen as the basic tool of fire simulation owing to the fact that it is a modern program under constant improving. DSLAYV was used for test fire simulations in order to control and compare results. Both CFAST and DSLAYV are zone-model based programs. As the zone-model based programs predict the average gas parameters in the various regions, but do not provide information on local conditions which may be obtained from field model studies, another program, SMAFS, was used to estimate the danger of flashover effects, and for evaluating the temperature field near the ventilation terminal. These simulations and their results will be discussed further.

2.4 Airtighteness

The expansion of gas caused by heat released during the fire increases the pressure in the compartment and drives some gas out of the room through leakage paths. All openings through which gas flows out are called vents. If a window is open in the room of fire origin little flow occurs through the remainder of the building. When doors and windows are closed and there are no ventilation openings, flow will move towards cracks and leaks wherever they may be in the room. All these flows are initially nonbuoyant. As the fire grows, hot gas flows buoyantly out of the place of origin, while cold gas flows in below (Figure 2.8). To evaluate gas flux (mass flow) out of the burning room with the help of the simulation programs, it is essential to know the sizes of such vents.

Air leakage occurs as a consequence of building design, workmanship and materials used. The amount of air leakage depends on the magnitude of the driving forces in combination with the size and shape of the leakage paths. In the normal case, these driving forces are pressure differences across the structure, temperature differences between the inside and outside of the structure and, if there is one, the ventilation system.

For new houses, the standard requirements specified in Swedish Building Regulations, BBR 94, must be followed. According to BBR 94, air infiltration should not exceed 0.8 l/s,m^2 (3 m/h) for dwellings and 1.6 l/s,m^2 (6 m/h) for other types of buildings at 50 Pa pressure difference. This requirement relates to the area of the building envelope. The building envelope area is defined as the area exposed to outside air.

The objective of this evaluation is to summarise knowledge about the real magnitude of leakage, in relation to the whole building envelope including interior building constructions, for the types of enclosures, built at different times, which are described in Subsection 1.2.

Air leakage, normally divided into external and internal leakage, is of interest for this study in terms of average values for the whole building envelope of rooms or apartments. Tracer gas measurements and pressurisation measurement, performed in dwelling houses built in 1988 (Per Levin, [9]) have shown the following results.

Measured internal air leakage between apartments has been found to account for 12 - 33%, and in some cases up to 50 %, of the total air leakage at 50 Pa. Thus, small internal leaks have been found to exist.

Measured air leakage for the whole apartment has shown good agreement with the Swedish Building Regulations requirements for the external building envelope even for a corner apartment.

This study includes several experimentally built energy efficient apartment buildings of extremely good airtightness. The techniques used for building construction and building services systems are representative of those used for new Swedish multifamily buildings.

In different investigations, made both in Sweden and abroad, the problem of air leakage in single family houses was analysed and air infiltration under different conditions was measured (Technical Note AIVC [27], Åke Blomsterberg [10]). All these studies relate to comparatively newly built dwellings of good airtightness, and show very good agreement with Code requirements.

The analysis described above are not sufficient for this study which comprises different types of buildings. In particular, there are no data for older buildings. At the same time, the information from international scientific documents published abroad cannot be used as straightforward data, due to Swedish construction traditions and airtightness requirements which are different from those in other countries.

As a reasonable assumption in this respect, the air leakage according to the Swedish Building Regulations, BBR 94, applied to the whole buildings envelope, can be accepted as a suitable and probable value.

3 Fire simulations

In order to predict fire behaviour in the selected enclosures, a series of simulations was made with the help of different computer programs. The purpose of these simulations was to find reasonable peak values for different parameters, such as temperature of the hot gas layer, layer descent, pressure rise due to volume expansion and, what is most important, peak flow out of the fire room. This mass/volume flow affects the behaviour of the ventilation system, which can result in spread of smoke and hot gases to adjacent rooms via ventilation duct network.

3.1 Input data used in simulations

3.1.1 Geometrical data

As described in Chapter 2, the CFAST (HAZARD1) packet was chosen to simulate hazards in four types of buildings: dwellings, hospitals, offices and hotels. The geometrical data is presented in Table 3.1. All walls in all types of buildings have the same data, which is gypsum.

Table 3.1 Geometrical data for the examined cases.

Type of building	Area, m^2	Height, m	Volume, m^3
Dwelling house*	12	2.4	28.8
	20	2.4	48
	56	2.4	134.4
	62.2 1)	2.4	149.3
	75	2.4	180
	85	2.4	204
Hospital	14.4 2)	2.5	36
	14.4 2)	3.75	54
	20 2)	2.5	50
	20 2)	3.75	75
	30	3.75	112.5
Office	10.5	3	31.5
	15	3	45
	25	3	75
	40	3	120
Hotel	16	2.4	38.4
	24	2.4	57.6
	24	3.5	84
	64	3.5	224

* - Geometrical data for apartments correspond to average statistical size for students' lodgings, one-, two- and three-room apartments of standard height.

1) Average size of apartment per person in Sweden according to [11].

2) Geometrical data for hospital rooms according to [12].

The main purpose of this data was to choose the most typical sizes of the assumed types of buildings.

3.1.2 Fire scenario and fire position

The bed and sofa fires are assumed to be initiated in dwelling houses, the hospital bed fire in hospitals, the furnishing and equipment fire in offices and the bed fire in hotels. Flaming combustion is assumed. The fire growth model in the rooms discussed above conforms to the description of initial fires, given in Chapter 2 for "real fires". This was considered to give a more realistic picture of fire hazards in the examined types of buildings.

The position of the object in the room plays an important role in estimating fire behaviour as it determines fire plume wall and corner effects. Owing to the fact that few experimental data are available and the errors of such simulations are therefore difficult to estimate, different cases were tested in this study in order to assess the process. The cases tested were fire growth of the same fire, in the same room, placed in the centre of the room, in the corner of the room , and near one of the walls. The fire location affects plume expressions, which results in different values of predicted parameters.

3.1.3 Assumed airtightness

The room is closed except for leakage paths at the sill of the closed doorway (normal case). Other leakage paths, at the top of the doorway and vertically along the sides of the doorway, were also tested.

The size of vents is determined by requirements in the Swedish Building Regulations as discussed in Chapter 2. If a pressure drop, Δp, exists across a leakage path of a certain area, A, with a fluid density, ρ, the flow through the vent has volume flow

$$q = C A \sqrt{\frac{2 \Delta p}{\rho}} \qquad (m^3/s) \qquad (3.1)$$

In this formula the flow (or constriction) coefficient can be set at C = 0.68 for an orifice. The leakage paths can thus be estimated to be equal to 1.25 cm^2/m^2 of building envelope for dwellings and 2.5 cm^2/m^2 of building envelope for other types of buildings.

It is assumed that there is no ventilation system and, therefore, no influence on the fire progress.

3.2 Analysis of parameters evaluated by CFAST

3.2.1 Predicted variables

In this study the following set of variables, predicted with the simulation program CFAST, to be shown:

- upper layer gas temperature,
- room pressure,
- layer interface position,
- heat release rate,
- upper layer gas species concentration (oxygen),
- vent flow in and out of the room.

Although there are certainly other variables of interest, these will provide an indication of the characteristic fire behaviour in the fire room.

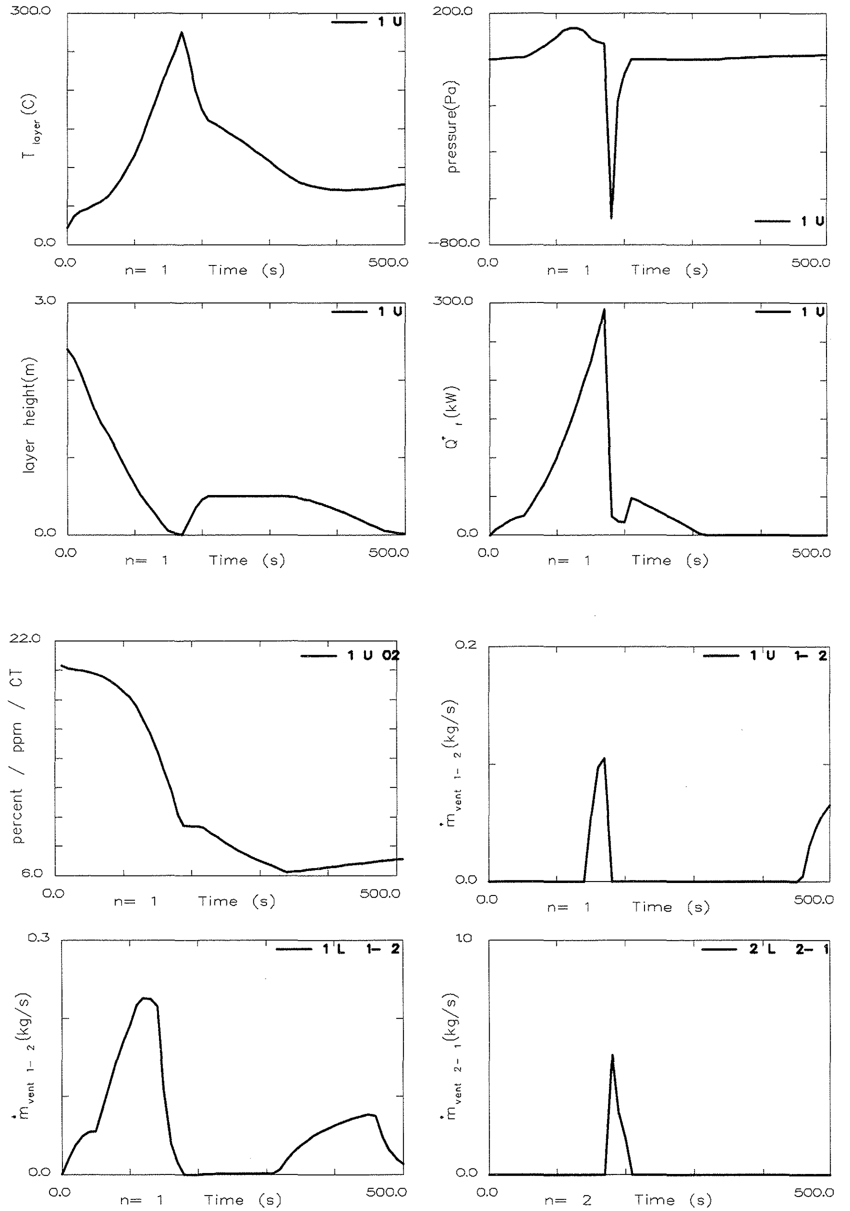
Table 3.1 shows predicted variables in the form of diagrams and a table for a fire in a 4x4x2.4 m hotel room.
This example was chosen to show the way the predicted results from simulations are evaluated. All in all, 29 fires were simulated according to the principles described in Table 3.1 and Subsection 3.1.2. Fire behaviour for the examined cases was simulated in rooms of different area and height, and with different fire placement. The results of these simulations in the form of diagrams are given in Appendix A. All the simulated fires have shown that only the ignition and growth stages occurred.

Table 3.1 CFAST results in the form of diagrams and table for fire behaviour in a 4x4x2.4 m hotel room (beginning).

Time (s)	Temperature , °C	Pressure, Pa	Interface, m	Heat release, kW
0	22.0	-0.004	2.40	0.00
10	37.4	1.17	2.29	7.66
20	43.9	3.67	2.10	14.0
30	47.1	6.34	1.85	19.0
40	51.4	8.00	1.63	22.7
50	56.0	8.26	1.45	25.0
60	63.0	19.6	1.30	37.0
70	73.2	35.3	1.15	50.5
80	85.6	54.5	0.986	65.5
90	100.0	75.7	0.821	82.0
100	116.0	96.9	0.656	100.0
110	136.0	125.0	0.509	123.0
120	160.0	136.0	0.392	147.0
130	184.0	135.0	0.273	172.0
140	208.0	125.0	0.157	198.0
150	230.0	90.3	0.06	225.0
160	252.0	76.8	0.024	258.0
170	276.0	67.1	0.01	292.0
180.	246.0	-685	0.160	24.5
190	201.0	-181	0.355	17.5

Table 3.1 CFAST results in the form of diagrams and table for fire behaviour in a 4x4x2.4 m hotel room (end).

Time (s)	Species, O_2 %	$m_{vent\ 1\text{-}2}$, 1U, 1-2 kg/s	$m_{vent\ 1\text{-}2}$, 1L, 1-2 kg/s	$m_{vent\ 2\text{-}1}$, 2U, 2-1 kg/s
0	20.7	0.00	0.000	0.00
10	20.5	0.00	0.021	0.00
20	20.4	0.00	0.037	0.00
30	20.4	0.00	0.049	0.00
40	20.3	0.00	0.055	0.00
50	20.2	0.00	0.056	0.00
60	20.0	0.00	0.086	0.00
70	19.7	0.00	0.115	0.00
80	19.4	0.00	0.143	0.00
90	19.0	0.00	0.169	0.00
100	18.6	0.00	0.191	0.00
110	18.0	0.00	0.217	0.00
120	17.1	0.00	0.226	0.00
130	16.1	0.00	0.225	0.00
140	15.0	0.00	0.216	0.00
150	13.7	0.057	0.110	0.00
160	12.3	0.097	0.04	0.00
170	10.7	0.105	0.016	0.00
180	9.83	0.00	0.00	0.510
190	9.80	0.00	0.00	0.262



1 - fire room, 2 - adjacent space, n - room number
U - upper layer, L - lower layer, $m_{vent\ 1-2}$ - mass flow from the fire room to the adjacent space

As can be seen from Table 3.1, the fire in this specific room can be analysed in the above chosen terms. Peak temperature of 276°C is reached 170 s after ignition. Peak heat release rate, 292 kW, is reached at the same time. The lower limit of oxygen, which is assumed at 12% in CFAST, determines the point below which burning will not take place. As can be seen, the rate of burning decreases as the oxygen level drops. Pressure reaches its peak of 136 Pa after 120 s, and causes fire gas and smoke to move through the leakage paths with a mass flow which reaches its peak value at the same time, 120 s. As smoke travels away from the fire, its temperature drops due to heat transfer and dilution. The upper layer reaches the floor after 150 s, and once the buoyant outward flow exceeds gas expansion due to the fire, the pressure at the floor falls below atmospheric. Outside air thus flows in at the bottom 180 s after ignition.

As can be seen, in a ventilation controlled compartment fire which is extinguished due to lack of oxygen, there is a limit to the heat developed, the temperature rise and the volume of smoke produced.

3.2.2 Peak pressure, peak heat release rate and peak temperatures in fire rooms

As mentioned before, the peak temperature and peak pressure in the fire room can be predicted with the help of simulations. Some of these peak values are presented in Table 3.2.

Table 3.2 Peak pressure, peak heat release rate and peak temperature, simulated with CFAST for the examined cases.

No	Type of building	V, m^3	Heat release rate, kW	Temp, °C	p, Pa
1	Dwelling house (sofa)	48.00	300	281	575
2		134.40	1035	322	2057
3		149.28	1035	344	1856
4		180.00	1298	344	1758
5		204.00	1569	345	1619
6	Dwelling house (bed)	28.80	160	240	172
7		134.40	422	208	86.1
8		149.28	442	206	77.1
9		180.00	500	202	74.3
10		204.00	500	197	68.2
11	Hospital	36.00	225	244	76.7
12		50.00	225	257	96.5
13		54.00	287	260	125
14		75.00	287	220	108
15		112.50	287	185	121
16	Office	31.50	187	331	122
17		45.00	224	318	40
18		75.00	275	290	28.3
19		120.00	350	155	48.5
20	Hotel	38.40	309	262	187
21		57.60	528	286	300
22		84.00	410	315	410
23		224.00	1167	293	548

In the table, the peak values for temperature, heat release rate and pressure are the maximum values obtained in these simulations. These parameters may reach their peaks at different times.

As can be seen in Table 3.2, the temperature in the upper layer of the majority of examined rooms varies between 150 and 300°C, which is acceptable. In several cases, in dwellings, offices, and hotels, it exceeds 300°C. Pressure in the majority of the rooms is relatively low and in dwellings (bed), hospitals and offices it does not exceed 135 Pa. In dwellings where the sofa is burning, the pressure is considerably higher - up to 2057 Pa.

As this value seems high enough to be discussed, some assessments have been made in order to predict some more "real" pressures in these rooms. Simulations were made of the same fires as before in the above rooms, on the assumption that ventilation terminals were not blocked in addition to leakage paths. The results have shown considerably lower pressures in dwellings with sofa-burning fires. The highest value does not exceed 647 Pa, as against 2057 Pa in the model assumed above.

The peak heat release rate shows considerable variation between 160 and 1569 kW.

3.2.3 Mass and volume flow

Mass flow is the dominant source term for predicting the probability of smoke spread to the adjacent rooms via ventilation ducts and other paths. It fluctuates very rapidly and is highly sensitive to changes in the environment. Flow through vents comes in two varieties. There can be a vertical flow through horizontal vents. This occurs if there are vents in the floor or ceiling of the compartment. The other flow is a horizontal flow through vertical vents such as ventilation terminals and cracks in the walls. These horizontal flows are of interest in this study as all leakage paths are assumed to be concentrated around the doors.

Prediction of vent flow that is governed by the pressure difference across a vent is based in CFAST on the equation

$$\dot{m} = b\int_{z_1}^{z_2} \rho\, v(z)\, dz \qquad (3.2)$$

where b is width and z height of the vent.

CFAST defines the limits of integration with neutral planes, i.e. the height at which flow reversal occurs, and physical boundaries such as sills. As hot gases from the source compartment leave that compartment and flow into an adjacent space, a door jet can exist which is analogous to a normal plume.

Ventilation systems operate with volume flows. The term “flow“ or ”fire flow” will be used to mean volume flow. Combination of two parameters - mass flow and its temperature at a certain time - determines the magnitude of volume flow. Peak values of flows, predicted by source simulations, are used later in assessing the probability of smoke spread in ventilation systems.

3.3 Comparisons of predicted by CFAST parameters with experimental data

Comparison of model predictions with experimental measurements serves the purpose of determining the accuracy in predicting variables in relation to hazard. As the present study is based only on computer simulations, it seems reasonable to compare results from these with some reference values obtained during experiments. Some experimental data relating to this area are presented in [15]. Simulations and experimental tests were made for a fire under conditions different from those in the present study. Certain results for a single-room fire case are limited to a special type of fire - with a burning wall involved. Such fires are not typical of the studied hazards, but considering the general lack of experimental data on the subject they cannot be ignored. A short summary of such a comparison, presented in [15], is described in this Subsection.

Predicted temperatures for the single-room tests show obvious similarities with the measured values. Peak values occur at similar times, with comparable rise and fall for most comparisons. In general, upper layer temperature and interface position predicted by the model are somewhat higher than experimental measurements, with the differences ranging from -110 to 180°C for the temperature and -0.1 to -0.3 m for the interface position. These peak temperatures, varying between 590 and 970°C, occur at approximately 500 s after the start of the fire. Before this time, measured and predicted temperatures are always close. For all the tests, the time to peak values predicted by the model is on average within 25 s of experimentally measured values.

Predicted values of the single-room test concentrations of O_2 are lower than those measured experimentally (on average 5% low).

For the pressure predicted in the single room with certain leakage, agreement can be considered reasonable only for small leakage areas. Otherwise, both temperatures and pressures change by more than a factor of two. For the type of cases examined in the present study, with relatively small leakage areas, agreement can be considered reasonable.

For the mass flow through vents in a single-room test, the simulated values were somewhat underpredicted by the model.

However, owing to the scarcity of experimental data and the complexity of comparing the numerous variables in a complex fire model, true validation of the model cannot be made (true validation of a model would involve proper statistical analysis of a variety of compared variables). Nevertheless, in view of the lack of experimental data and the results of the comparison discussed above, it may be assumed that fire parameters predicted by CFAST agree quite well with measurements.

3.4 Analysis of parameters evaluated by CFAST, DSLAYV and SMAFS

Hazard parameters predicted by the simulation program CFAST are based on the analysis of a two-zone model and McCaffrey's plume equations. As described before, this model assumes homogeneous layers with no variation in conditions within the layer. In other words, the parameters characterising both layers are average values of variables. Another type of program based on a field model provides an opportunity to predict variations in conditions within the layer. SMAFS (simulation of fires in enclosures) is such a program. For the purpose of evaluating the results obtained with CFAST, a special case was studied.

Bengt Hägglund of the Swedish Defence Research Establishment FOA has simulated different t^2-fires in compartments of certain size with the help of DSLAYV, and his results are presented in [16]. One of the cases from this study was chosen as a reference case and the similar fire scenario in a similar room under similar conditions was simulated with the help of SMAFS and CFAST. A fire scenario for medium fast fire in a 6 x 5 x 2.5 m room was tested.

The purpose of this comparison was to see how well the magnitude of the mass flow predicted by CFAST agrees with those predicted by the two other programs.

Some parameters predicted by these three programs are shown in Table 3.3.

Table 3.3 Comparison of temperatures and mass flow, predicted with the three simulation programs DSLAYV, CFAST and SMAFS for a medium fast fire in a compartment of 75 m^3.

	DSLAYV	CFAST	SMAFS
Temperature, °C / time, s	200 / 180	313 / 200	377 / 300
Mass flow, kg/s / time, s	0.250 / 180	0.296 / 200	0.36 / 300
Volume flow, m^3/s / time, s	0.333 / 180	0.488 / 200	0.663 / 300

Mass flows predicted by DSLAYV, CFAST and SMAFS are peak values, obtained at a certain time in the studied cases. As seen in Table 3.3, both mass and volume flows predicted by SMAFS simulations for the medium fast fire in the compartment of 75 m^3 are higher than those predicted by CFAST, which is in turn higher than those predicted by DSLAYV. Flows obtained with SMAFS cannot be considered as determining values because they are very approximate and are the results of only one simulation, which is not enough for any conclusions to be drawn. Unlike CFAST and DSLAYV, SMAFS assumes no limit to oxygen. This means that combustion proceeds even at low values of oxygen in the room, in other words if there is available oxygen in the room. This explains the “continuation“ in fire growth compared with then, predicted by DSLAYV and CFAST.

SMAFS is a field model program which divides the room into thousands or even hundreds of thousands of grid points, as described in Chapter 3. Such models can predict the variation in conditions within layers. In this case it was used to determine parameters under the ceiling near the possible ventilation terminals. Results from SMAFS simulations cannot be used directly in smoke spread assessment, but they can show the trend in such evaluations, such as:

- the pressure rise in the burning room can be approximately at least double that predicted by CFAST
- temperatures near ventilation terminals can attain higher values than those predicted by the two-zone model; it is however difficult to draw any conclusions regarding flashover effects in ducts due to lack of data on the subject
- mass and volume flows can exceed values predicted by two-zone models.

One of the important conclusions in this connection is that it is reasonable for safety evaluation to prefer higher parameters of the kind, if possible, to lower ones.

3.5 Window breakage modelling

As seen from Table 3.1, a compartment fire can go out by the depletion of available oxygen. The CFAST fire model assumes that the envelope of the room of fire origin is perfectly airtight except for leakage paths. Window breakage sets limits for the ”closed” fire scenario.

If a window in the building envelope were to be broken during the fire, the whole fire scenario would change and other fire phases and hazard parameters would be observed. The fire model discussed above and the whole fire behaviour would not therefore be valid any longer. Before breaking, the window acts as a wall, and after breaking, as a vent for the escape of toxic fire gases and as an inlet for outdoor air. As the breaking of window glass due to thermal stress and pressure in compartment fires is a very commonly observed phenomenon, it is necessary to predict the time at which the window breaks and the ambient conditions which make this possible. CFAST can not predict breakage of window glass during a fire and it assumes that the building envelope is of solid construction.

The results of simulations should therefore be analysed further concerning glazing behaviour. There are a lot of parameters which can play an important role in the assessment of window breakage:

- temperature in the room,
- pressure in the room,
- outdoor temperature,
- window geometry and size,
- number of panes of glass,
- quality of glass,
- construction of the window,
- rapidity of fire,
- direct/indirect contact with flames,
- vertical temperature gradient in the room,
- window bars,
- glass absorption,
- etc.

3.5.1 Study of the literature

The initiation and propagation of cracks in glass and the breaking of glass due to the heat developed by a fire is a very complicated problem, and its analysis is beyond this study. In order to evaluate window behaviour and to estimate or assume some characteristics, the following study of the literature relating to this was made. This study is based on different sources, but mainly on the summary made by Joachim Bergström in his report [13], which carries out a survey of the literature, including 61 reports, computer programs and articles in order to summarise present knowledge concerning the behaviour of glazing in fire. Certain experimental data have been published, and the first computer program "BREAK-1" has been written by A. Joshi and P.J.Pagni [14].

Several conclusions and general statements can be made.

- There is a lack of data on window behaviour during real fires, theoretical models are based on constant temperature in the burning room, experimental data are insufficient.

- No unequivocal conclusions, with a satisfactory level of uncertainty, can be drawn regarding window breakage for different window constructions.
- There are no data on window behaviour during a fire as a function of two parameters, temperature rise and pressure.
- The simulation program "BREAK-1" examines single-pane window behaviour, which is an unusual construction for real windows in northern climates.

But
- All studies have shown that glass cracks due to thermal stress if the temperature difference in the glass itself varies between 58°C and 100°C.
- Window glazing breaks at 200-400°C in the burning room.

3.5.2 Simple window breakage model

A theoretical analysis can be made regarding the risk of window breakage in the case of a compartment fire.

The one dimensional thermal stress, σ_t in glass due to a temperature difference ΔT between a large and a small area of glass can be written as

$$\sigma_t = \beta \Delta T E_Y \qquad \text{N/m}^2 \qquad (3.3)$$

where β is thermal expansion (K^{-1}), E_Y is Young's modulus/elastic modulus (N/m^2) and r is the proportion of glass heated.

The window glass breaks when the thermal stress is larger then the tensile strength, σ_b.

Only the temperature difference between different parts of glass matters. The geometry is normally the central part of a window vs. frame/edges, but can also be inside surface vs. outside surface.

Some typical values for window glass are

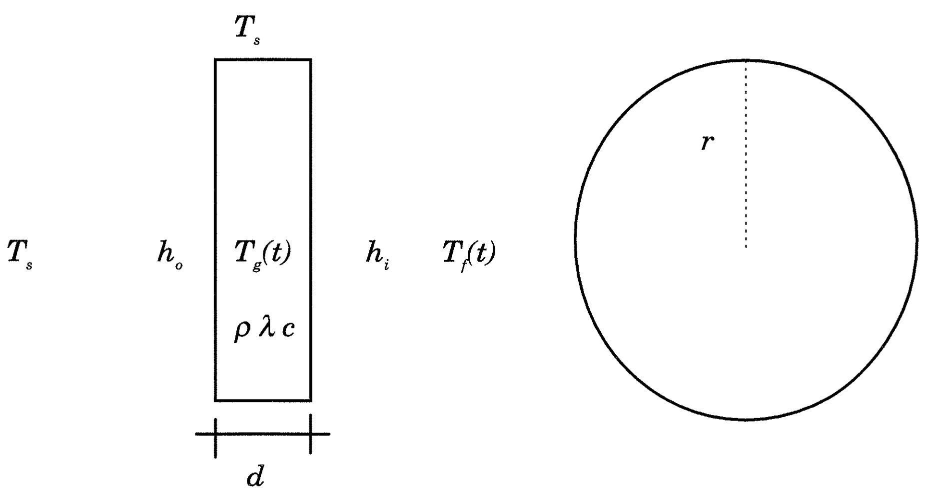
β 8.5 - 9.5 10^{-6} (K^{-1}),
E_Y 7.0 - 7.25 10^{10} (N/m^2),
σ_b 2.0 - 13.8 10^{7} (N/m^2).

The corresponding temperature difference which causes glass breakage ranges from 31 K to 213 K, which agrees with experimental data presented above.

A model is needed to predict the window glass breakage temperature. Such a model has been developed and it is presented in Subsection 3.5.3.

3.5.3 Window glass temperature model

Physical model



Assumptions and simplifications:

- total heat transfer for both radiation and convection between fire and window glass is given by a constant h_i (W/m^{2}K)
- total heat transfer for both radiation and convection between outside air and window glass is given by a constant h_o (W/m^{2}K)
- infinite heat conduction in window glass between inside and outside surfaces
- heat conduction from window glass to the frame is described through area πrd and assumed distance $r/2$
- the window glass temperature is connected to a single heat capacity

$C = \pi r^2 d \rho c$ J/K

Derived model parameters are

$Q_i = \pi r^2 h_i$ W/K

$Q_o = \pi r^2 h_o$ W/K

$Q_c = \pi r^2 d \lambda / (r/2) = 2 \pi r d \lambda$ W/K

Heat balance equation for a circular disc of glass is

$$C \frac{dT_g}{dt}(t) = -(Q_i + Q_o + Q_c) T_g(t) + (Q_o + Q_c) T_s + Q_i T_f(t) \quad (3.4)$$

where $T_g(t)$ is glass temperature at time *t*, $T_f(t)$ is fire temperature at point *t* and T_s is a start and surrounding temperature.

Assuming, that T_s=0 and, hence, Tg(0)=0, and simplifying the model with parameters T, time constant, and g, the gain,

$$T = C / (Q_i + Q_o + Q_c)$$

$$g = Q_i / (Q_i + Q_o + Q_c)$$

we have

$$T \frac{dT_g}{dt}(t) = -T_g(t) + g T_f(t) \quad (3.5)$$

Heat conduction, Q_c, is much smaller than heat convection, Q_i and Q_o, and can be neglected. Thus

$$T = \frac{C}{Q_i + Q_o} = \frac{\pi r^2 d \rho c}{\pi r^2 (h_i + h_o)} = \frac{d \rho c}{(h_i + h_o)}$$

The time constant determines in a simple way how fast the state of the models changes. In our case it determines the change in glass temperature. For the case with a temperature step it seems that the glass temperature would achieve a steady state after the time interval of one time constant.

Notice that steady state temperature is not a fire temperature T_f, but a reduced value gT_f. Notice also that the reduced temperature parameter g with $Q_c = 0$ becomes $g = h_i / (h_i + h_o)$.

In the case of a linearly increasing fire temperature the product gkT tells how much the glass temperature can be delayed after the reduced fire temperature.
For the window glass of d=0.004 m, ρ=2800 kg/m^3, c=800 J/kg,K, λ=0.81 W/m,K and assuming that h_i=16 W/m^{2}K and h_o=6 W/m^{2}K, gives T=410 s=7 min. Fire dynamics is fast.

Fire temperature cases

$$T_f(t)= \begin{cases} k, & k=T_{fd} \quad \text{constant} \\ kt, & k=T_{fd}/t_d \quad \text{linear} \\ kt^2, & k=T_{fd}/t_d^{\,2} \quad \text{quadratic} \end{cases} \quad °C \qquad (3.6)$$

where T_{fd} is a specific fire temperature at the specific time t_d.
This can *be illustrated with Figure 3.1.*

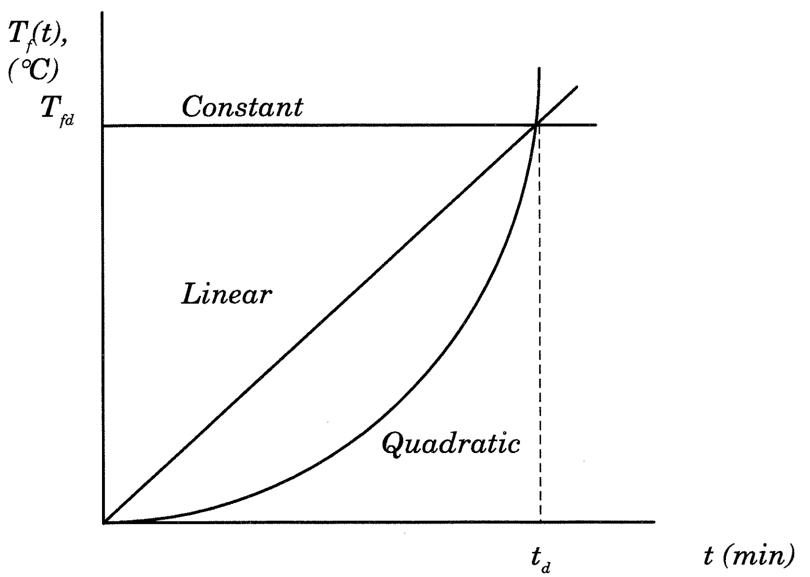


Figure 3.1 Schematic evaluation of temperature for different fire progresses.

Solving (3.4) along with fire temperature functions (3.5) for natural start condition gives the following expressions

$$T_f(t)=(1-e^{-t/T})gT_{fd} \qquad \text{constant}$$

$T_f(t)=kt-kT(1-e^{-t/T})$ linear

$T_f(t)=kt^2-2kTt+2kT^2(1-e^{-t/T})$ quadratic

Solving the above presented equations for the window glass with ρ=2800 kg/m^3, c=800 J/kg K, λ=0.81 W/m K and assuming that temperature rise T_f=300°C in the fire room is achieved at different times after ignition, t, the values presented in Table 3.4 are obtained for different values of the thickness, d.

Table 3.4 Temperature differences in studied window glass of different thickness at different time points.

t_d, min	$T_g(t_d)$, K											
	Constant				Linear				Quadratic			
	d, mm											
	3	4	5	6	3	4	5	6	3	4	5	6
2	71	56	46	39	38	29	24	20	25	20	16	14
3	97	78	65	56	53	42	34	29	37	29	24	20
4	118	97	82	71	67	53	44	38	48	37	31	26
5	136	114	97	85	79	64	53	46	57	45	37	32

Table 3.4 shows that as the thickness of glass increases, the temperature differences in the glass itself decrease. Standard window glass thickness are 3, 4 and 5 mm.

The above presented temperatures can be interpreted as temperature differences, as the start temperature for this case is assumed to be equal to zero. The highest values of temperatures for the same thickness of glass at the same time interval are observed for constant fires, and the lowest for quadratic fires.

The most realistic fires are quadratic fires, i.e. $Q \approx t^2$.
The temperature rise is less then 60 K for all cases with quadratic temperature progress. This simple analysis shows that the windows will not crack during first phase of the fire growth.

The radiation absorption length for glass is about 1 mm. This means that most of the radiation is absorbed close to the entering surface. The radiation intensity reduces with *a* factor of e^{-1} for each mm. This increases the normal temperature difference between the inside and outside surfaces in case of fire (heavy radiation).

Owing to the lack of knowledge and experimental data, it appears difficult to make a proper analysis of window breakage conditions, but it may be assumed for the purpose of this study that a temperature interval of 200-300°C in the burning room can be considered a "dangerous" temperature interval. As the goal of this research is to provide the most reliable parameters (volume flows) which determine the progress of fire in a space, one more assumption can be made regarding the peak temperature that occurs in the fire. Although the "dangerous temperatures" for window breakage should not exceed 300°C, even higher temperatures can be accepted in the upper layer in the room of fire origin in order to predict the peak volume flow out of the room.

4 Single peak fire flow models

The main purpose of this chapter is to test a simple method and algorithm for the prediction of peak fire flows which are illustrated by Figure 4.1. This method has been developed for the present study.
The natural question is whether peak fire flow can be calculated with explicit expressions if the type of fire or the heat release curve and the room volume are known?

The answer is yes if the following assumptions are made:

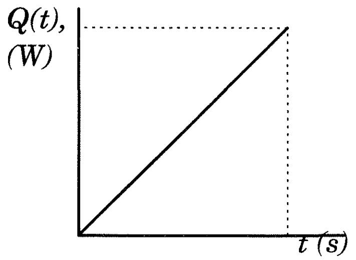
Each MJ heat release consumes a (m^3) of room air

Each MW heat release produces f (m^3/s) fire flow to the room

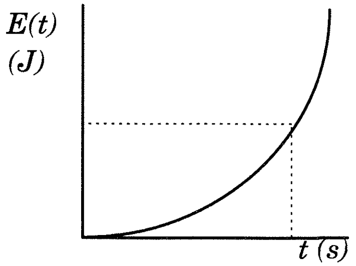
The share of room air volume used by the fire is given by the factor r. This parameter can also be interpreted as the oxygen reduction factor.

The fire flow depends directly on the rate of heat release. The heat released is accumulated as released energy. The released energy corresponds to the given amount of consumed room air. The volume of room air limits the fire at a certain time. Thus the peak fire flow is determined indirectly by the heat release at this time.

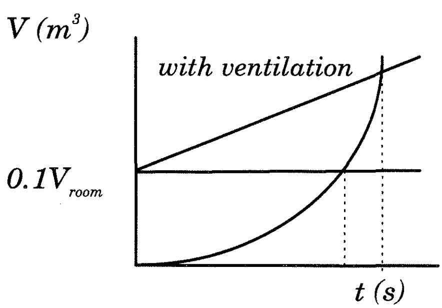
The problem can be solved if the rate of heat release is a simple function that can be integrated. One example is a t^n-function. It is also found that a heat release function described by linear segments can be treated. A minor drawback is that the calculation has to be made segment by segment until a solution is found.



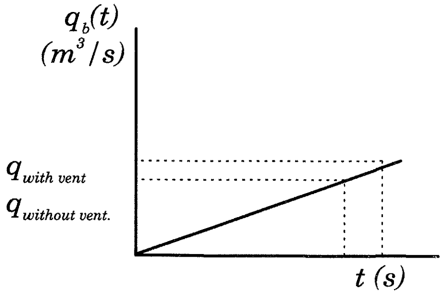
Fire progress (here described as a linear function of time) produces certain heat at time t.
$Q(t) = f(t)$



Energy released by the fire during the period of t seconds.
$E(t) = \int_0^t Q(t)\, dt$



Energy can be expressed in terms of the volume of room air consumed and also in terms of the air utilisation factor r.
$V(t) = a\, E(t) / r$



The fire flow is proportional to the heat release rate at time t.
$q_b(t) = f\, Q(t)$

Figure 4.1 Logical sequence of problem solution.

The above schematic process description corresponds to a linear fire progress. A more detailed and general analysis is presented in this chapter.

4.1 Simple general model

There are different ways in which fire progress can be described. A general description can be made on the assumption that the growth phase of a fire can be characterised as a function of time to the *n-th* power. These idealised fire energy release rates are described as follows:

$$Q(t) = \alpha t^n \qquad \text{W} \qquad (4.1)$$

where Q is in W and t is in seconds, α is in W/s^n and is specific for a certain fire progress. The energy released by fire during the period of t seconds is defined by

$$E(t) = \int_0^t Q(t)dt \qquad \text{J} \qquad (4.2)$$

Substituting equation 4.1 in 4.2 leads to

$$E(t) = \alpha t^{n+1} / (n+1) \qquad \text{J} \qquad (4.3)$$

Energy can be expressed in terms of the volume of air consumed in the room

$$a E(t) = V (t) \qquad \text{m}^3 \qquad (4.4)$$

where a is a coefficient which expresses the volume of air that is consumed by fire up to time t.

All oxygen in the room cannot be consumed. This air/oxygen utilisation can be described by the factor r, normally around 0.5. Equation (4.4) is modified to

$$a E(t) = r V \qquad \text{m}^3 \qquad (4.5)$$

Substituting of $E(t)$ by (4.3) in (4.5) gives

$$a \alpha t^{n+1} / (n+1) = r V \qquad \text{m}^3 \qquad (4.6)$$

Solving equation (4.6) for t, we have

$$t = ((n+1)\, rV \,/\, a))^{1/n+1} \quad \text{s} \qquad (4.7)$$

Energy released by the fire in a certain room during time t produces flow due to gas expansion

$$q(t) = f\, Q(t) \quad \text{m}^3/\text{s} \qquad (4.8)$$

where $f\ ((m^3/s)/MW)$ is a coefficient of volumetric expansion due to energy input.

Substitution of (4.1) and (4.7) into (4.8) gives

$$q(t) = f\, \alpha [(n+1) r\ V \,/\, a\, \alpha]^{n/n+1} \quad \text{m}^3/\text{s} \qquad (4.9)$$

$$q(t) = f\, [(n+1) r \,/\, a]^{n/(n+1)}\ \alpha^{1/(n+1)}\ V^{n/(n+1)}\ \text{m}^3/\text{s} \qquad (4.10)$$

Therefore, if

n=0	$q \approx V^0 \alpha^1$	m^3/s	(4.11)
n=1	$q \approx V^{1/2}\, \alpha^{1/2}$	m^3/s	(4.12)
n=2	$q \approx V^{2/3}\, \alpha^{1/3}$	m^3/s	(4.13)
n=3	$q \approx V^{3/4}\, \alpha^{1/4}$	m^3/s	(4.14)

One remark on the above numbers is that the peak fire flow increases less than in proportion to the room volume. This means that a fire in a small room creates a relatively large peak fire flow.

4.1.1 Maximum fire flows predicted with DSLAYV results

In [16], Bengt Hägglund presented the results of twenty four simulations of t^2-fires in closed rooms of different sizes. The fire flows generated by these fires were analysed. The MINITAB program [17] was used for this purpose. The resulting equation showed good agreement with predicted flows:

$$q = 0.28\, V^{0.53}\ \alpha^{0.425} \quad \text{m}^3/\text{s} \qquad (4.15)$$

The coefficient of determination, R^2, is equal to 99.3%, and R^2 adjusted for degrees of freedom, $R^2(adj)$, is equal to 99.2%.

Equation (4.15) can be rewritten with certain approximation, as

$$q \approx 0.3\sqrt{V\alpha} \qquad \text{m}^3/\text{s} \qquad (4.16)$$

A more precise conclusion is that the flow q (4.16) predicted by DSLAYV corresponds to the flow q described by (4.12) and (4.13) when the value of n for αt^n fires is between 1 and 2.

Flows predicted by the model (4.15) are slightly larger then those predicted by DSLAYV. The difference between them can however be considered acceptable.

4.2 Analysis of fire flow prediction models

The flows predicted by CFAST and described in Chapter 2 are generated by real fires in buildings of different types and sizes. In order to generalise these predicted flows and to describe them as a function of some variables well known to the user, the following analysis is made.

4.2.1 Flows, predicted by CFAST simulations

For the purpose of the study, the peak flows, q (m^3/s), predicted by CFAST simulations were analysed.

Table 4.2 Results of CFAST simulations (beginning).

No	Type of buildings	V, m^3	t, s	O_2, %	m_b, kg/s	T, °C	T, K	ρ, kg/m^3	q, m^3/s
1	Dwelling house (sofa)	48.0*	120	10.5	0.250	281	554	0.6368	0.39
2		48.0*	120	10.9	0.235	263	536	0.6582	0.36
3		48.0*	120	10.5	0.250	280	553	0.6378	0.39
4		134.4	150	10.8	1.170	322	595	0.5929	1.97
5		149.3	150	11.3	1.210	312	585	0.6031	2.01
6		180.0	160	10.4	1.350	327	600	0.5880	2.30
7		204.0	170	9.3	1.460	345	618	0.5709	2.56
8	Dwelling house (bed)	28.8	200	16.8	0.079	153	426	0.8282	0.10
9		134.4	400	13.0	0.216	184	457	0.7720	0.28
10		149.3	440	11.3	0.221	199	472	0.7475	0.30
11		180.0	450	12.4	0.257	185	458	0.7703	0.33
12		204.0	410	15.3	0.289	151	424	0.8321	0.35
13	Hospital	36.0	260	10.9	0.127	244	517	0.6824	0.19
14		50.0	260	13.4	0.230	207	480	0.7350	0.31
15		54.0	270	13.8	0.189	213	486	0.7260	0.26
16		75.0	270	15.7	0.247	175	448	0.7875	0.31
17		112.5	270	17.4	0.421	138	411	0.8584	0.49
18	Office	31.5*	100	6.3	0.118	331	604	0.5841	0.20
19		31.5*	60	15.9	0.163	209	482	0.7320	0.22
20		31.5*	70	10.1	0.118	331	604	0.5841	0.20
21		45.0*	130	5.3	0.135	318	591	0.5970	0.23
22		45.0*	80	16.9	0.223	174	447	0.7893	0.28
23		75.0*	170	5.4	0.159	290	563	0.6266	0.25
24		75.0*	100	16.6	0.261	158	431	0.8186	0.32
25		120.0	140	16.6	0.273	155	428	0.8243	0.33

Table 4.2 Results of CFAST simulations (end).

No	Type of buildings	V, m^3	t, s	O_2, %	m_b, kg/s	T, °C	T, K	ρ, kg/m^3	q, m^3/s
26		38.40	250	10.5	0.301	262	555	0.6357	0.31
27	Hotel	57.60	270	10.7	0.331	286	559	0.6311	0.52
28		84.00	280	12.7	0.483	269	542	0.6509	0.74
29		224.0	190	16.2	1.109	300	573	0.6157	1.45

* - Hazards with different placement of burning items.

Table 4.2 shows that in certain cases peak flows are obtained when the temperature of the upper hot gas layer is higher then 300°C. Although such temperatures can be dangerous with regard to window breakage, they are considered acceptable (see Subsection 3.5).

Note that the values of oxygen in the room at the time corresponding to maximum flows vary quite a lot even in the same room, depending on fire placement.

It is seen from Table 4.2 that peak fire flow occurs shortly after ignition. This period of time varies between 1 and 5 min. One exception is a fire in a dwelling with a bed as the source of ignition, where this period can be as long as 7 min 30 sec.

All fire flows presented in Table 4.2 are obtained for closed spaces with assumed leakage paths at the sill of the closed doorways. Some other leakage paths were also tested - at the top of the door and vertically along the sides of the door. Mass flows through leakage at the sill were larger then those at the other locations (5-20%) which depends on higher density of air at the sill of the door. At the same time temperature, pressure, heat release rate and interface position were insignificantly affected. The location of fire in the room affects fire progress as burning can be constrained by the available oxygen. Wall and corner effects describes with an "image method" in CFAST model, which uses different coefficients - 1/2 open fire for a wall fire and ¼ open fire fore a corner fire.

Owing to the complications in the program in determining fire location according to given fire position co-ordinates, different cases for the same rooms were tested. For the purpose of generalisation, fire locations which give cases highest fire flow values were chosen.

A regression analysis of the flows presented in Table 4.2 for the studied cases was made with the statistical program Minitab [17]. Owing to the paucity of data and generalisation of the whole range of predicted flows, the results are poor since there are different fire models which determine different fire flows.

The results of the analysis for each fire model are set out below.

Table 4.3. Results of regression analysis with Minitab.

Type of building	Regression equation	R^2, %	R^2(adj), %
Dwelling house (sofa)	$q = 0.0018\ V^{1.39}$	98.7	98.4
Dwelling house (bed)	$q = 0.01\ V^{0.68}$	99.8	99.7
Hospital	$q = 0.013\ V^{0.76}$	88.0	84.0
Office	$q = 0.066\ V^{0.34}$	76.2	72.2
Hotel	$q = 0.016\ V^{0.85}$	97.7	96.5

Table 4.3 shows good agreement (R^2 and R^2(adj)) between flows predicted by CFAST and the regression line in the case of fires in dwellings and fires in hotels. The paucity of data could influence the results of this analysis.

4.2.2 Model 1. Used linear segment fires as t^n-fires

The actual fires used for fire simulation and shown earlier in Figures 2.3 - 2.6 can be described as curves consisting of linear segments. Such functions cannot be easily used to calculate the peak fire flow, as Subsection 4.1. The fire curves used have been approximated as t^n-fires using two points on the fire curve. The exponent of interest n is calculated as

$$n = \ln(Q_1 / Q_2) / \ln(t_1 / t_2)$$

The selected points and calculated exponent n are shown in Table 4.4.

Table 4.4 Values of n for αt^n model.

Type of building	t_1, s	Q_1, kW	t_2, s	Q_2, kW	n
Dwelling house (sofa)	60/ 110*	100/ 260*	120/ 150*	300/ 1035*	1.584/ 4.454*
Dwelling house (bed)	150	49.9	270	160	1.982
Hospital	150	75	270	262	2.128
Office	50	105	100	187	0.833
Hotel	200	100	300	900	5.419

* - Compartment fires in "larger" flats.

It will be seen from Table 4.4 that the values of n exhibit considerable variation between 0.833 and 5.419.

Flows predicted with the help of this method are presented in Table 4.5.

4.2.3 Model 2

The heat release rate given as a linear segment function can for the *n-th* segment be stated as

$$Q(t) = Q_{n-1} + k_{n-1}\, t \qquad \text{W} \qquad (4.17)$$

where t is the relative time in the interval $(0\,,\, t_n - t_{n-1})$ and the slope k_{n-1} is given by

$$k_{n-1} = (Q_n - Q_{n-1}) / (t_n - t_{n-1}) \qquad \text{W/s} \qquad (4.18)$$

It is possible to calculate when the room air is consumed to the extent of the factor *r*. This gives the relation similar to (4.7) and a second order equation in *t*.

$$a(E_{n-1} + Q_{n-1}t + k_{n-1}t^2 / 2) = rV \qquad \text{m}^3 \qquad (4.19)$$

Where E_{n-1} is energy released up to time t_{n-1} and is simply integrated from *Q(t)*. If the relative time *t* is larger than the time interval, the calculation of (4.19) has to be repeated for the next time and segment interval until the solved relative time is within the actual time interval. All tested fires have been described with only three segment for the increasing part of the fire.

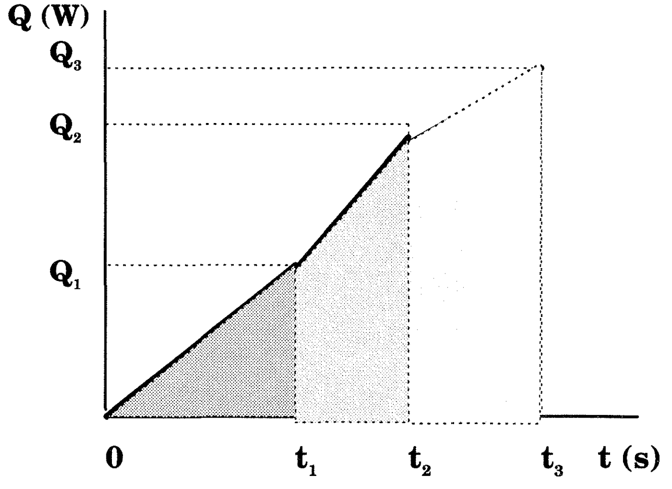


Figure 4.2 Fire growth curve assumed for Model 2.

Flows predicted with the help of this method are presented in Table 4.5.

4.2.4 Model 3

The two previous models assume that no volume is driven out of the room during time *t*.

This subsection presents a model which predicts flows according to the principle outlined in Subsection 4.2.1. It describes the studied hazards in terms of αt^n -fires on the assumption that a certain volume is driven from the burning room during time *t*.

We have

$$rV / (1 + E(t) / CT_0) = a\,E(t)\text{, and}$$

$$rV = a\,E(t) + a\,E^2(t) / CT_0,$$

By solving the last equation for *E(t)* and substituting it in the equation for *Q* and *q* (algorithm 1, Subsection 4.2.2), the corresponding flow can be calculated.

Flows predicted with the help of this method depend on the value of *C*. The major problem in this method is to evaluate *C*.

Due to the complexity of the problem, method 3 was not chosen as a working method.

4.3 Flows predicted by computer simulations and different models

The table below summarises the results and conclusions of this chapter.

Table 4.5 Flows predicted by CFAST, model 1 and model 2 (beginning).

No	Type of building	V, m^3	q CFAST, m^3/s	q_1, m^3/s	q_2, m^3/s	f, $(m^3/s)/$ MW	q_2 (edited), m^3/s
1		48.0*	0.39	0.42	0.40	1.30	0.40
2		48.0*	0.36	0.42	0.40	1.20	0.40
3	Dwelling	48.0*	0.39	0.42	0.40	1.30	0.40
4	house	134.4	1.97	2.09	*1.66*	1.80	1.93
5	(sofa)	149.3	2.01	2.27	*1.77*	1.87	2.08
6		180.0	2.30	2.54	*1.97*	1.70	2.36
7		204.0	2.56	2.70	*2.12*	1.60	2.56
8		28.8	0.10	0.16	0.14	1.00	0.14
9	Dwelling	134.4	0.28	0.44	0.42	0.80	0.42
10	house	149.3	0.30	0.48	0.44	0.70	0.44
11	(bed)	180.0	0.33	0.54	0.49	0.75	0.49
12		204.0	0.35	0.59	0.52	1.00	0.52
13		36.0	0.19	0.22	0.22	0.83	0.22
14		50.0	0.31	*0.28*	*0.28*	1.70	0.30
15	Hospital	54.0	0.26	0.30	0.29	1.00	0.29
16		75.0	0.31	0.37	0.36	1.20	0.37
17		112.5	0.49	*0.48*	*0.47*	1.90	0.56

Table 4.5 Flows predicted by CFAST, model 1 and model 2 (end).

No	Type of building	V, m^3	q CFAST, m^3/s	q_1, m^3/s	q_2, m^3/s	f, $(m^3/s)/MW$	q_2 (edited), m^3/s
18	Office	31.5*	0.20	0.23	0.23	1.10	0.23
19		31.5*	0.22	0.23	0.23	1.80	0.23
20		31.5*	0.20	0.23	0.23	1.30	0.23
21		45.0*	0.23	0.27	0.26	1.00	0.26
22		45.0*	0.28	*0.27*	*0.26*	1.80	0.34
23		75.0*	0.25	0.34	0.30	1.00	0.30
24		75.0*	0.32	0.34	*0.30*	1.73	0.41
25		120.0	0.33	0.42	0.42	1.43	0.42
26	Hotel	38.4	0.31	0.46	0.41	1.50	0.41
27		57.6	0.52	0.65	0.56	1.30	0.56
28		84.0	0.74	0.90	*0.73*	1.70	0.84
29		224.0	1.45	2.06	*1.29*	1.61	1.58

* - Hazards with different placement of burning items.

q_1 flows predicted by the model 1
q_2 flows predicted by the model 2
q_2 (edited) flows predicted by the model 2 (edited).

Table 4.5 shows flows predicted by CFAST and by both models. Flows predicted by model 1 are overestimated over almost the whole range of values, with the exception of cases 14, 17, 22 (in italics). Overestimation varies between 9% and 61%.

The method described in Section 4.1 for predicting flows due to an αt^n fire in a certain room, which in the case of this study is based on a real fire scenario, does not yield realistic values and cannot be used. This can be illustrated with the following (exaggerated) figure.

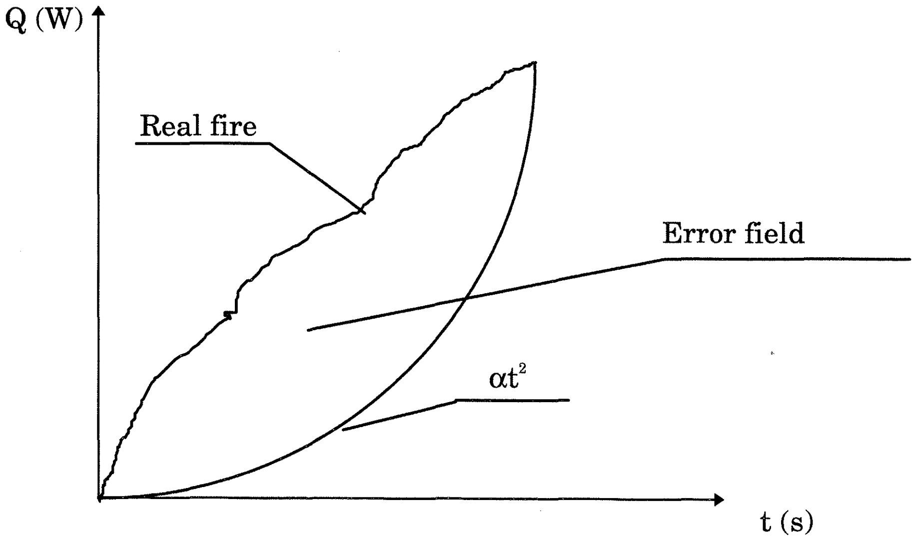


Figure 4.8. Prediction of energy released by fire during the period of t seconds.

As seen from Figure 4.8, the error in estimating energy released by fire during the period *t* (s) can differ considerably in an arbitrary "real fire" case from the t^2-fire growth case. Note that this figure shows the growth stage of fire.

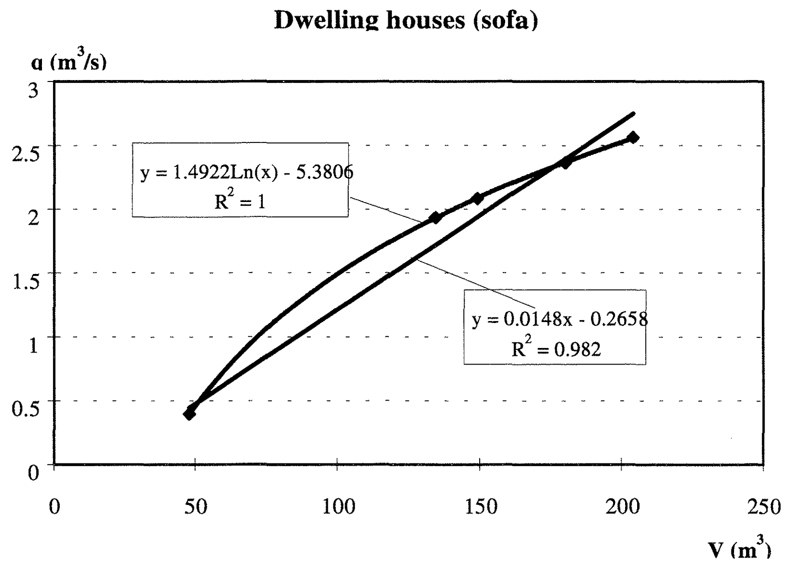
Flows predicted by model 2 show better agreement with those predicted by CFAST, but there are more underestimated cases for larger rooms (in italics). These underestimated flows appear to be directly related to the value of *f* assumed in the model (1.0 $(m^3/s)/MW$). When the value of *f* exceeds 1.6, the results show lower flows. Portion of heat released by a fire which is absorbed by the room air increases in larger rooms. When in such cases it is assumed that $f = 1.6$ $(m^3/s)/MW$, the flows presented in the column "q model 2 (edited), m^3/s" are obtained.

4.4 Generalisation of predicted flows

Flows predicted by the above simulation program and different models were presented in Table 4.5. A regression analysis made by Minitab for flows predicted by CFAST showed insufficient agreement for fires in hospitals and offices (see Table 4.3). A very brief comparison of flows predicted by CFAST with experimental data showed underestimated predicted flows. At the same time, prediction of flows by the field model program SMAFS showed that flows can actually exceed those predicted by CFAST. It seems reasonable to prefer higher flows to lower ones. In this connection, flows predicted by the edited model 2 can be considered to be designed flows.

4.4.1 Equations describing flows as a function of volume

In order to describe predicted flows, the computer program EXCEL was used. The resulting equations and their statistical analysis are presented in Figures 4.9 - 4.12.



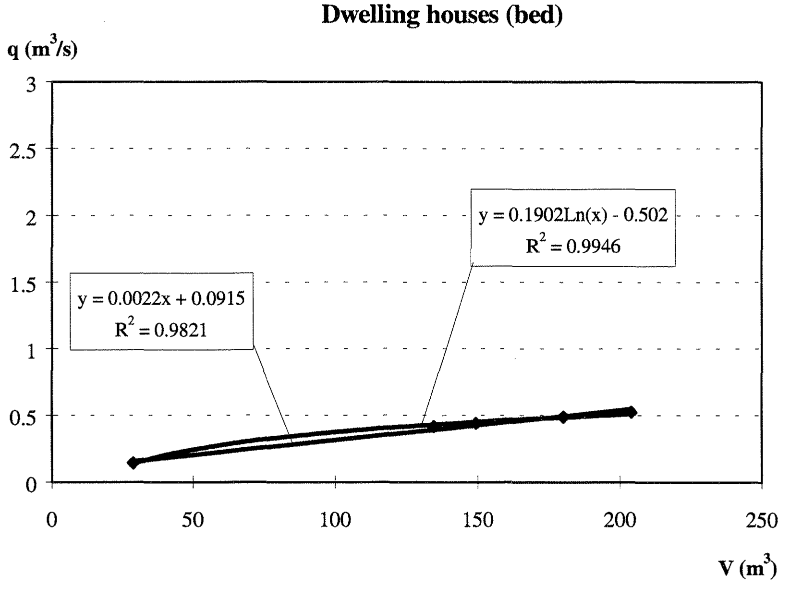


Figure 4.9 *Predicted flows (rhombus) and trend lines for dwelling houses.*

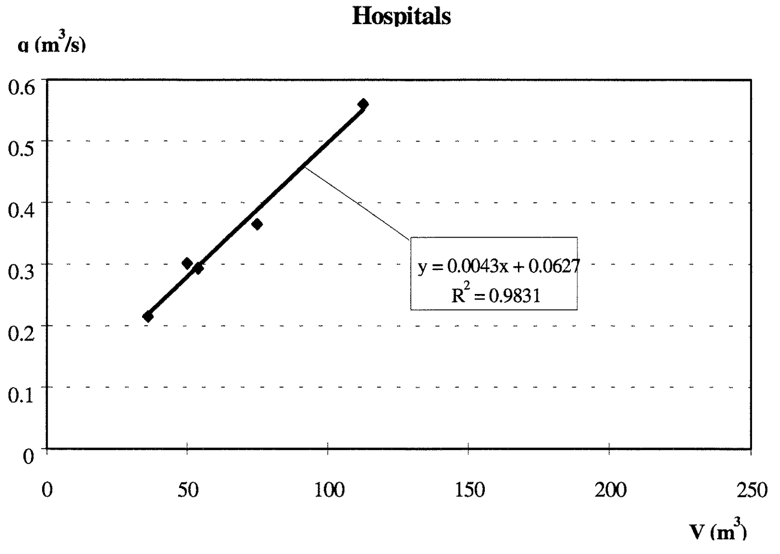


Figure 4.10 Predicted flows (rhombus) and trend line for hospitals.

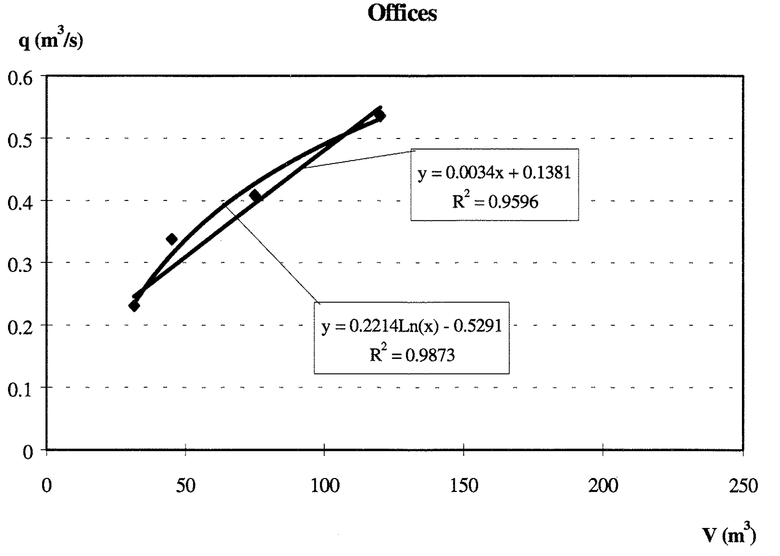


Figure 4.11 Predicted flows (rhombus) and trend lines for offices.

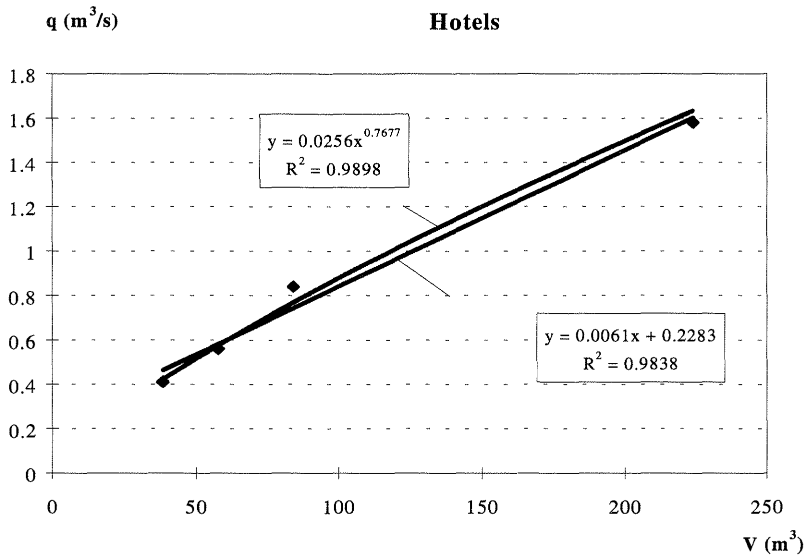


Figure 4.12 Predicted flows (rhombus) and trend lines for hotels.

It is seen from the Figures 4.9 - 4.12 that linear equations describe predicted flow values in all the studied cases with sufficient agreement. In certain cases better agreement was obtained for the same variables with other types of equation. The equations which describe the phenomena with the best accuracy are presented in Table 4.6.

Table 4.6 Equation describing flows in the buildings.

Type of building	Equation	R^2
Dwelling house (sofa)	$q = 1.4922 \ln(V) - 5.3806$	1.0000
Dwelling house (bed)	$q = 1.1902 \ln(V) - 0.502$	0.9946
Hospital	$q = 0.0043 V + 0.0627$	0.9831
Office	$q = 0.2214 \ln(V) - 0.5291$	0.9873
Hotel	$q = 0.0256 V^{0.7677}$	0.9898

Flows obtained in dwellings with a burning sofa are essentially larger then those obtained in dwellings with a burning bed. As it is the most dangerous case that is of interest for flow assessment, only the case with a sofa as the burning item will be presented below for fires in dwellings.

Flow obtained for a 100 m^3 hospital room according to Table 4. 6 agrees with that presented in [34].

As the equations presented in Table 4.6 show sufficient agreement with predicted flows, they can be applied to corresponding types of buildings of different sizes, i.e. they can be used for generalisation of the results obtained. Characteristic flow curves for the chosen buildings are presented in Figure 4.13. Space volume varies from 30 m^3 to 240 m^3. These volumes are assumed to be those most usual for the described types of buildings. Flows in spaces smaller then 30 m^3 can be assumed to be equal to those for rooms of 30 m^3.

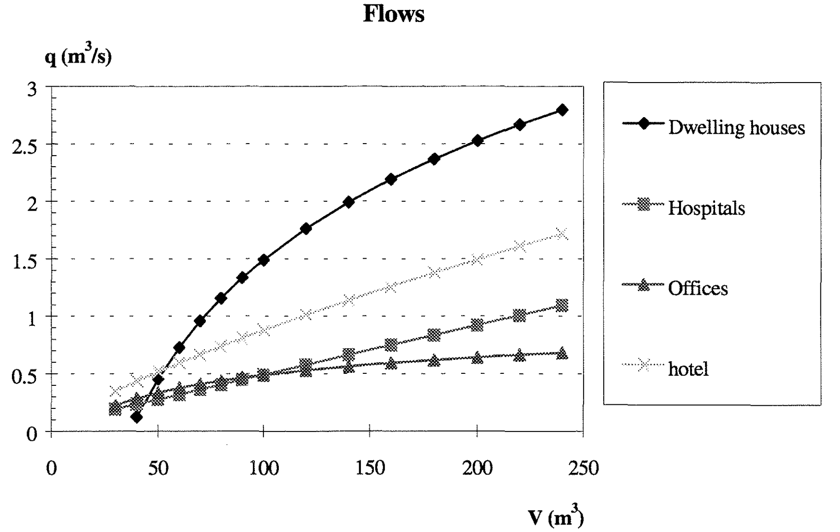


Figure 4.13 Flows in the chosen types of buildings.

Hotel rooms are usually furnished with a bed which was assumed to be the item that initiates fire. This statement can be true for relatively small rooms. In larger hotel rooms and suites, which can also be furnished with a sofa, another curve for dwellings can be used in order to evaluate flow in the fire room.

Curves of (4.18) for different αt^2 - fires, simulated with the computer program DSLAYV, are plotted in the figure below.

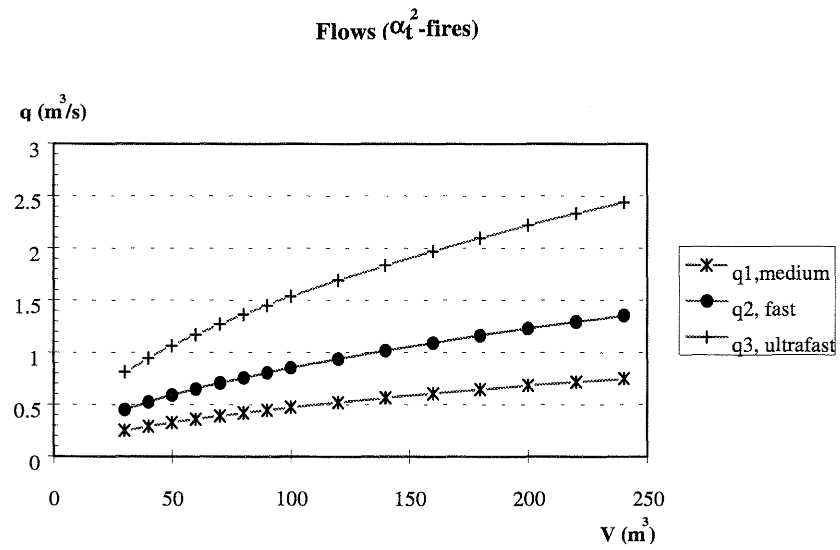


Figure 4.14 Flows for different αt^2 - fires according to the equation (4.18).

Curves in the above figures are all plotted in the figure below for purposes of comparison.

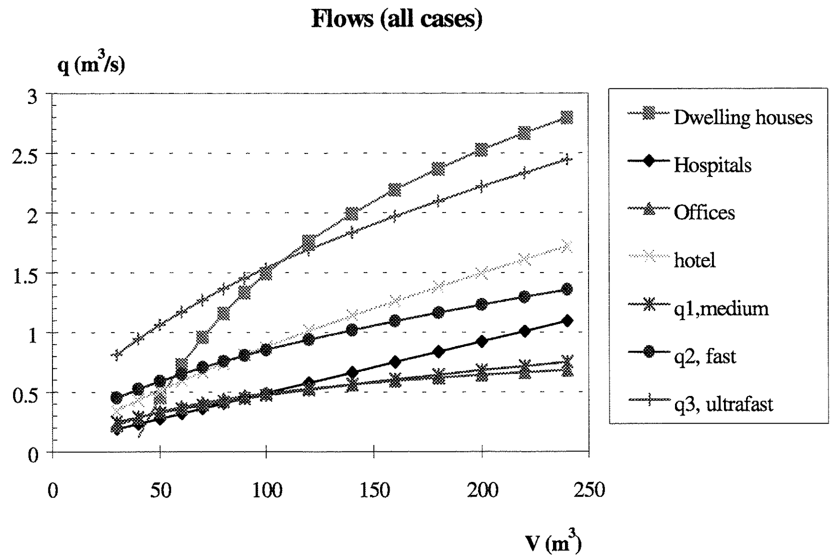


Figure 4.15 Flows according to the equations in Table 4.3 and equation (4.18).

Figure 4.15 shows that flows obtained for offices agree very well with those predicted for the medium fast αt^2 - fires. Flows obtained for hospitals correspond to values between those predicted for medium and fast αt^2 - fires over the whole range of volumes. Flows obtained for hotels up to approximately 100 m^3 are insignificant lower than those predicted for fast αt^2 - fires, while flows in hotels larger than 100 m^3 correspond to values between those predicted for fast and ultrafast αt^2 - fires.
Flows obtained for dwellings up to approximately 100 m^3 are lower than those predicted for ultrafast αt^2 - fires. In contrast, flows in dwellings larger than 100 m^3 have higher values than those predicted for ultrafast αt^2 - fires.

Analyses presented in this Section 1 consider fire progress in a single space limited to the object in which it started. According to the Table 2.4, between 23% and 53% of all fires spread to other objects in the room of fire origin. This case was not examined in the present study. It could be interesting to examine such cases.

However, the results of the study show that it is relatively difficult even in the case of the studied fires to assess whether windows in the building envelope will be broken, as the temperatures which develop in the hot gas layer during the examined fires of one - four minutes' length can exceed the temperature level which is dangerous for glass breakage. This means that fire flow generation process which is of interest for this particular study can be limited so far to the above presented cases.

Section 2. Operation of ventilation systems during fires

5 Study of the literature

In order to ascertain the current state of knowledge regarding smoke spread through a ventilation duct network, the following study was made.

According to the building regulations and codes in different countries the only recommended way to prevent the spread of smoke is to install different kinds of dampers and smoke barriers and to shut down the ventilation system in the event of fire, or to rely only on shutting down the ventilation system, designed according to given pressure drop relations. Other solutions were also allowed in Sweden until 1967. The operation of fans during fires was not excluded by the Building Code SBN 1967. Subsequent regulations recommended that fans should be turned off in case of fire. In the present Swedish Building Regulations [8], 1994, it is recommended that under certain conditions the existing ventilation system, which removes hot smoky gases from the compartment without spreading them to adjacent rooms, should be run. A handbook [16], 1996, further improves the safety design of ventilation systems and proposes some calculation methods in order to reduce and even eliminate the risk of smoke spread via ventilation ducts to adjacent rooms.

The state of knowledge in this regard and research publications have been searched through different databases in science and technology and via several search programs in Internet. In addition, current publications on this matter in different scientific and technical periodicals were followed, and an attempt was also made to discuss the subject with researchers via scientific news groups on the Net. The last one failed, as no researchers have responded.

5.1 Databases

All in all seven major databases were searched through twice with a one year interval. These databases are as follows:

-IBSEDEX, which covers all aspects of building services world-wide, published since 1960. It includes information on technical books, reports, conference papers, journal articles and standards,

-ICONDA, which covers the world-wide literature on all fields of building construction and design, energy conservation, civil and structural engineering, architecture and town planning, published since 1976. Sources of information are technical books, conference papers and journal articles,

-COMPENDEX, which is a comprehensive interdisciplinary engineering database, covering different areas of engineering, civil, energy, mechanical, environmental, etc. Sources of information are technical reports, conference papers and proceedings, published since 1970,

-BRIX-FLAIR, which covers technical information published since 1960,

-TRADE and INDUSTRY Database, which covers technical information for industrial needs published since 1976,

-CORDIS, which includes nine different databases, provides information on all aspects of EU R&D activities including current calls for proposals and tenders, events, publications and activities in preparation. Publications contain abstracts and bibliographic information on publications, reports and scientific papers arising from EU research activities as well as other scientific and technical documents in the fields of the environment, energy and information sciences,

- AIRBASE, which is the Bibliographic Database of the International Energy Agency's Air Infiltration and Ventilation Centre. It contains abstracts of articles and publications relating to energy efficient ventilation and includes topics on ventilation strategies, design and retrofit methods, calculation techniques, standards and regulations, measurement methods, indoor air quality and energy implications. Entries are based on articles and reports published in journals, internal publications and research reports.

The information search showed that there are few articles on this issue. Some of these are comparatively old, from the 60s and early 70s, which makes them nearly unobtainable. The author was unsuccessful in getting information on corresponding research with regard to the operation of ventilation systems during a fire or, at least, in discussing its possibilities.

6 Theoretical methods

In this chapter the main principles of treating ordinary ventilation systems during compartment fires will be discussed. On the basis of up-to-date research results on the subject, as well as knowledge about smoke spread via ventilation ducts, the following analysis has been performed.

6.1 Background

The main principles of running ordinary ventilation systems during compartment fires were formulated in [1], [2], and [3]. The principal points in these reports are as follows..

Whether or not smoke spread will occur is determined by the energy released by the fire, the airtighteness of buildings and the layout of the ventilation system. There are three main types of ventilation systems: exhaust, supply and exhaust, and natural ventilation. If a natural ventilation system serves each separate room with a separate duct, smoke spread will never occur unless the duct itself leaks. In both exhaust and supply-exhaust mechanical ventilation systems, on the contrary, spread of smoke via ducts is always possible as a certain number of rooms are connected by those ducts.

Assuming that air in the burning room is heated from T_f to T_e, at every point in the room during a fuel controlled fire, the air volume V will increase by

$$(T_e \ / \ T_f - 1)V \tag{6.1}$$

This means that the volume of smoke is of the same magnitude as the room volume and is limited by it.

A very rough estimate of fire gas flow can be made as follows:

$$q_m = (T_e \ / T_f - 1) V / t_p \tag{6.2}$$

If the temperature, measured in K, doubles over a period of one or two minutes, the mean flow according to (6.2) will be V/60 and V/120 respectively. These flows are much larger than ordinary ventilation flows in the room. For example, in a room of 30 m3 with 10 l/s (36 m3/h) air flow, the estimated fire gas flow is 500 l/s (1800 m3/h).

The conditions when smoke from the burning room starts spreading via ducts to the adjacent rooms can be defined as limit or boundary case conditions. There is only one boundary case, whether it is based on the pressure in the fire room or the fire flow. This boundary case can be determined by a certain pressure or flow in the burning room, at which smoke will start to spread from the fire room to the adjacent room(s) via the ventilation duct. The boundary case for smoke spread via ventilation ducts can be described by zero air flux in the adjacent room(s). While pressure rise in the fire room depends on different parameters, such as airtightness and the number of openings, flow is a function of the energy released over a certain period of time, as discussed in Chapter 3, and was chosen as a characteristic value in this study.

Expressions and models presented in this Subsection are the summary of algorithms and conclusions discussed in [1], [2] and [3].

6.2 Flow model

A pressure difference, created by a fan, causes airflow. Airflow in the ventilation system is governed by the total pressure p_t, which is a sum of the dynamic and static pressure. The total pressure diminishes downstream because of friction in the ductwork and pressure losses in fittings.

In order to describe an arbitrary ventilation system the following variables are used:

p_i pressure drop in a component i

q_i flow in a component i
R_i resistance (turbulent) of a component i

For turbulent flow

$$p_i = R_i \, q_i^2 \tag{6.3}$$

For two resistances connected in series for turbulent flow

$$R_s = R_1 + R_2 \tag{6.4}$$

and for parallel coupling

$$R_p^{-0.5} = R_1^{-0.5} + R_2^{-0.5} \tag{6.5}$$

For a flow junction, the sum of all inlet and outlet flows is equal to zero, which gives

$$0 = \sum_{junction} q_i \tag{6.6}$$

For an arbitrary loop duct, the sum of all pressure looses in the loop is always equal to zero, which gives

$$0 = \sum_{loop} p_i \tag{6.7}$$

6.3 Theoretical model for the analysis of ventilation systems

A very short description of basic principles and a theoretical model of ventilation systems, determining boundary conditions of smoke spread through ventilation ducts, is presented in this subsection. In the following analysis certain common assumptions were made:

the ventilation system serves two rooms
all pressure drop are turbulent
the pressure, produced by the fan is equal to 1 and do not depend on the flow fluctuations
total flow is normalised to 1
flow in room A is equal to q
flow in room B is equal to 1-q

room A is a "burning room".

6.3.1 Exhaust ventilation system

The layout of an exhaust ventilation system for two rooms and its model are presented in Figure 6.1.

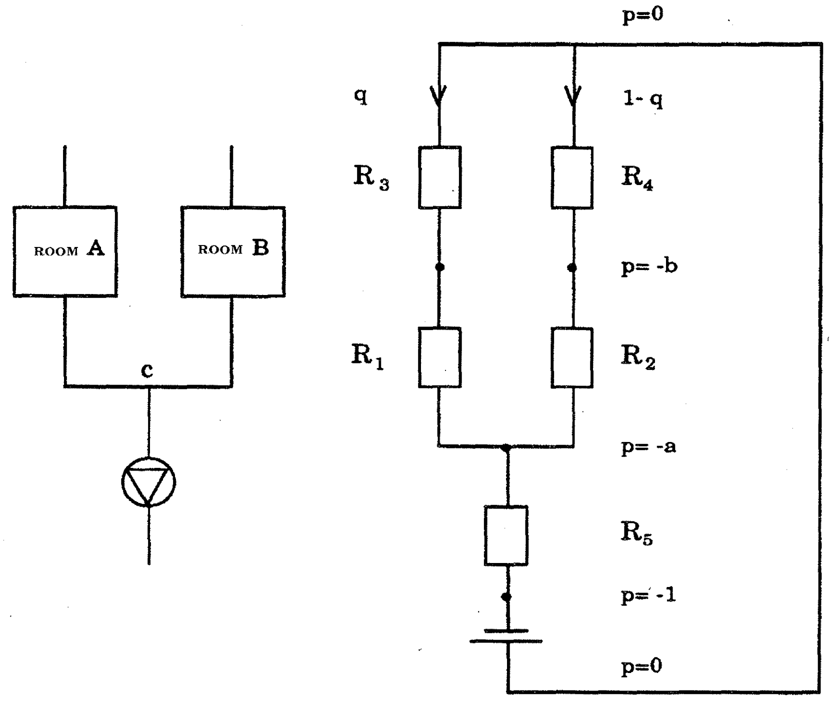


Figure 6.1 Layout of exhaust ventilation system for two rooms and its model [3].

In the following analysis further assumptions were made:

total pressure drop is normalised to 1
pressure before the plenum (collecting duct) is equal to -a
pressure in both rooms is equal to -b

All the resistance R_i can be described as

$$R_1 = (a - b) / q^2 \tag{6.8}$$

$$R_2 = (a - b) / (1 - q)^2 \tag{6.9}$$

$$R_3 = b / q^2 \tag{6.10}$$

$$R_4 = b / (1 - q)^2 \tag{6.11}$$

$$R_5 = 1 - a \tag{6.12}$$

In case of fire, smoke spread will occur if pressure in the junction c changes from -a to 0 (zero). This results in increased flow q in room A and reduced flow in room B from $(1\text{-}q)$ to 0 (zero). If flow in the main duct is equal to q_k, inlet flow through the facade is equal to q_f, and fire pressure in the room a is equal to p_b, the following expressions are valid:
for the main duct

$$1 = R_5 q_k^2 \tag{6.13}$$

for the branch to the room A

$$p_b = R_1 q_k^2 \tag{6.14}$$

for the facade to the room A

$$p_b = R_3 q_f^2 \tag{6.15}$$

This gives

$$q_k^2 = 1 / (1 - a) \tag{6.16}$$

$$q_f^2 = (a - b) / ((1 - a)b) \tag{6.17}$$

The total needed fire flow

$$q_b = q_k + q_f \tag{6.18}$$

and the corresponding pressure rise is

$$p_b = (a - b) / ((1 - a)q^2) \tag{6.19}$$

Some important conclusions can be drawn :

- fire flow does not depend on the ventilation flow

- fire flow is larger, than the total ventilation flow (>1)
- large pressure drop in the main duct requires large fire flow and high pressure in the burning room. This statement shows that the ordinary way to prevent smoke spread via the ventilation duct is to make the pressure drop in the branch much larger than that in the main duct.
- $q_f > q_k$ if $a/b > 2$. This statement can be interpreted as a ratio of the two flows

q_f / q_k, if

$$q_f / q_k = (a/b - 1)^{0.5}$$

If the pressure drop in the main duct is high, the danger of smoke spread is significant. A relatively little fire flow can be enough to cause spread of smoke and fire gases to the other room.

6.3.2 Exhaust and supply ventilation system without air leakage

The layout of an exhaust and supply ventilation system for two rooms without air losses and its model is presented in Figure 6.2.

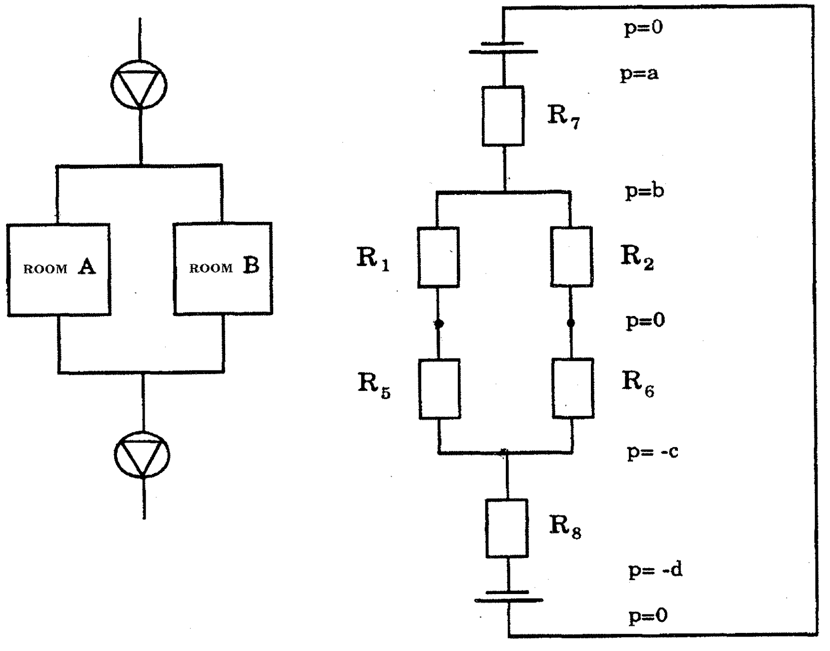


Figure 6.2 Layout of an exhaust and supply ventilation system for two rooms without air leakage and its model [3].

In the following analysis the following assumptions were made in addition to the general ones presented in Subsection 6.3:

pressure in the rooms is equal to 0
pressure in the supply plenum (collecting duct) is equal to *-a*
pressure before the supply plenum (collecting duct) is equal to *-b*
pressure before the exhaust plenum (collecting duct) is equal to *-c*
pressure in the exhaust plenum (collecting duct) is equal to *-d*
pressure in both rooms is equal to 0

Parameters R_i can be calculated from the following expressions

$$R_1 = q^2 / b \tag{6.20}$$

$$R_2 = (1-q)^2 / b \tag{6.21}$$

$$R_5 = q^2 / c \tag{6.22}$$

$$R_6 = (1-q)^2 / c \tag{6.23}$$

$$R_7 = 1/(a-b) \tag{6.24}$$

$$R_8 = 1/(d-c) \tag{6.25}$$

In case of fire with fire flow q_b in room A, smoke spread will occur if the inlet flow q_1 is equal to 0 (zero). The boundary condition for smoke spread from the burning room A, assuming that the pressure drop in terminals does not change, gives

$$(R_1 + R_5)q_1^2 = R_1 0^2 + R_5 q_b^2 \tag{6.26}$$

Using the subscripts i for supply air, o for exhaust air and n for ordinary operation, the last equation can be rewritten as

$$q_b = (R_i / R_o + 1)^{0.5} q_n \tag{6.27}$$

If $R_i = R_o$

$$q_b = \sqrt{2}\, q_n \tag{6.28}$$

Pressure in the burning room, which causes spread of smoke, is

$$p_b = b \tag{6.29}$$

Some important conclusions can be drawn :

- fire flow does not depend on the pressure drop in registers
- fire flow is approximately $\sqrt{2}$ times higher than ordinary ventilation flow
- pressure in the burning room is always higher than the pressure drop in terminals
- pressure in the burning room is lower than pressure produced by the fan.

In this case two fans can be interpreted as only one fan, because both the duct network and the building are closed systems.

Switched off the exhaust fan affects the evaluated fire flow and pressure for boundary case as d=0 in Figure 6.2.

Switched off the supply fan will cause spread of smoke which does not depend on the pressure in the fire room, because an outdoor air terminal is closed. The exhaust fan will have no effect in this case if the inlet terminal is tight.

The proportion of smoke, k, which spreads to the other room is

$$k = f\ /\ (1 + f) \qquad (6.30)$$

where

$$f = (R_5\ /\ (R_1 + R_2 + R_6))^{0.5} \qquad (6.31)$$

If both fans are switched off, this would also result in smoke spread, which is similar to the previous case.
The smoke goes the normal way through R_5 and the non desired "wrong" way through R_1, R_2, the other way, and R_6.

If equal flows goes both ways, q_1=q_2=$q/2$, then

R_1=R_5=R_2=R_6, and
$f = 1/\sqrt{3}$,
$k = 1/(\sqrt{3} + 1) = 0.366$

Conclusion: a lot of smoke goes the wrong way.

If only one out of ten ordinary flows goes non desired way (from a small room to a big one), then
R_1=R_5 and R_2=R_6,

$$R_1\, q_n^2 = R_2\, q_n^2\, 9^2 \text{ and } R_5\, q_n^2 = R_6\, q_n^2\, 9^2$$

$$R_2 = R_6 = R_1\ /\ 81 = R_5\ /\ 81$$

According to (6.30), (6.31)

$$f = (R\ /\ R\ \ (1 + 1/81 + 1/81))^{0.5} \approx 1 \text{ and } k \approx 0.5$$

Conclusion: 50% smoke goes the non desired way to the rest of the building or rooms.

If nine out of ten ordinary flows go the non desired way (from a large room to a small one), then

R_1=R_5 and R_2=R_6,

$$R_1\,q_n^2\;9^2 = R_2\,q_n^2 \text{ and } R_5\,q_n^2\;9^2 = R_6\,q_n^2$$

$$R_2 = R_6 = R_1\,/\,81 = R_5\,/\,81$$

According to (6.30), (6.31)

$$f = (R\,/\,81R\;\;(1/81+1+1)^{0.5} \approx 0.79 \text{ and } k \approx 0.07$$

Conclusion: 7% smoke goes the non desired way to the rest of the building or rooms.

To sum up the above estimate of the risk of spread of smoke to the adjacent room(s) in the case with the supply fan or both fans switched off, it is seen that

the maximum proportion of smoke goes the non desired way from a small burning room to a large one, or from one of several rooms to other rooms,

a lot of smoke goes the non desired way from one burning room to another equal one,

a small amount of smoke goes the non desired way from a large burning room to a small one.

a little share goes non desired way from a big burning room to a small one.

6.3.3 Exhaust and supply ventilation system with air leakage

The layout of an exhaust and supply ventilation system for two rooms with air leakage and its model are presented in Figure 6.3.

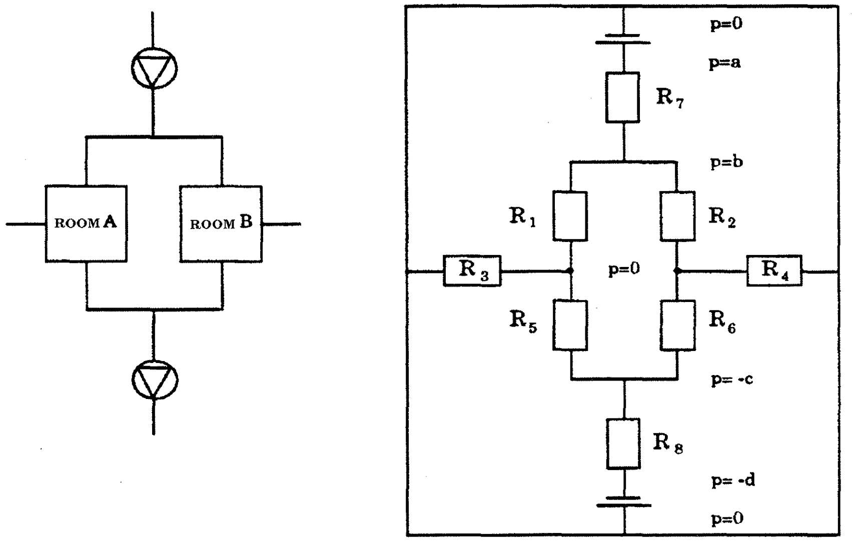


Figure 6.3 Layout of exhaust and supply ventilation system for two rooms with air leakage, and its model.

Air leakage is assumed to be equal to ordinary ventilation flow q_n at the normalised pressure difference p_i.
This gives

$$R_3 = p_i \,/\, q_n^2 \tag{6.32}$$

$$R_4 = p_i \,/\, (1 - q_n)^2 \tag{6.33}$$

The open system boundary flow can be approximately calculated as the boundary fire flow of the closed systems with the leakage flow added. The leakage flow is easily calculated from the fire pressure and the airtightness of the rooms.

$$q_{b_o} = q_{b_c} + q_{b_l} \tag{6.34}$$

$$q_{b_l}^2 = p_b / R_l \tag{6.35}$$

Pressure in the fire room for the boundary case is approximately

$$p_b = b, \tag{6.36}$$

and the corresponding flow is

$$q_b = 2^{0.5} q_n + (p_b / p_i)^{0.5} q_n. \tag{6.37}$$

Some important conclusions can be drawn:

-fire flow varies between √2 and √2+√10 power air flow, depending on the pressure drop in terminals (*b* changes between 0 and 1) and on the normalised pressure difference $p_i = 0.1$
-fire flow is larger than in the case without air leakage
-pressure in the burning room is always higher than pressure drop in terminals
-pressure in the burning room is lower than the pressure produced by the fan
-pressure in the burning room here is smaller than in the case without air losses.

The above model was tested and confirmed experimentally. Experimental data for the three-room case and its comparison with the variables predicted by the model are presented in [2]. The agreement can be considered reasonable.

7 Design of ventilation systems

7.1 Characteristic ventilation systems

In very general terms, evaluation of the risk of smoke spread via ventilation ducts in an arbitrary building can be shown in Table 7.1.

Table 7.1 Evaluating of the risk of smoke spread in buildings via the ventilation systems duct network.

Ventilation system	Running	Not running
Buildings envelope, whole	little	great
Buildings envelope, damaged	none	little

As can be seen, running the ventilation system during a fire can reduce the risk of smoke spread via ventilation ducts.
Mechanical ventilation systems can be generally divided into three major system groups:

-exhaust ventilation system
-supply-exhaust ”closed” ventilation system (without air losses)
-supply-exhaust ”opened” ventilation system (with air losses).

As this project is focused on certain types of buildings, the most typical ventilation systems used in them will be discussed later on.

One of the most typical ventilation systems in residential buildings is an exhaust ventilation system with one exhaust fan and a distribution system consisting of one or two main ducts with branches to each flat. Another type of ventilation system, supply-exhaust ventilation system, with supply and exhaust fans and distribution ductwork to each flat is also used in dwellings.

In both types of ventilation systems plenums can be both vertical and horizontal.

Hospitals are usually ventilated by supply-exhaust ventilation systems with branches connected to the dampers in each hospital section.

Offices can be ventilated in different ways with the help of ordinary supply-exhaust ventilation systems with dampers in each of the departments or rooms. “Zero“-ducts can be also used in such buildings. This means that supply air is distributed via terminals direct to office rooms, while exhaust air collects in corridors (“zero“-ducts) and is removed via exhaust terminals by the exhaust ventilation system.

Hotels are usually ventilated by supply-exhaust ventilation systems with branches connected to the dampers in each hotel room or each hotel suite.

These ventilation systems can include different variations of system layout, and the degree of complexity of these systems can be widely different. The problems of air distribution in spaces and the types of terminals, and their position in the rooms, are not discussed here. Problems concerning the ventilation plant, its construction and components, including air leakage in the heat exchanger, are beyond this study.

7.2 Fire compartments

In order to define the term "adjacent room" in evaluating the risk of smoke spread via ventilation ducts in the building, the question on fire compartmentation seems to be of interest. The layout of a ventilation system greatly depends on the building's inherent compartmentation, for the purpose of the present study - on fire compartmentation.

According to Swedish Building Codes [8] and Quality assurance requirements [20] a fire compartment is defined as a room or a group of rooms, in which activity has no direct connection with the activities in the rest of the building.

-In dwellings it embraces each self-contained flat.
-In hospitals it comprises each ward.
-In offices it comprises all rooms in each office.
-In hotels it comprises each hotel room or hotel suite.

Since the layout of the ventilation system generally conforms to the layout of compartments, the risk of the spread of smoke to adjacent fire compartments via ducts connecting different fire compartments will be discussed with reference to fire compartmentation.

The problem of smoke spread within a fire compartment can also be analysed in certain cases. In such cases the problem will be confined to the evaluation of the risk of smoke spread to adjacent rooms, instead of to adjacent fire compartments.

In this study the risk of smoke spread via ducts to adjacent fire compartments will be evaluated.

8 Models and tools

The following analysis of the schematic models, evaluation of the risk of smoke spread and estimation of smoke spread in “real“ ventilation systems are based on the main flows produced by fires in the examined types of buildings, which were set out in Section 1, along with the features presented in Chapters 5 and 7 of Section 2.

8.1 PFS program

For the purpose of evaluating of smoke spread through ducts, a computer program PFS was used. This program, developed and written by Lars Jensen, is based on the semi graphical circuit drawings and treats arbitrary flow systems of any structure and layout, any media, and any problem: design or investigation. The program manual for PFS includes three major reports and four reports with applications [21]-[27]. The following assumptions were made concerning ventilation systems analysed in the present study:

-all ventilation systems are mechanical
-all pressure losses are governed by expressions for the ”cold” flow (under normal conditions)
-all ordinary ventilation flows correspond to fire compartment grouping
-all room flows are equal.

8.2 Schematic model

The main principles of describing the ventilation system, and its analysis, will be presented in this part. A simpler study of different ventilation systems, serving four rooms, and the expected behaviour of these systems under certain conditions, will also be shown. The main purpose of this study is to show how smoke spread via ventilation ducts can be predicted for a certain ventilation system with the help of the computer program PFS. The schematic layout of the analysed ventilation systems is shown in Figure 8.1.

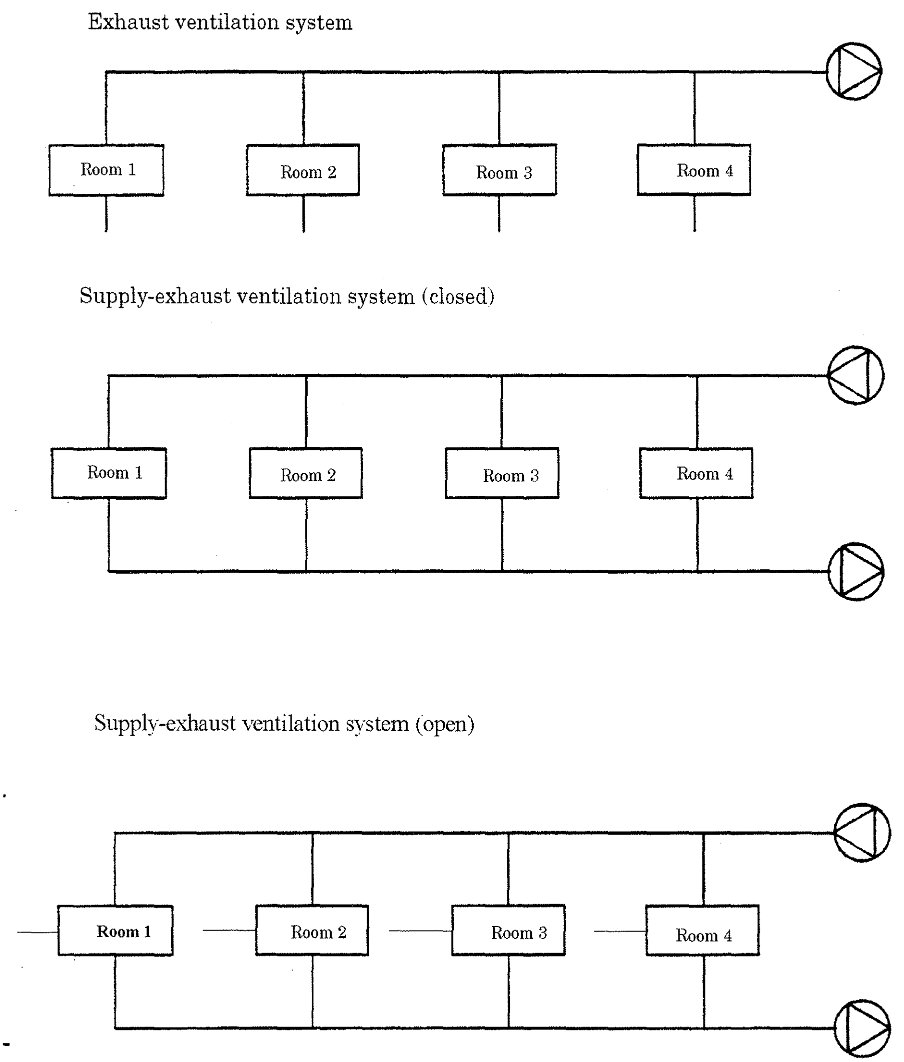


Figure 8.1 Schematic layout of four-room ventilation system.

Some of the usually occurring PFS elements and symbols are as follows:

"+"	define flow direction downwards and to the right as positive
"-"	define flow direction upwards and to the left as negative
h?0	printout pressure
h?200	describes a fire with a flow of 200 l/s, downwards or to the right, and prints out pressure
h?-200	describes flow of 200 l/s, upwards or to the left, and prints out pressure
h,100:q	describes pressure of 100 Pa and prints out flow
h?:q	describes boundary case conditions and prints out pressure and flow in a room
q,0	describes boundary case's zero flow
s,value	describes some initial flow for calculation, which facilitates convergence
FF:hq<	describes a fan with flow direction upwards and to the left, and prints out pressure and flow produced by this fan
FF:hq>	describes a fan with a flow direction downwards and to the right, and prints out pressure and flow produced by this fan
t,10,50:q	describes an unit with quadratic pressure loss of 10 Pa at flow of 50 l/s and prints out flow
d,200,6	describes 6 m long ventilation duct of 200 mm diameter
UD	notation for outdoor air intake
TD	notation for transfer air device.

Calculations were made for the fan with the following characteristics.

Pressure, Pa	100	100	0
Air flow, l/s	0	200	800

There are four rooms with 50 l/s air flow in each. Air leakage of 50 l/s at 50 Pa pressure difference is assumed in this case.
PFS provides the opportunity to describe resistance properties of wyes and junctions in two different ways: as a quadratic function

and with the help of empirical equations. This is ruled by the control operator con=1 and con=2 respectively. Both types were tested.

8.2.1 Exhaust ventilation

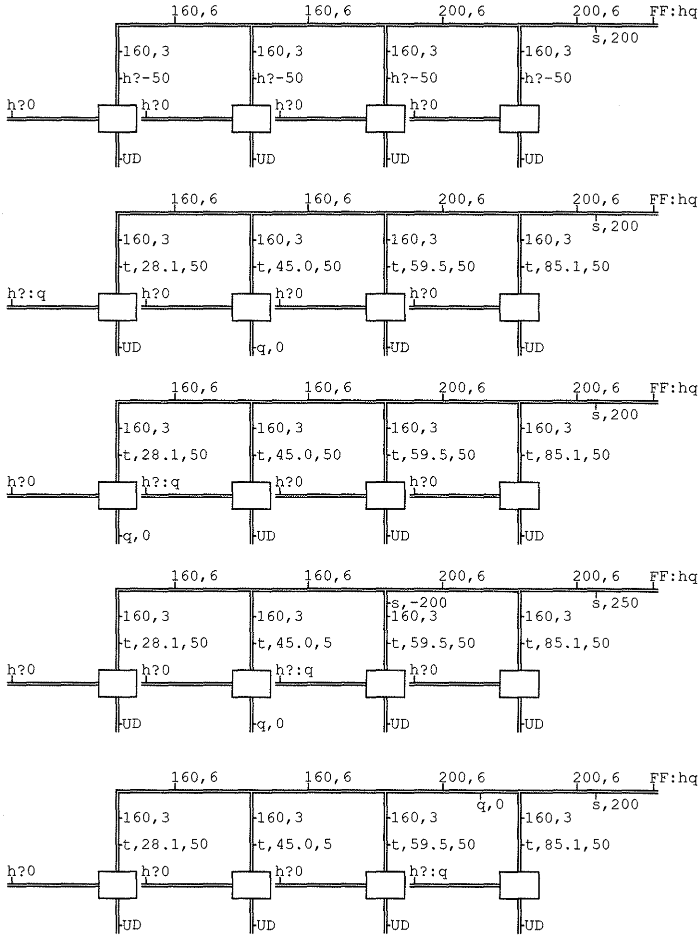
The layout of the exhaust ventilation system with the total air flow of 200 l/s at 100 Pa pressure is presented in Figure 8.2. Five cases were studied: a "normal" case and four boundary cases with fire in each of the rooms in turn. Results are presented in Table 8.1. and Figure 8.3 (for con=1).

Table 8.1 Flows and pressure for boundary cases in rooms of fire origin for the examined exhaust ventilation system.

Case	Flow in the fire room, l/s		Pressure in the fire room, Pa	
	con=1	con=2	con=1	con=2
Normal	0	0	-10	-10
Boundary case for room 1	949	455	1551	392
Boundary case for room 2	483	559	444	597
Boundary case for room 3	810	957	1342	1772
Boundary case for room 4	641	1350	921	4053

As Table 8.1 shows, flows and pressures for boundary cases differ significantly from one fire room to another. This generally depends on the resistance properties of wyes and the resulting pressure drop in these. As calculated in Subsection 6.1.3, the expected flows and pressures for boundary cases are considerably higher than in the normal (ordinary) case. Boundary flows and pressure drops predicted with con=1 are higher then those for con=2, except for fire case in room 1. According to Table 8.2 flow values show sufficient agreement with theoretically predicted q_b. The deviation is due to the resistance properties of wyes and the resulting pressure drop in these.

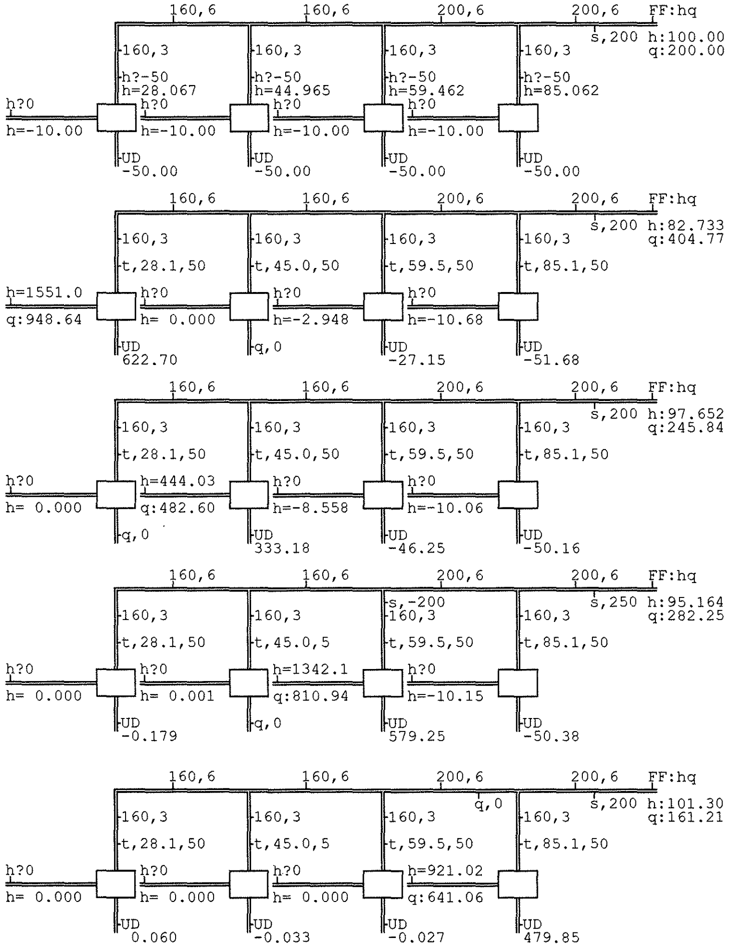
```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  table=12 dxs=25
set         UD=t,10,50:q  160=d,160  200=d,200
fan         FF  100:0  100:200 0:800
```




```
end
```

Figure 8.2 PFS-layout of exhaust ventilation system for four rooms.

```
begin
flow      l/s
pressure  Pa
control   bend=1  con=1  duct=1  itmax=99  table=12 dxs=25
set       UD=t,10,50:q  160=d,160  200=d,200
fan       FF  100:0  100:200 0:800
```




```
end  block     1  problems   5  elements 162
```

Figure 8.3   PFS-result of exhaust ventilation system for four rooms.

8.2.2 Closed supply-exhaust ventilation (without air leakage)

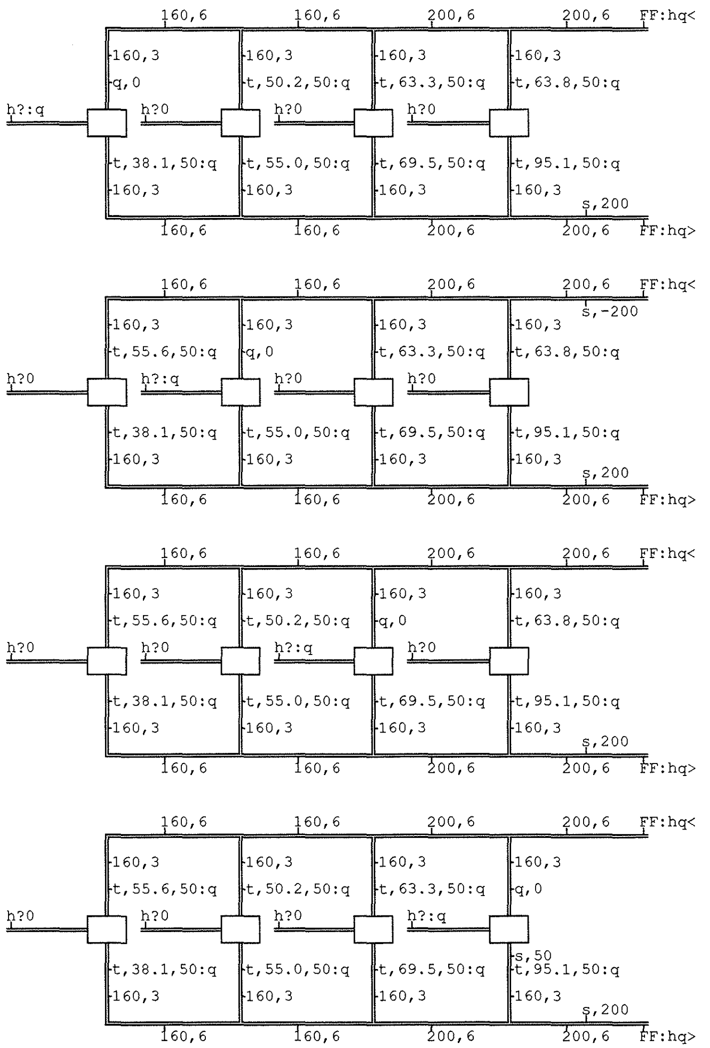
The layout of the closed supply-exhaust ventilation (without air leakage) system with the total air flow of 200 l/s at 100 Pa pressure is presented in Figure 8.4. Five cases were studied: a "normal" case and four boundary cases with fire in each room in turn. The results are presented in Table 8.2 and Figure 8.5 (for resistance of wyes as a quadratic function, con=1).

Table 8.2 Flows and pressures for boundary cases in rooms of fire origin for the examined closed supply-exhaust ventilation system.

Case	Limit fire flow, l/s		Limit fire pressure, Pa	
	con=1	con=2	con=1	con=2
Normal	0	0	0	0
Boundary case for room 1	76	82	81	83
Boundary case for room 2	72.5	68	80	79
Boundary case for room 3	71	68	81	82
Boundary case for room 4	66	61	71	81

As Table 8.2 shows, boundary values for both flows and pressures are considerably lower than those in the case with exhaust ventilation, and the difference between con=1 and con=2 cases is insignificant. As calculated in Subsection 6.1.4, the expected flow for the boundary case is $q_b = \sqrt{2}\, q_n$, which in the present case is 71 l/s. According to Table 8.2, the difference between flows and pressures for the boundary cases is insignificant from one fire room to another, and flow values show sufficient agreement with the theoretically predicted q_b. The deviation is due to the resistance properties of wyes and the resulting pressure drop in these.

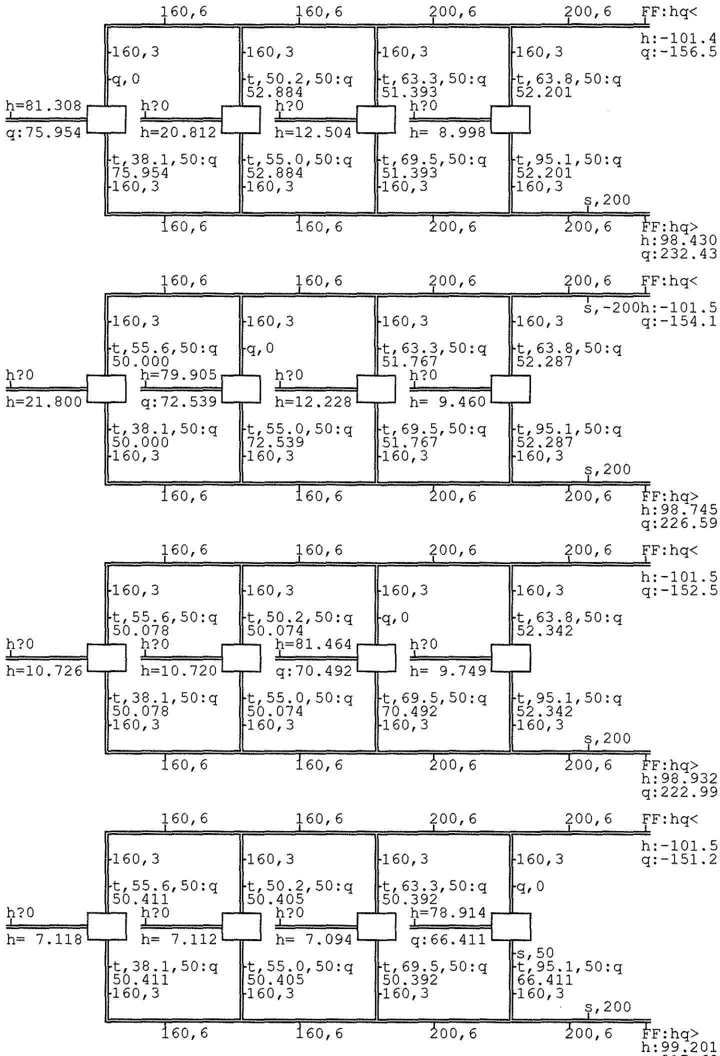
```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=20
set         160=d,160  200=d,200
fan         FF  100:0  100:200  0:800
```



end

Figure 8.4 *PFS-layout of closed supply-exhaust ventilation system for four rooms.*

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1   itmax=20
set         160=d,160  200=d,200
fan         FF  100:0  100:200  0:800
```




```
end  block      1  problems   5  elements 257
```

Figure 8.5 ***PFS-result of closed supply-exhaust ventilation system for four rooms.***

8.2.3 Open supply-exhaust ventilation (with air leakage)

The layout of the open supply-exhaust ventilation (with air leakage) system with the total air flow of 200 l/s at 100 Pa pressure is presented in Figure 8.6. Five cases were studied: a "normal" case and four boundary cases with fire in each room in turn. The results are presented in Figure 8.6 and Figure 8.7 (for resistance of wyes as a quadratic function, con=1).

Table 8.3 Flows and pressures for boundary cases in rooms of fire origin for the examined open supply-exhaust ventilation system.

Case	Limit fire flow, l/s		Limit fire pressure, Pa	
	con=1	con=2	con=1	con=2
Normal	0	0	0	0
Boundary case for room 1	140	144	78	77
Boundary case for room 2	134	130	76	76
Boundary case for room 3	134	132	79	80
Boundary case for room 4	128	128	77	90

As Table 8.3 shows, the boundary values for both flows and pressures are considerably lower than those in the case with exhaust ventilation, but higher than those in the case with a closed supply-exhaust ventilation system, and the difference between con=1 and con=2 cases is insignificant. As calculated in Subsection 6.1.4, the expected flow for the boundary case follows (6.37) and the fire flow varies between $\sqrt{2}$ and $(\sqrt{2}+\sqrt{10})$ of ordinary air flow. Fire flow in the present case should vary between 71 l/s and 229 l/s. According to Table 8.2, the difference between flows and pressures for boundary cases is insignificant from one fire room to another and flow values show sufficient agreement with theoretically predicted

q_b. The deviation is due to the resistance properties of wyes and the resulting pressure drop in these.

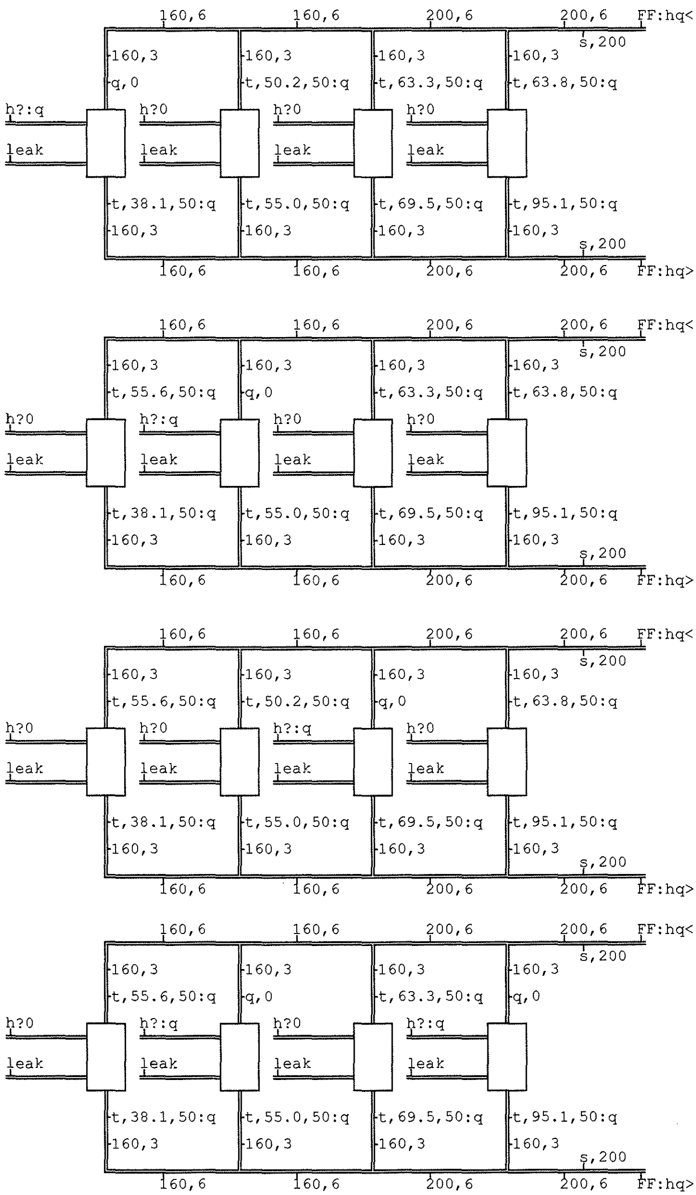
Boundary fire flows, leakage flows and duct flows for resistance of wyes as a quadratic function, con=1, are shown in more detail in Table 8.4.

Table 8.4 Fire flows, leakage flows and duct flows for boundary cases in rooms of fire origin for the examined open supply-exhaust ventilation system.

Case	Total flow in the fire room, l/s	Flow in the duct to the fire room, l/s	Leakage flow out from the fire room, l/s
Boundary case for room 1	139.5	77.1	63.4
Boundary case for room 2	134.4	72.8	61.6
Boundary case for room 3	133.4	70.5	62.9
Boundary case for room 4	128.2	66.1	62.1

Table 8.4 shows, that flows in the duct in this case agree with those presented in Table 8.2 for the closed supply-exhaust ventilation system. Leakage flow can be evaluated with the help of (6.35).

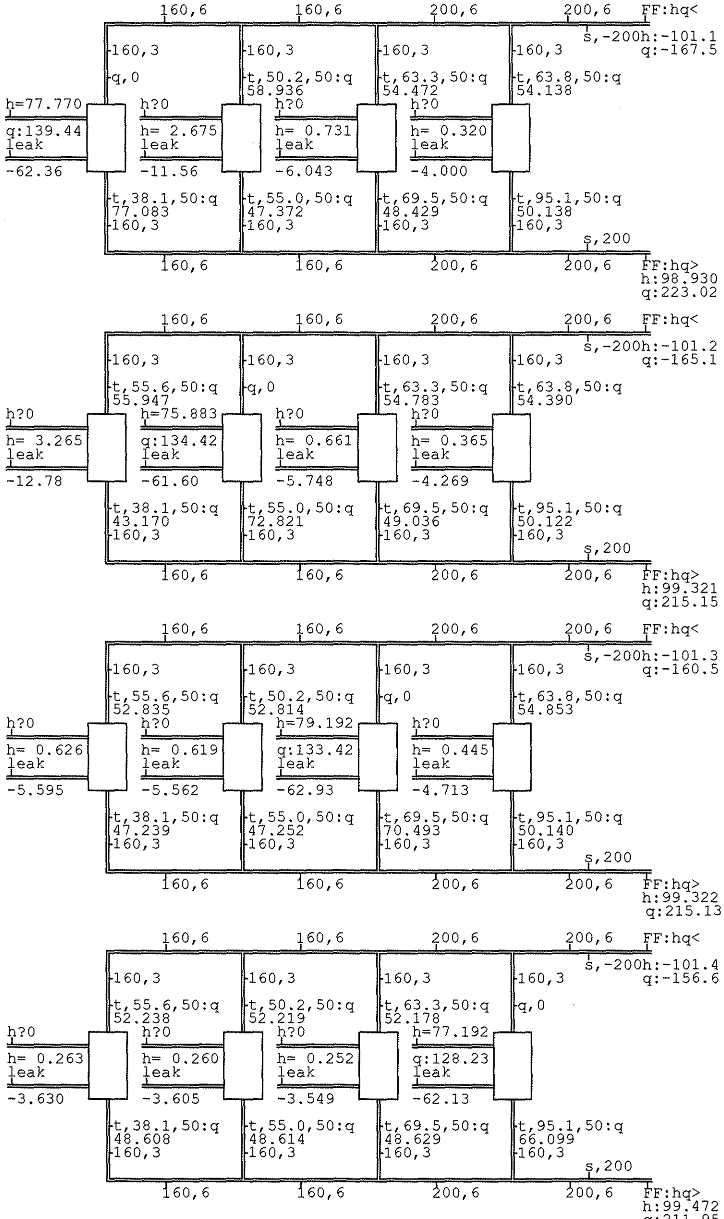
```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=20
set         leak=t,50,50:q  160=d,160  200=d,200
fan         FF  100:0  100:200  0:800
```




```
end
```

Figure 8.6 *PFS-layout of open supply-exhaust ventilation system for four rooms.*

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=20
set         leak=t,50,50:q  160=d,160  200=d,200
fan         FF  100:0  100:200  0:800
```




```
end  block     1  problems   5  elements 280
```

Figure 8.7 *PFS-result of open supply-exhaust ventilation system for four rooms.*

8.2.4 Open supply-exhaust ventilation with a "zero" - duct

The layout of the open supply-exhaust ventilation system with a "zero" duct, with the total air flow of 200 l/s at 100 Pa pressure, is presented in Figure 8.8. Five cases were studied: a "normal" case and four boundary cases with fire in each room in turn. The results are presented in Table 8.5 and Figure 8.9 (for resistance of wyes as a quadratic function, con=1).

Table 8.5 Flows and pressures for boundary cases in rooms of fire origin for the examined open supply-exhaust ventilation system with a "zero" duct.

Case	Limit fire flow, l/s		Limit fire pressure, Pa	
	con=1	con=2	con=1	con=2
Normal	0	0	0	0
Boundary case for room 1	177	175	79	77
Boundary case for room 2	176	175	77	77
Boundary case for room 3	179	180	81	81
Boundary case for room 4	179	180	79	81

As Table 8.5 shows, boundary values for flows are somehow higher than those in the case of ordinary supply-exhaust ventilation system. According to Table 8.5, the difference between flows and pressures for boundary cases is insignificant from one fire room to another. The deviation is due to the resistance properties of wyes and the resulting pressure drop in these.

This case can be analysed in a more detailed way with the help of equation 6.27. R_o is a subscript for exhaust air up to the corridor. Figure 8.8 shows that $R_t \approx 60$ Pa and $R_o \approx 15$ Pa. Hence,

$$q_{b_k} = (R_i \; / \; R_o + 1)^{0.5} q_n = 5^{0.5} \; q_n,$$

and in this case q_{bk}≈115 l/s. For leakage paths in the case of fire yields

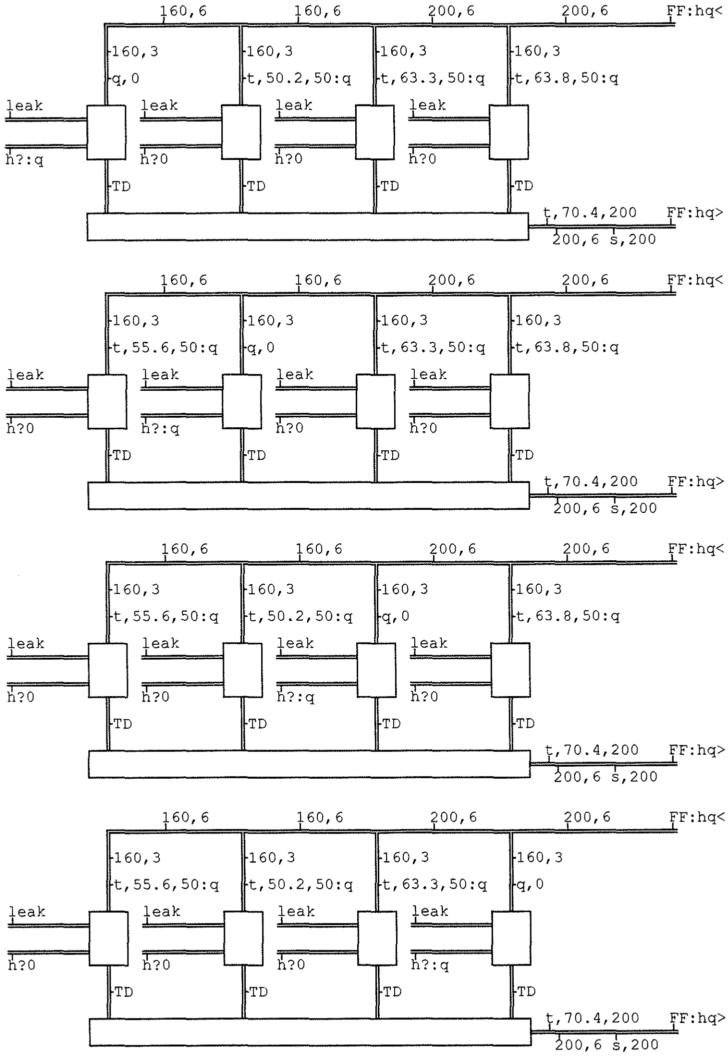
$$\frac{p_{bf}}{50} = (\frac{q_{bf}}{50})^2$$

$$q_{bf} = 50(\frac{80}{50})^{0.5}$$

and in this case q_{bf}≈65 l/s. Total expected boundary fire flow is 180 l/s. This agrees very good with the presented results (Table 8.5).

Note, that in the open supply - exhaust ventilation with a "zero"-duct smoke spreads via exhaust ducts and collects in the corridor.

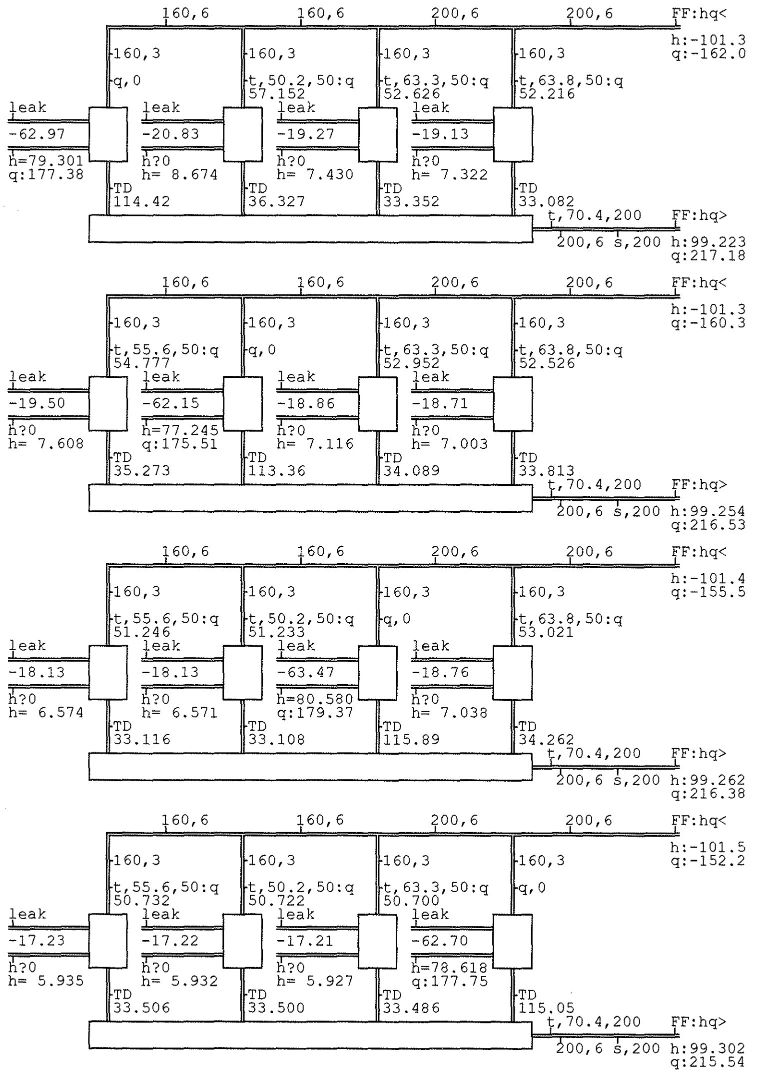
```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  dxs=20
set         160=d,160  200=d,200  TD=t,15,50:q leak=t,50,50:q
fan         FF  100:0  100:200  0:800
```




```
end
```

Figure 8.8 *PFS-layout of open supply-exhaust ventilation system for four rooms with a "zero-duct".*

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  dxs=20
set         160=d,160  200=d,200  TD=t,15,50:q leak=t,50,50:q
fan         FF  100:0  100:200  0:800
```




```
end   block      1  problems   5  elements 195
```

Figure 8.8 *PFS-result of open supply-exhaust ventilation system for four rooms with a "zero-duct".*

8.2.5 Some conclusions on different types of flows and pressure estimation

The analysis of boundary flows and pressures obtained in the types of ventilation systems examined above, with two different ways of defining the resistance of wyes (as a quadratic function, con=1, and with the help of empirical equations, con=2), shows that

- all results agree quit well with predicted theoretical values,
- for the exhaust ventilation system, all values obtained for con=1 are somewhat higher than those obtained for con=2, except for the case with fire in room 1 where the opposite result is obtained,
- in all cases for the supply-exhaust ventilation systems', the values obtained for con=1 differ insignificantly and without a clear trend from those obtained for con=2.

It seems reasonable to use both control operators in calculating the simulated cases for supply-exhaust ventilation systems of all types, while the choice of operator for exhaust ventilation systems is not so simple. As a matter of fact, it is more reliable to use lower boundary flow values than to use higher ones. Regarded in that light, con=2 should be chosen as a default operator. One of the reasons for not using con=2 in evaluating the boundary fire flow is that all pressure drops in wyes are based on empirical measurements for normal flow directions. As this study is interested in "abnormal" flow behaviour, i.e. changes in flow directions and the consequent reduction in flow in certain parts of junctions to zero, it is not obvious how wyes would respond. Higher flows cause higher velocities in ducts, and, as a result, higher Reynolds numbers. Along with increasing flow turbulence, the pressure field described as a quadratic function increases.

For these reasons, control variable con=1 will be used in further analysis.

8.3 Measures to prevent smoke spread via ventilation ducts

It will have been seen from Subsection 8.2 that fire flows and corresponding pressures in fire rooms, caused by smoke spread via ventilation ducts, can be calculated with the help of the PFS program for different ventilation systems. Flows exceeding boundary flows will always cause smoke spread. The open supply-exhaust ventilation system with air leakage, presented in Figure 8.5 for the case of fire in room 1 which produces 200 l/s fire flow, as well as some measures to prevent smoke spread through the system, will be presented in this part. The flow of 200 l/s which is larger than the boundary flow (Table 8.3) was chosen arbitrarily.

8.3.1 Examination of possible measures to prevent smoke spread

The PFS layout and PFS results for flow directions in the open supply-exhaust ventilation system serving four rooms, in the case of fire in room 1 (fire flow 200 l/s), are presented in Figures 8.7 - 8.12. Seven possible solutions are studied. Table 8.4 presents data regarding the examined measures.

Table 8.4 Data regarding the examined measures to prevent smoke spread

Case	Supply fan	Exhaust fan
1	normal	normal
2	rotational speed doubled	rotational speed doubled
3	closed	closed
4	closed	normal
5	closed with bypass to the exhaust fan	normal
6	closed with bypass to the exhaust fan	rotational speed doubled
7	converted into exhaust fan	normal

Case 1 is an ordinary case. Case 3 corresponds to natural venting. Cases 2 and 6 use the same fan(s), with the rotational speed doubled which is a very hard measure and can be applied in e.g. ventilation systems with reduced normal capacity.

8.3.2 Analysis of risk of smoke spread in the examined cases

Case 1.

As expected, smoke spreads to the adjacent room 2 (34.55 l/s), where it mixes with supply air and is removed from the room via the exhaust system. As a general observation, it must be emphasised that the whole pressure and flow configuration in both ventilation systems changes due to the fire in the room 1 (some pressurisation of all rooms, increased air losses through leakage passes, decreased air flow, produced by the supply fan (141.3 l/s instead of 200 l/s in normal case), and increased supply air flow to each room).

Case 2.

In case of fire, usual fans can be used in an unusual way. This case examines fans with the rotational speed doubled (FF,2). The fans produce increased flows and pressures, and there is no smoke spread at all via ducts.

Case 3.

This case studies the behaviour of the systems with both fans shut down (natural ventilation). It shows total spread of smoke to all rooms through all branches.

Case 4.

This case examines the behaviour of the whole system, with the supply fan shut down and the exhaust fan in operation. The calculation shows that smoke spreads to all three rooms via supply ducts.

Case 5.

This case studies the behaviour of the systems with the supply fan shut down and the supply plenum connected to the exhaust plenum and to the exhaust fan. The result is no smoke spread at all and insignificant underpressure, 40-52 Pa, in three "clear" rooms.

Case 6.

This case studies the behaviour of the systems with the supply fan shut down and the supply plenum connected to the exhaust plenum, combined with doubling the rotational speed of the exhaust fan. The result is no smoke spread at all and significant underpressure, up to 228 Pa, in three "clear" rooms. The last observation can be decisive in choosing this measure since the underpressure, converted into door opening force, should never exceed 130 N.

Case 7.

This case examines the theoretical possibility of converting the supply fan into an exhaust fan. The calculation shows that there is no spread of smoke via the ventilation system, but underpressure of up to 72.5 Pa can occur in rooms. This case can be combined with increasing n times the rotational speed of one or both fans, which will result in lower pressure in the rooms.

A very rough estimate of smoke spread can be made with the help of flow direction and PFS layout, which are shown in Figures 8.9 and 8.12.

The studied cases do not cover all possible measures to prevent smoke spread via ventilation ducts, nor do they examine the behaviour of the systems with fire dampers.

The main principles set out in this part will be used in evaluating “real“ ventilation systems.

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=20
set         leak=t,50,50:q  160=d,160  200=d,200
fan         FF  100:0  100:200  0:800
```

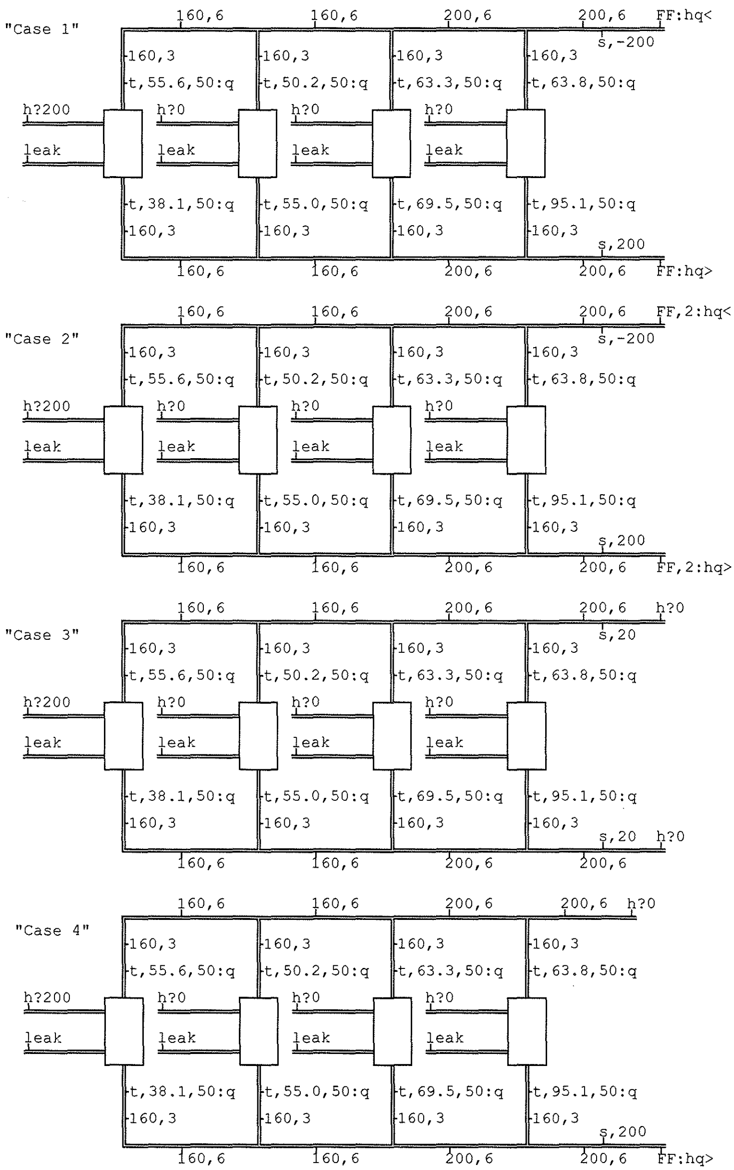


Figure 8.7 *PFS-layout of open supply-exhaust ventilation system for four rooms with 200 l/s flow in the fire room and four cases 1-4.*

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=20
set         leak=t,50,50:q  160=d,160  200=d,200
fan         FF  100:0  100:200  0:800
```

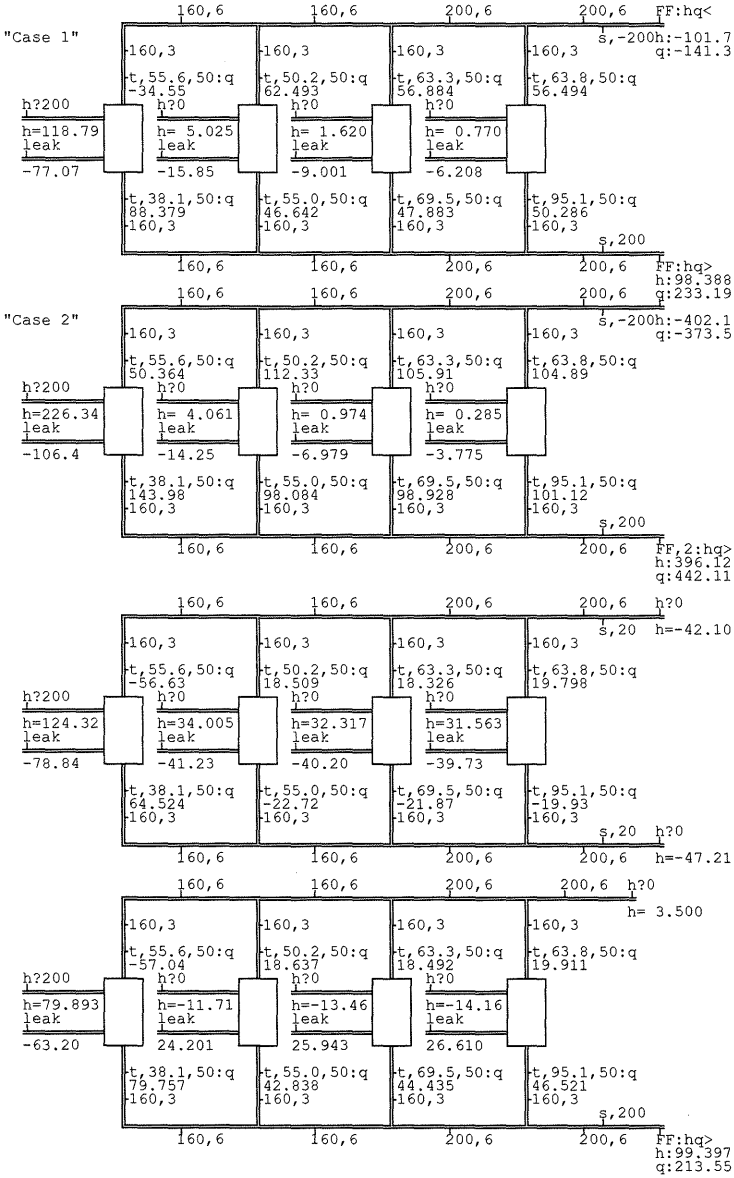
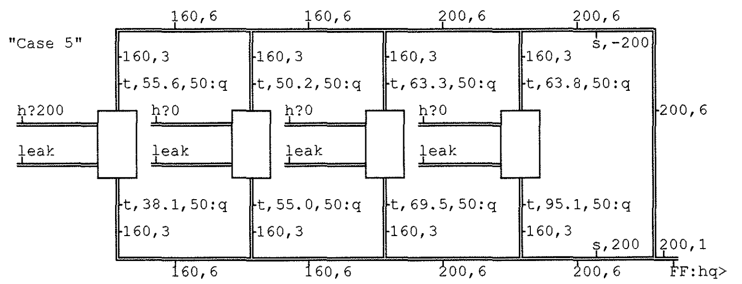


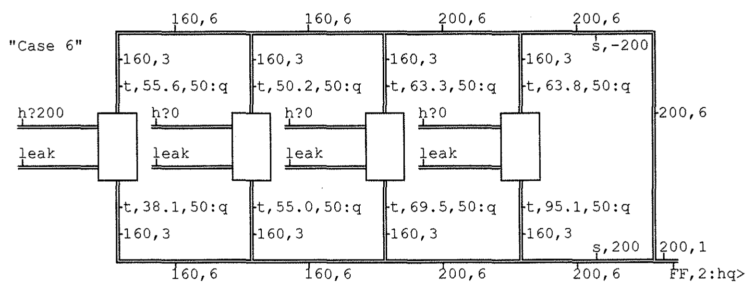
Figure 8.8 ***PFS-result for open supply-exhaust ventilation system for four rooms with 200 l/s flow in the fire room and cases 1-4.***

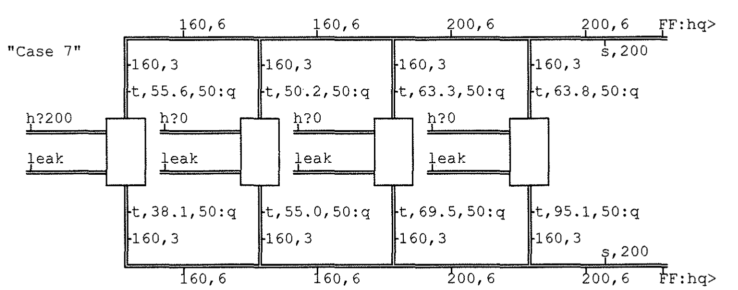
```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=20
set         leak=t,50,50:q  160=d,160  200=d,200
fan         FF  100:0  100:200  0:800

                 160,6         160,6         200,6         200,6   FF:hq<
            ╔+++++++++++++╦-------------╦-------------╦--------------
"case 1"    -             +             +             +       s,-200
            -160,3        +160,3        +160,3        +160,3
            -             +             +             +
            -t,55.6,50:q  +t,50.2,50:q  +t,63.3,50:q  +t,63.8,50:q
            -             +             +             +
  h?200   ┌─-─┐ h?0     ┌─+─┐ h?0     ┌─+─┐ h?0     ┌─+─┐
 +++++++++++- │00000000000+ │00000000000+ │00000000000+ │
  leak    │   │ leak    │   │ leak    │   │ leak    │   │
 -----------+ │-----------+ │-----------+ │-----------+ │
          └─+─┘         └─+─┘         └─+─┘         └─+─┘
            +             +             +             +
            +t,38.1,50:q  +t,55.0,50:q  +t,69.5,50:q  +t,95.1,50:q
            +             +             +             +
            +160,3        +160,3        +160,3        +160,3
            +             +             +             +       s,200
            ╚+++++++++++++╩+++++++++++++╩+++++++++++++╩+++++++++++++++
                 160,6         160,6         200,6         200,6   FF:hq>
                 160,6         160,6         200,6         200,6   FF,2:hq<
            ╔-------------╦-------------╦-------------╦--------------
"case 2"    +             +             +             +       s,-200
            +160,3        +160,3        +160,3        +160,3
            +             +             +             +
            +t,55.6,50:q  +t,50.2,50:q  +t,63.3,50:q  +t,63.8,50:q
            +             +             +             +
  h?200   ┌─+─┐ h?0     ┌─+─┐ h?0     ┌─+─┐ h?0     ┌─+─┐
 ++++++++++++ │00000000000+ │00000000000+ │00000000000+ │
  leak    │   │ leak    │   │ leak    │   │ leak    │   │
 -----------+ │-----------+ │-----------+ │-----------+ │
          └─+─┘         └─+─┘         └─+─┘         └─+─┘
            +             +             +             +
            +t,38.1,50:q  +t,55.0,50:q  +t,69.5,50:q  +t,95.1,50:q
            +             +             +             +
            +160,3        +160,3        +160,3        +160,3
            +             +             +             +       s,200
            ╚+++++++++++++╩+++++++++++++╩+++++++++++++╩++++++++++++++
                 160,6         160,6         200,6         200,6   FF,2:hq>

                 160,6         160,6         200,6         200,6   h?0
            ╔+++++++++++++╦+++++++++++++╦+++++++++++++╦000000000000000
"case 3"    -             +             +             +       s,20
            -160,3        +160,3        +160,3        +160,3
            -             +             +             +
            -t,55.6,50:q  +t,50.2,50:q  +t,63.3,50:q  +t,63.8,50:q
            -             +             +             +
  h?200   ┌─-─┐ h?0     ┌─+─┐ h?0     ┌─+─┐ h?0     ┌─+─┐
 +++++++++++- │00000000000+ │00000000000+ │00000000000+ │
  leak    │   │ leak    │   │ leak    │   │ leak    │   │
 -----------+ │------------ │------------ │------------ │
          └─+─┘         └───┘         └───┘         └───┘
            +             -             -             -
            +t,38.1,50:q  -t,55.0,50:q  -t,69.5,50:q  -t,95.1,50:q
            +             -             -             -
            +160,3        -160,3        -160,3        -160,3
            +             -             -             -       s,20  h?0
            ╚+++++++++++++╩+++++++++++++╩+++++++++++++╩000000000000000
                 160,6         160,6         200,6         200,6
                 160,6         160,6         200,6         200,6  h?0
            ╔+++++++++++++╦+++++++++++++╦+++++++++++++╦000000000000
"case 4"    -             +             +             +
            -160,3        +160,3        +160,3        +160,3
            -             +             +             +
            -t,55.6,50:q  +t,50.2,50:q  +t,63.3,50:q  +t,63.8,50:q
            -             +             +             +
  h?200   ┌─-─┐ h?0     ┌─+─┐ h?0     ┌─+─┐ h?0     ┌─+─┐
 +++++++++++- │00000000000+ │00000000000+ │00000000000+ │
  leak    │   │ leak    │   │ leak    │   │ leak    │   │
 -----------+ │+++++++++++++ │+++++++++++++ │+++++++++++++ │
          └─+─┘         └─+─┘         └─+─┘         └─+─┘
            +             +             +             +
            +t,38.1,50:q  +t,55.0,50:q  +t,69.5,50:q  +t,95.1,50:q
            +             +             +             +
            +160,3        +160,3        +160,3        +160,3
            +             +             +             +       s,200
            ╚+++++++++++++╩+++++++++++++╩+++++++++++++╩+++++++++++++++
                 160,6         160,6         200,6         200,6   FF:hq>
```

Figure 8.9 ***PFS-layout and flow direction for open supply-exhaust ventilation system for four rooms with 200 l/s flow in the fire room and four cases 1-4. "+" shows flow direction downwards and to the right, while "-" shows flow direction upwards and to the left. "0" corresponds to no flow.***

```
        begin
flow           l/s
pressure       Pa
control        bend=1  con=1  duct=1  itmax=20
set            leak=t,50,50:q  160=d,160  200=d,200
fan            FF  100:0  100:200  0:800
```



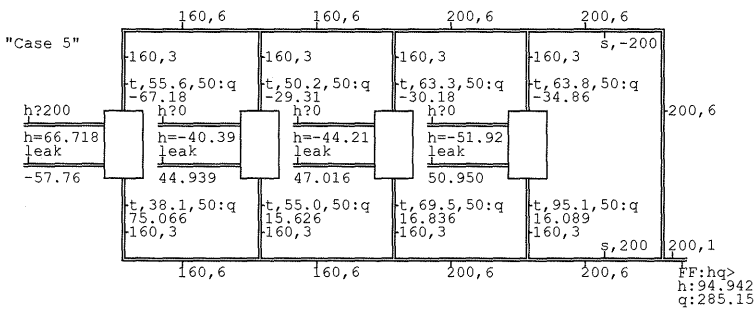


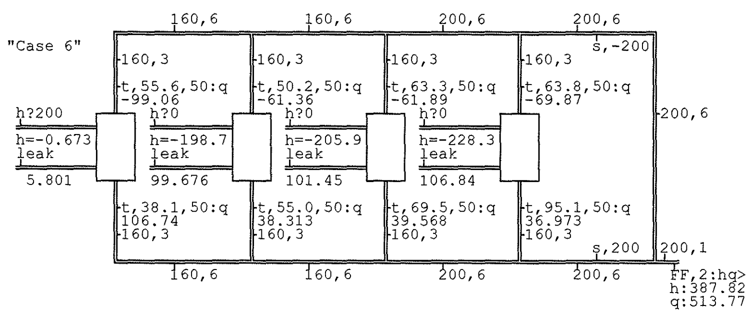


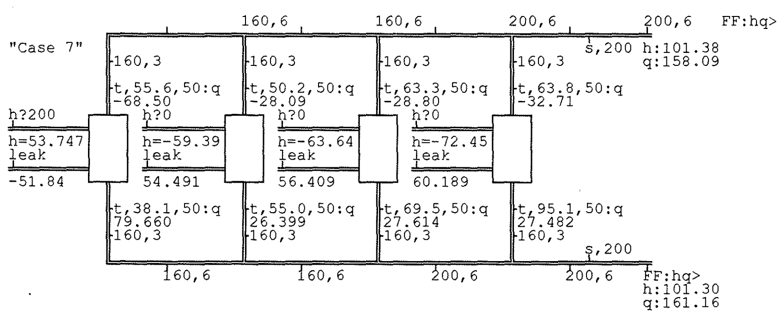

```
end
```

Figure 8.10 PFS-layout of open supply-exhaust ventilation system for four rooms with 200 l/s flow in the fire room and cases 5, 6 and 7.

```
     begin
flow         l/s
pressure     Pa
control      bend=1  con=1  duct=1  itmax=20
set          leak=t,50,50:q  160=d,160  200=d,200
fan          FF  100:0  100:200  0:800
```








```
end  block      1  problems    7  elements 401   warnings 8
```

Figure 8.11 PFS-result for open supply-exhaust ventilation system for four rooms with 200 l/s flow in the fire room and cases 5, 6 and 7.

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=20
set         leak=t,50,50:q  160=d,160  200=d,200
fan         FF  100:0  100:200  0:800



                  160,6         160,6         200,6         200,6
            ╔+++++++++++++╦+++++++++++++╦+++++++++++++╦++++++++++++╗
"case 5"    -             -             -             -      s,-200+
            -160,3        -160,3        -160,3        -160,3       +
            -             -             -             -            +
            -t,55.6,50:q  -t,50.2,50:q  -t,63.3,50:q  -t,63.8,50:q +
            -             -             -             -            +
  h?200   ┌─-─┐ h?0     ┌─-─┐ h?0     ┌─-─┐ h?0     ┌─-─┐          +200,6
 +++++++++│+- │000000000│0- │000000000│0- │000000000│0- │          +
          │   │                                                  +
  leak    │   │ leak    │   │ leak    │   │ leak    │   │          +
 ---------│-+ │+++++++++│++ │+++++++++│++ │+++++++++│++ │          +
          └─+─┘         └─+─┘         └─+─┘         └─+─┘          +
            +             +             +             +            +
            +t,38.1,50:q  +t,55.0,50:q  +t,69.5,50:q  +t,95.1,50:q +
            +             +             +             +            +
            +160,3        +160,3        +160,3        +160,3       +
            +             +             +             +      s,200 +200,1
            ╚+++++++++++++╩+++++++++++++╩+++++++++++++╩++++++++++++╩+++
                  160,6         160,6         200,6         200,6    FF:hq>



                  160,6         160,6         200,6         200,6
            ╔+++++++++++++╦+++++++++++++╦+++++++++++++╦++++++++++++╗
"case 6     -             -             -             -      s,-200+
            -160,3        -160,3        -160,3        -160,3       +
            -             -             -             -            +
            -t,55.6,50:q  -t,50.2,50:q  -t,63.3,50:q  -t,63.8,50:q +
            -             -             -             -            +
  h?200   ┌─-─┐ h?0     ┌─-─┐ h?0     ┌─-─┐ h?0     ┌─-─┐          +200,6
 +++++++++│+- │000000000│0- │000000000│0- │000000000│0- │          +
          │   │                                                  +
  leak    │   │ leak    │   │ leak    │   │ leak    │   │          +
 +++++++++│++ │+++++++++│++ │+++++++++│++ │+++++++++│++ │          +
          └─+─┘         └─+─┘         └─+─┘         └─+─┘          +
            +             +             +             +            +
            +t,38.1,50:q  +t,55.0,50:q  +t,69.5,50:q  +t,95.1,50:q +
            +             +             +             +            +
            +160,3        +160,3        +160,3        +160,3       +
            +             +             +             +      s,200 +200,1
            ╚+++++++++++++╩+++++++++++++╩+++++++++++++╩++++++++++++╩+++
                  160,6         160,6         200,6         200,6    FF,2:hq>



                  160,6         160,6         200,6         200,6    FF:hq>
            ╔+++++++++++++╦+++++++++++++╦+++++++++++++╦+++++++++++++++
"case 7"    -             -             -             -      s,200
          -160,3        -160,3        -160,3        -160,3
            -             -             -             -
            -t,55.6,50:q  -t,50.2,50:q  -t,63.3,50:q  -t,63.8,50:q
            -             -             -             -
  h?200   ┌─-─┐ h?0     ┌─-─┐ h?0     ┌─-─┐ h?0     ┌─-─┐
 +++++++++│+- │000000000│0- │000000000│0- │000000000│0- │
          │   │                                     
  leak    │   │ leak    │   │ leak    │   │ leak    │   │
 ---------│-+ │+++++++++│++ │+++++++++│++ │+++++++++│++ │
          └─+─┘         └─+─┘         └─+─┘         └─+─┘
            +             +             +             +
            +t,38.1,50:q  +t,55.0,50:q  +t,69.5,50:q  +t,95.1,50:q
            +             +             +             +
            +160,3        +160,3        +160,3        +160,3
            +             +             +             +      s,200
            ╚+++++++++++++╩+++++++++++++╩+++++++++++++╩+++++++++++++++
                  160,6         160,6         200,6         200,6    FF:hq>

end
```

Figure 8.12 ***PFS-layout and flow direction for open supply-exhaust ventilation system for four rooms with 200 l/s flow in the fire room and four cases 5, 6 and 7. "+" shows flow direction downwards and to the right, while "-" shows flow direction upwards and to the left. "0" corresponds to no flow.***

9 "Real case" study

The study presented in Chapter 8 refers to a simple ventilation system serving four rooms. Such systems are not usual in reality. The types of buildings examined in this study are usually equipped with much more advanced systems, the degree of complexity of which can be different. In this chapter, smoke spread will be evaluated in the most typical ventilation systems installed in the examined types of buildings.

9.1 Description of the main types of ventilation systems

In spite of the fact that a great variety of different ventilation systems are used in the studied types of buildings, the most widely used systems can be described.

The mechanical ventilation systems usual in dwellings (blocks of flats) can be of both exhaust and supply-exhaust type.

The duct network of the exhaust ventilation system can have one vertical plenum, exhausting air via branches and terminals from each flat, or two vertical plenums, exhausting air from different rooms in the same flat separately (e.g. one from the kitchen, and one from toilet and bathroom). An exhaust fan in this case exhausts air at a rate which sets up a slight negative pressure in the ventilated space to ensure that the required quantity of outside air is introduced. The outside air enters the space through outdoor louvers and terminals.

Exhaust branches from each space can also pass vertically through the building and connect to the plenum just before the fan.

These types of exhaust ventilation systems can be combined with supply ventilation system with a similar duct layout.

The design of ventilation systems in hospitals is much more complicated than in other types of buildings because of the variety of services they provide. Mechanical ventilation systems in hospitals are usually of the supply-exhaust type. Each ward is supplied with air through one or several terminals, and air is exhausted via terminals in lavatories and wash rooms. In some wards, operating theatres, delivery rooms, labour rooms and nurseries, both supply and exhaust systems can deliver and exhaust air directly from the room served.

Accommodation in hotels and motels is usually in the form of single rooms with toilet and bathroom adjacent to a corridor, flanked on both sides by other guest rooms. Mechanical ventilation systems in hotels are usually of the supply-exhaust type. Each hotel room or each suite is supplied with air through one or more terminals, and air is exhausted via terminals in lavatories and bathrooms.

The variety of functions and range of design criteria applicable to office buildings have allowed the use of almost every available ventilation system. While multi-storey structures are discussed here, the principles are similar for all sizes of office buildings. Mechanical ventilation systems in offices are usually of the supply-exhaust type described before. Another type of ventilation system which can also be used in offices is the "zero duct" ventilation system in which the corridor, the "zero duct", collects vitiated air through transfer air devices from all rooms in the office and transfers it to the exhaust plenum in the ceiling through terminals.

Some of the above systems will be analysed further in Chapter 10 in connection with the danger of CO poisoning when smoke spreads to adjacent spaces.

9.2 Designed air flows

The quantities of ventilation air in most types of buildings are specified in Building Codes. [8] requires minimum outdoor air of 0.35 l/s,m^2 in all types of rooms. In rooms for sleeping the minimum outdoor air required is 4 l/s and person. In a room or part of a room with more then casual occupation the minimum outdoor air recommended is 7 l/s and person. There are requirements for minimum exhaust air flow also:

10 l/s	air flow from a kitchen, high sped extraction rate min 75% of extraction capacity
15 l/s	air flow from a pantry
10 l/s	air flow from a bathroom with openable window (if area exceeds 5 m^2, required air flow increases by 1 l/s, m^2)
15 l/s	air flow from a bathroom without window (if area exceeds 5 m^2, required air flow increases by 1 l/s,m^2)
10 l/s	air flow from a toilet

According to these air flow requirements, the ordinary air flow in an average flat and hotel room can be assumed to be 30 l/s (15 l/s for kitchenette or kitchen cubicle and 15 l/s for bathroom without openable window).

Rooms and occupancy in office buildings can vary significantly. Occupancy in e.g. accounts or other sections where clerical work is done can be approximately one person per 15 m^2 of floor area. In waiting rooms and conference rooms occupancy can be as high as one person per 1.5 m^2. According to air flow recommendations (7 l/s and person) and assuming average occupancy of 6-7 persons, air flow in offices is 50 l/s.

In Section 1, flows obtained in all the examined types of buildings are shown in Figure 4.13. Values from Figure 4.13 are used for a simplified estimation of fire flows for the volumes set out in Table 9.1.

Table 9.1 Fire flows obtained in different types of buildings of certain volumes.

Room volume, m^3	Fire flows in different types of building, m^3/s			
	Dwelling houses	Hospital	Office	Hotel
50	0.48	0.3	0.30	0.55
100	1.5	0.5	0.45	0.85
150	2.0	0.7	0.60	1.20*
200	2.5	0.9	0.65	1.50*

* - Flows according to curve for hotels.

9.3 Exhaust ventilation system

The analysis of exhaust ventilation systems described in Subsection 8.2.1 comprises only schematic models. In this section more complicated ventilation systems will be analysed.

9.3.1 Exhaust ventilation system with single outlet in each room

The layout of the examined exhaust ventilation systems is presented in Figure 9.1.

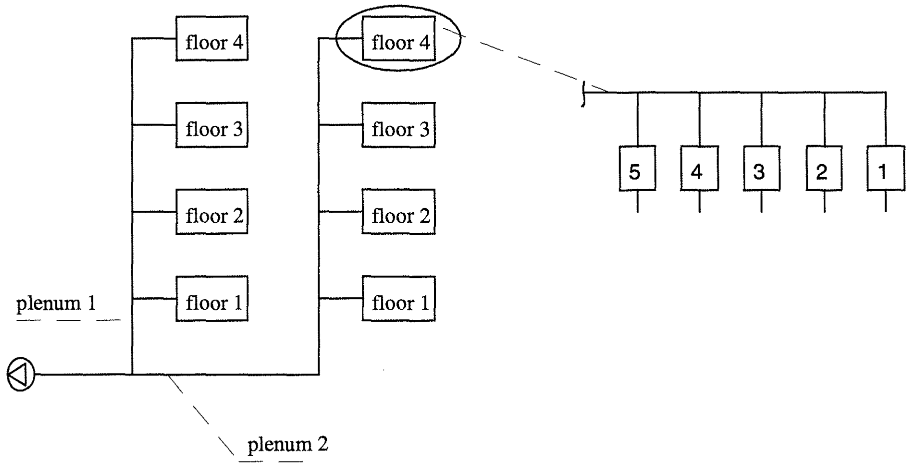


Figure 9.1 Layout of exhaust ventilation system for four floors and ten rooms on each floor.

The layout of the exhaust ventilation system with the total air flow of 1200 l/s at 107 Pa pressure, which exhausts via two vertical plenums from four floors, and further via branches from ten rooms on each floor, is presented in Figure 9.2. The exhaust fan has the following characteristics:

Pressure, Pa	100	125	75
Air flow, l/s	200	750	1500

Results for a "normal" case are presented in Figure 9.3.

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  table=3
set         UD=t,10,30
fan         FF 100:200 125:750 75:1500
```

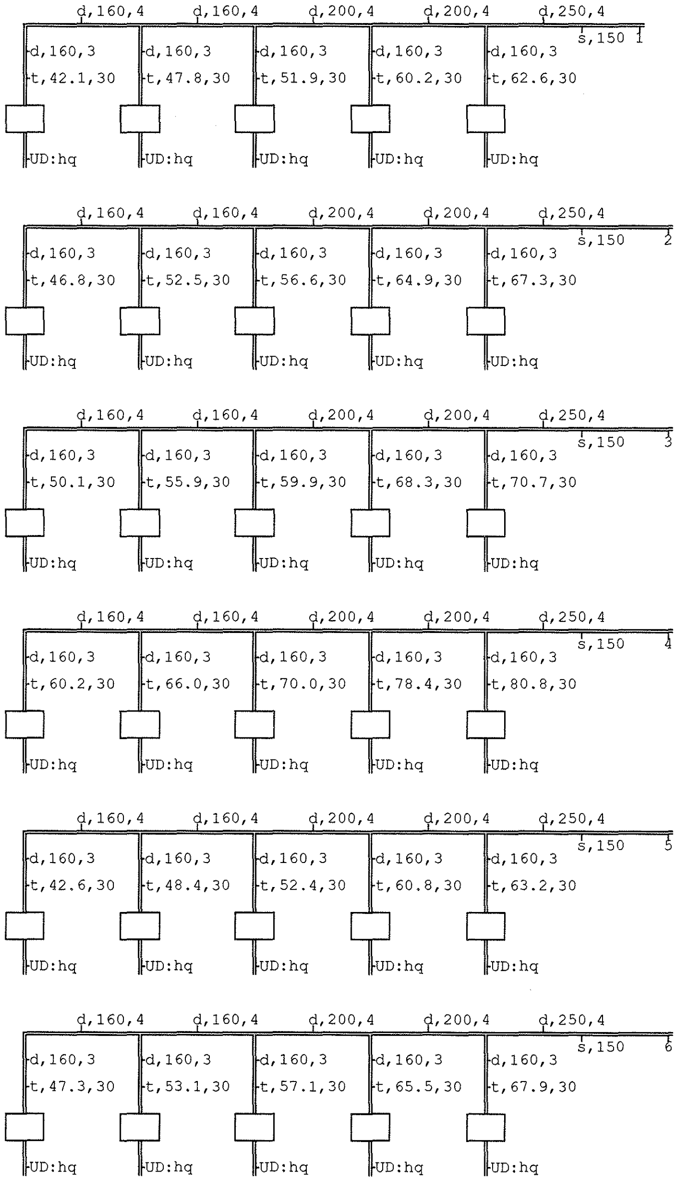
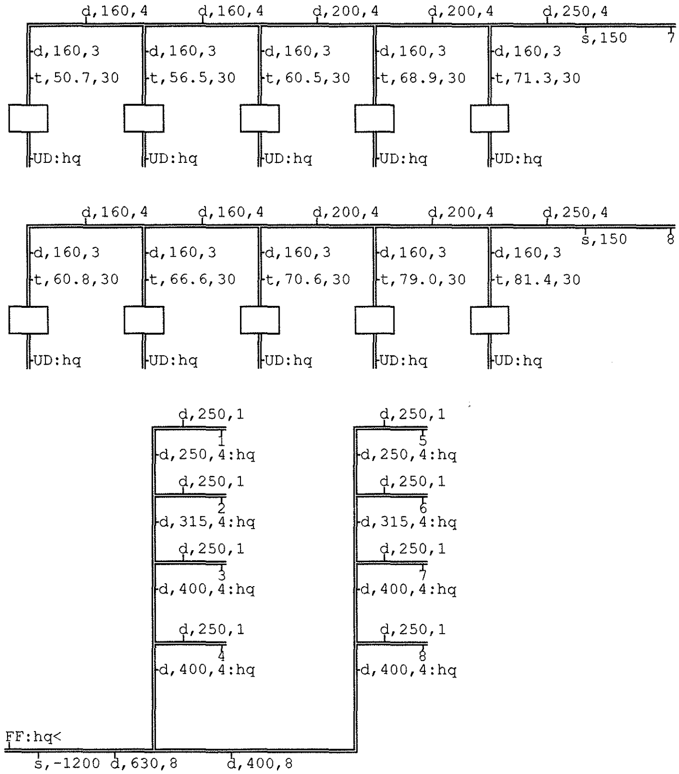


Figure 9.2 *PFS-layout of exhaust ventilation system according to figure 9.1 (beginning).*



end

Figure 9.2 *PFS-layout of exhaust ventilation system according to figure 9.1 (end).*

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  table=3
set         UD=t,10,30
fan         FF 100:200 125:750 75:1500
```

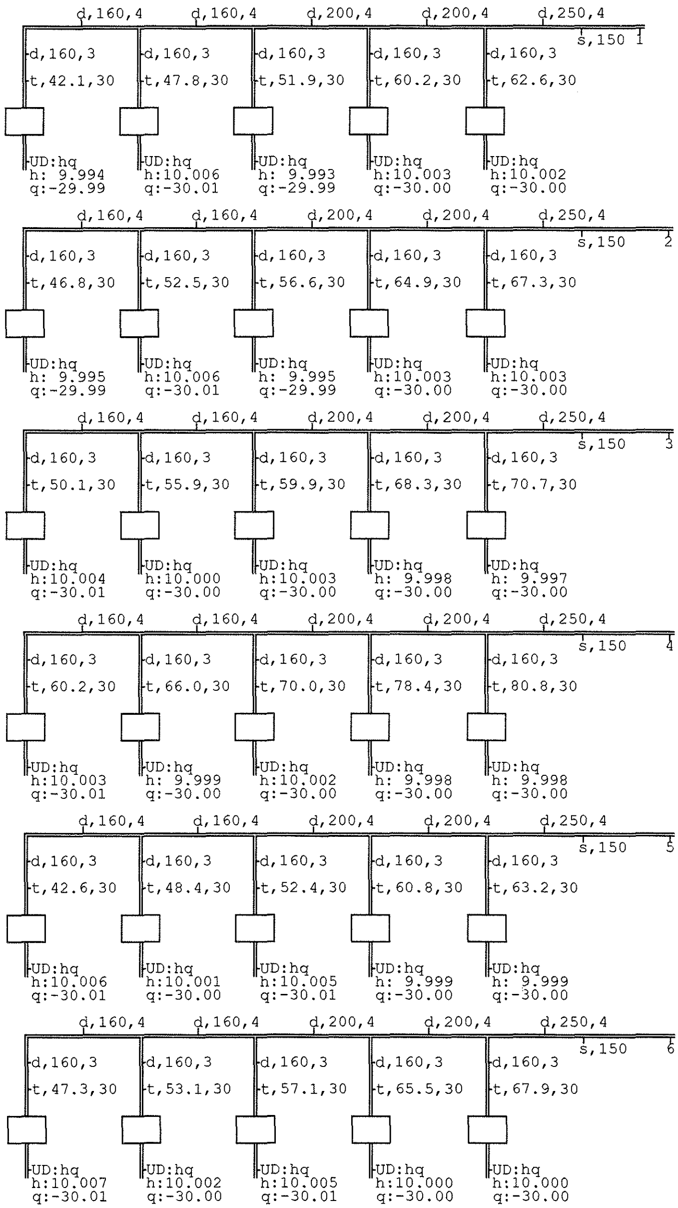
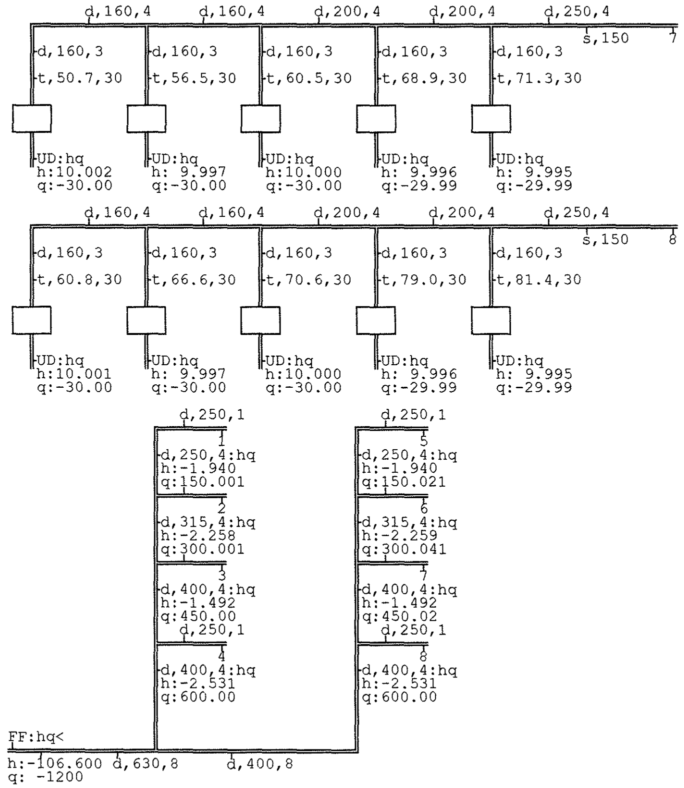


Figure 9.3 ***PFS-result of exhaust ventilation system according to figure 9.1 (beginning).***




```
end  block     1  problems   1  elements 316
```

Figure 9.3 *PFS-result of exhaust ventilation system according to figure 9.1 (end).*

Different cases were studied in order to figure out boundary fire air flows and corresponding pressures in different rooms. This problem is very numerically complex for such ventilation systems with several branches, because the flow in the boundary room must be equal to zero, while other flows and pressures are much higher then normal. There is an impossible case in exhaust ventilation systems, where zero air flow can never be achieved owing to the entraiment effect in the side branch of a converging wye. This problem was studied in [27].

The above presented statements agree sufficiently well with the results from test simulations. In some simulations the program did not manage to get any result at all and informed about different types of faults. Because of this it seems more reasonable to test the behaviour of the ventilation system regarding smoke spread to the adjacent rooms by using flows predicted in Section 1 and Table 9.1.

According to Building Code requirements for minimum outdoor air which are 0.35 l/s,m^2, and taking into account the assumed 30 l/s air flow in and out of each room along with usual height of dwellings in Sweden, 2.4 m, the volume of a ventilated room is approximately 200 m^3. According to Table 9.1, the flow produced by fire in e.g. hotel rooms of this volume is 1500 l/s.

"Fires" were placed in different rooms and the behaviour of ventilation systems was studied with the PFS-program. According to the results obtained, a flow of 1500 l/s from the majority of burning rooms will definitely cause spread of smoke to all adjacent rooms on the same floor which are served by the same branch as the burning room. One of the PFS-results with fire flow of 1500 l/s in the first room in branch 5 is set out in Figures 9.4.

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  table=3 dxs=25
set         UD=t,10,30
fan         FF 100:200 125:750 75:1500
```

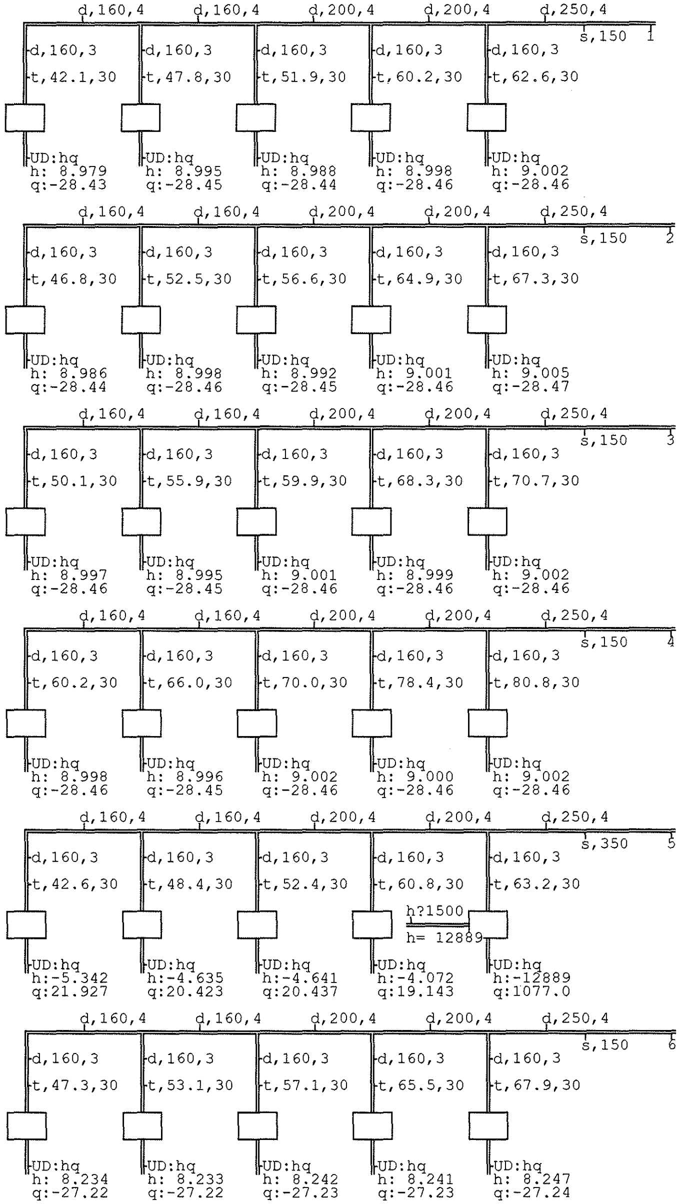
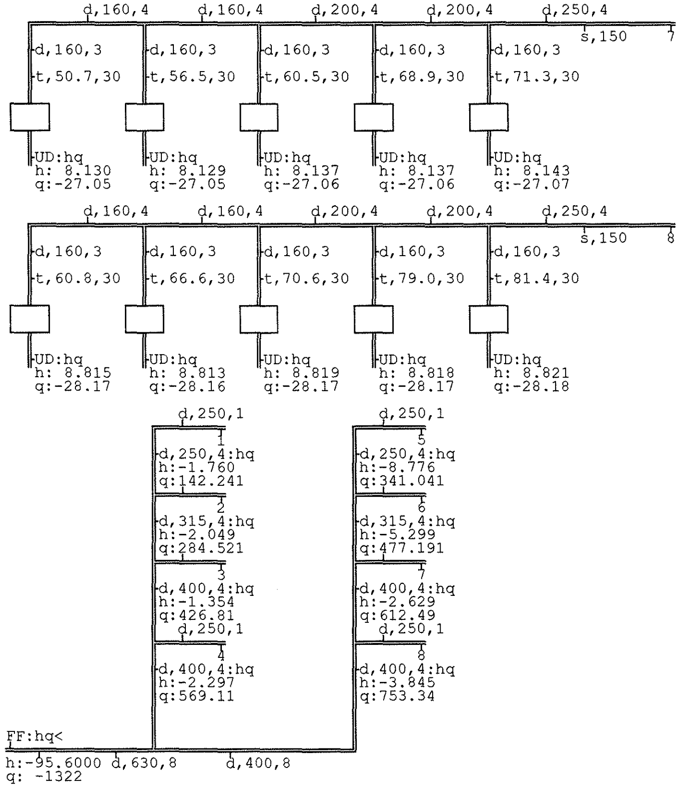


Figure 9.4 ***PFS-result of exhaust ventilation system according to figure 9.1 with a flow of 1500 l/s in the first room in branch 5 (beginning).***




```
end  block       1  problems    1  elements 317  warnings  11
```

Figure 9.4 *PFS-result of exhaust ventilation system according to figure 9.1 with a flow of 1500 l/s in the first room in branch 5 (end).*

```
begin
flow          l/s
pressure      Pa
control       bend=1  con=1  duct=1  itmax=99  table=3 dxs=25
set           UD=t,10,30
fan           FF 100:200 125:750 75:1500

          d,160,4     d,160,4     d,200,4     d,200,4     d,250,4
 ╓+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++++++++
 -           -           -           -           -        s,150  1
 -d,160,3    -d,160,3    -d,160,3    -d,160,3    -d,160,3
 -           -           -           -           -
 -t,42.1,30  -t,47.8,30  -t,51.9,30  -t,60.2,30  -t,62.6,30
 -           -           -           -           -
┌-┐         ┌-┐         ┌-┐         ┌-┐         ┌-┐
└-┘         └-┘         └-┘         └-┘         └-┘
 -           -           -           -           -
 -UD:hq      -UD:hq      -UD:hq      -UD:hq      -UD:hq
 -           -           -           -           -

          d,160,4     d,160,4     d,200,4     d,200,4     d,250,4
 ╓+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++++++++++
 -           -           -           -           -        s,150    2
 -d,160,3    -d,160,3    -d,160,3    -d,160,3    -d,160,3
 -           -           -           -           -
 -t,46.8,30  -t,52.5,30  -t,56.6,30  -t,64.9,30  -t,67.3,30
 -           -           -           -           -
┌-┐         ┌-┐         ┌-┐         ┌-┐         ┌-┐
└-┘         └-┘         └-┘         └-┘         └-┘
 -           -           -           -           -
 -UD:hq      -UD:hq      -UD:hq      -UD:hq      -UD:hq
 -           -           -           -           -

          d,160,4     d,160,4     d,200,4     d,200,4     d,250,4
 ╓+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++++++++++
 -           -           -           -           -        s,150    3
 -d,160,3    -d,160,3    -d,160,3    -d,160,3    -d,160,3
 -           -           -           -           -
 -t,50.1,30  -t,55.9,30  -t,59.9,30  -t,68.3,30  -t,70.7,30
 -           -           -           -           -
┌-┐         ┌-┐         ┌-┐         ┌-┐         ┌-┐
└-┘         └-┘         └-┘         └-┘         └-┘
 -           -           -           -           -
 -UD:hq      -UD:hq      -UD:hq      -UD:hq      -UD:hq
 -           -           -           -           -

          d,160,4     d,160,4     d,200,4     d,200,4     d,250,4
 ╓+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++++++++++
 -           -           -           -           -        s,150    4
 -d,160,3    -d,160,3    -d,160,3    -d,160,3    -d,160,3
 -           -           -           -           -
 -t,60.2,30  -t,66.0,30  -t,70.0,30  -t,78.4,30  -t,80.8,30
 -           -           -           -           -
┌-┐         ┌-┐         ┌-┐         ┌-┐         ┌-┐
└-┘         └-┘         └-┘         └-┘         └-┘
 -           -           -           -           -
 -UD:hq      -UD:hq      -UD:hq      -UD:hq      -UD:hq
 -           -           -           -           -

          d,160,4     d,160,4     d,200,4     d,200,4     d,250,4
 ╓-----------╥-----------╥-----------╥-----------╥+++++++++++++++++++
 +           +           +           +           -        s,350    5
 +d,160,3    +d,160,3    +d,160,3    +d,160,3    -d,160,3
 +           +           +           +           -
 +t,42.6,30  +t,48.4,30  +t,52.4,30  +t,60.8,30  -t,63.2,30
 +           +           +           +           -
┌+┐         ┌+┐         ┌+┐         ┌+┐ h?1500  ┌-┐
└+┘         └+┘         └+┘         └+┘+++++++++└+┘
 +           +           +           +           +
 +UD:hq      +UD:hq      +UD:hq      +UD:hq      +UD:hq
 +           +           +           +           +

          d,160,4     d,160,4     d,200,4     d,200,4     d,250,4
 ╓+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++╥+++++++++++++++++++
 -           -           -           -           -        s,150    6
 -d,160,3    -d,160,3    -d,160,3    -d,160,3    -d,160,3
 -           -           -           -           -
 -t,47.3,30  -t,53.1,30  -t,57.1,30  -t,65.5,30  -t,67.9,30
 -           -           -           -           -
┌-┐         ┌-┐         ┌-┐         ┌-┐         ┌-┐
└-┘         └-┘         └-┘         └-┘         └-┘
 -           -           -           -           -
 -UD:hq      -UD:hq      -UD:hq      -UD:hq      -UD:hq
 -           -           -           -           -
```

Figure 9.5 ***PFS-flow direction for exhaust ventilation system according to figure 9.1 with a flow of 1500 l/s in the first room in branch 5 (beginning).***

```
        d,160,4       d,160,4       d,200,4       d,200,4       d,250,4
╔++++++++++++╦++++++++++++╦++++++++++++╦++++++++++++╦++++++++++++++++++++++
-             -             -             -             -            s,150     7
-d,160,3      -d,160,3      -d,160,3      -d,160,3      -d,160,3
-             -             -             -             -
-t,50.7,30    -t,56.5,30    -t,60.5,30    -t,68.9,30    -t,71.3,30
-             -             -             -             -
┌-┐           ┌-┐           ┌-┐           ┌-┐           ┌-┐
└-┘           └-┘           └-┘           └-┘           └-┘
-             -             -             -             -
-UD:hq        -UD:hq        -UD:hq        -UD:hq        -UD:hq
-             -             -             -             -

        d,160,4       d,160,4       d,200,4       d,200,4       d,250,4
╔++++++++++++╦++++++++++++╦++++++++++++╦++++++++++++╦++++++++++++++++++++++
-             -             -             -             -            s,150     8
-d,160,3      -d,160,3      -d,160,3      -d,160,3      -d,160,3
-             -             -             -             -
-t,60.8,30    -t,66.6,30    -t,70.6,30    -t,79.0,30    -t,81.4,30
-             -             -             -             -
┌-┐           ┌-┐           ┌-┐           ┌-┐           ┌-┐
└-┘           └-┘           └-┘           └-┘           └-┘
-             -             -             -             -
-UD:hq        -UD:hq        -UD:hq        -UD:hq        -UD:hq
-             -             -             -             -

                     d,250,1                   d,250,1
                  ╔--------                 ╔--------
                  +     1                   +     5
                  +d,250,4:hq               +d,250,4:hq
                  +                         +
                  +  d,250,1                +  d,250,1
                  ╠--------                 ╠--------
                  +     2                   +     6
                  +d,315,4:hq               +d,315,4:hq
                  +                         +
                  +  d,250,1                +  d,250,1
                  ╠--------                 ╠--------
                  +     3                   +     7
                  +d,400,4:hq               +d,400,4:hq
                  +                         +
                  +                         +
                  +  d,250,1                +  d,250,1
                  ╠--------                 ╠--------
                  +     4                   +     8
                  +d,400,4:hq               +d,400,4:hq
                  +                         +
                  +                         +
                  +                         +
                  +                         +
FF:hq<            +                         +
------------------╩-------------------------╝
    s,-1300 d,630,8      d,400,8

end
```

Figure 9.5 ***PFS-flow direction for exhaust ventilation system according to figure 9.1 with a flow of 1500 l/s in the first room in branch 5 (end).***

Figures 9.4 and 9.5 show that in the studied case all flows in all adjacent rooms are positive (supply). It means that a flow of 1500 l/s exceeds the boundary flow and causes spread of smoke to all adjacent rooms on the same floor.

The layout of the ventilation system plays an important role in this kind of assessment, since the resistance properties of wyes and bends affect the resulting pressure drop and thus the flow distribution in these (e.g. Table 8.1 -Table 8.3). Normal ventilation flow of 30 l/s can ventilate even smaller spaces. The assumed fire flow of 1500 l/s seems high regarding smoke spread through the ventilation system. In this case it can be interesting to assess flow in the burning room that can be as close as possible to boundary flow. According to Table 8.1 the lowest expected boundary flow in a four-room duct system is the flow from the last but one room (room 2). Calculations show that a flow of 550 l/s from each last but one room in the present system layout, connected to each floor branch (rooms No 2, Figure 9.1), will cause smoke to spread to the adjacent room 1 on the same floor which is served by the same branch. At the same time there are some differences in "boundary" flows between different branches, with the lowest flow of 450 l/s in branch 5 situated furthest away from the fan. This calculation is presented in Figure 9.6. Some other fire cases were studied for the present ventilation system. Flows of 1100 l/s in the nearest room of each branch cause smoke to spread to all other four rooms on the same floor or a significant reduction, down to zero, in flows in other rooms, which is characteristic of flows close to boundary values. One of the calculations is presented in Figure 9.7.

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  table=3 dxs=25
set         UD=t,10,30
fan         FF 100:200 125:750 75:1500
```

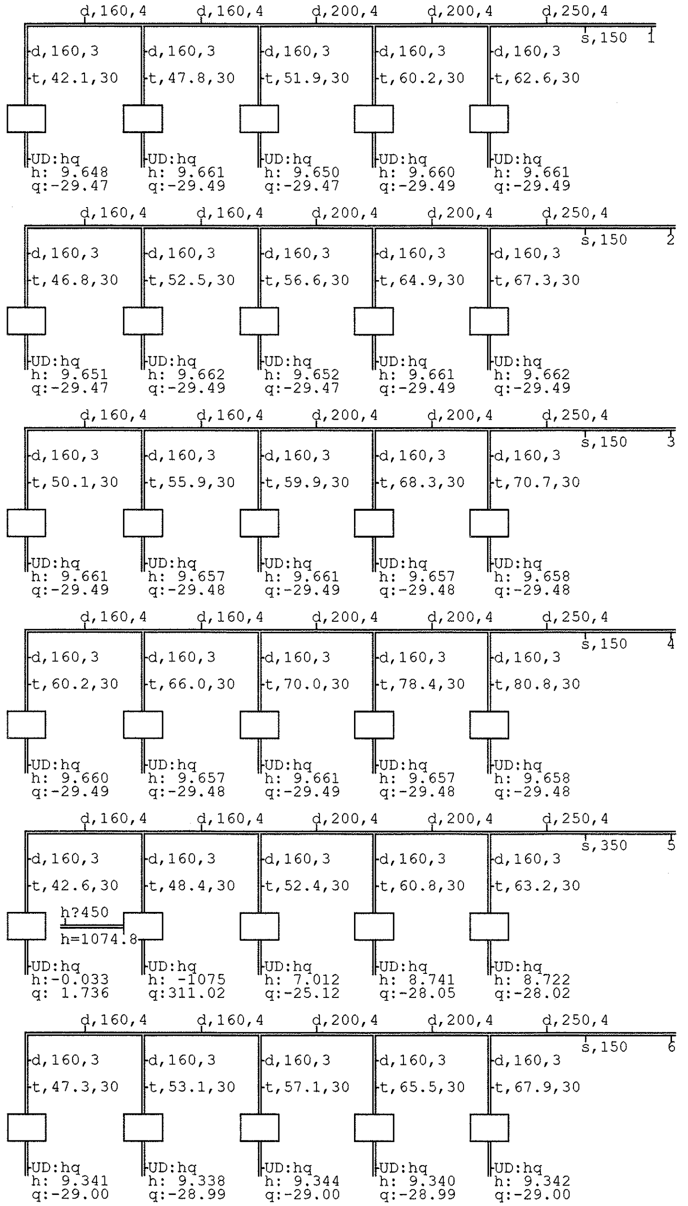
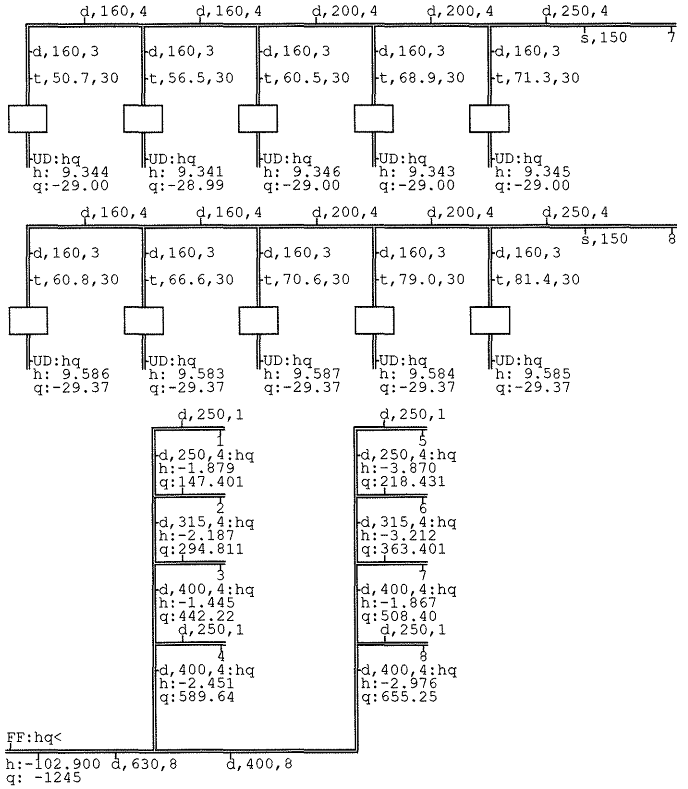


Figure 9.6 ***PFS-result of exhaust ventilation system according to figure 9.1 with a flow of 450 l/s in the last but one room in branch 5 (beginning).***




```
end  block      1  problems   1  elements 317  warnings  11
```

Figure 9.6   *PFS-result of exhaust ventilation system according to figure 9.1 with a flow of 450 l/s in the last but one room in branch 5 (end).*

```
begin
flow        l/s
pressure    Pa
control     bend=1  con=1  duct=1  itmax=99  table=3 dxs=25
set         UD=t,10,30
fan         FF 100:200 125:750 75:1500
```

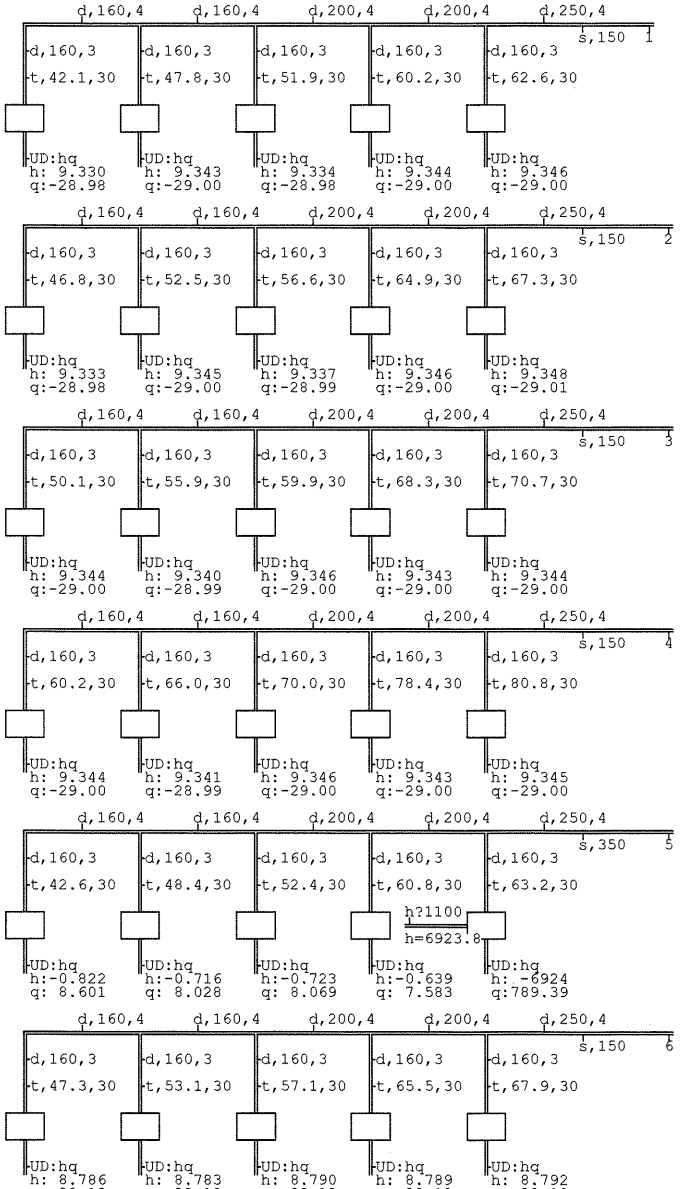
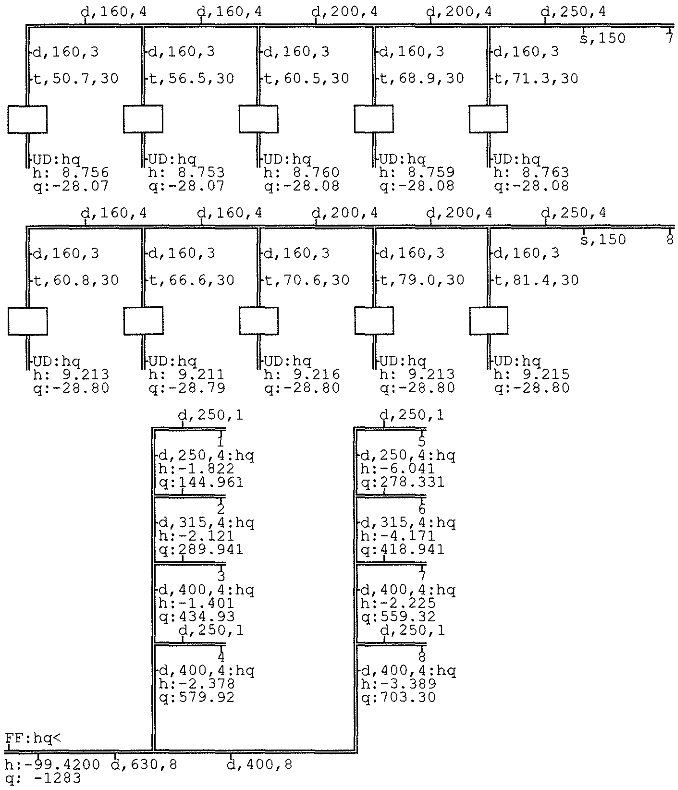


Figure 9.7 ***PFS-result of exhaust ventilation system according to figure 9.1 with a flow of 1100 l/s in the nearest room in branch 5 (beginning).***



end block 1 problems 1 elements 317 warnings 11

Figure 9.7 *PFS-result of exhaust ventilation system according to figure 9.1 with a flow of 1100 l/s in the nearest room in branch 5 (end).*

Figure 9.6 shows, that flow in one adjacent room has a positive value, i.e. air flows out of the room. The pressure drop in the other parts of the ventilation system and flows in the other branches and terminals are also affected by the fire flow in the tested room. Figure 9.7 shows that flows in all four rooms adjacent to the burning room have small positive values, i.e. air flows out of the room. In this case fire flow is very close to the boundary flow. The pressure drops in the other parts of the ventilation system and flows in the other branches and terminals are also affected by the fire flow in the tested room.

Calculations show that there are some differences in fire flow, causing smoke to spread to the adjacent room(s), in different branches (serving different floors) in similar rooms. Flows causing smoke spread via the same branch can differ significant from case to case. Note, that fire flows from different rooms can cause smoke to spread to different numbers of rooms served by the same branch.

Some measures to prevent smoke spread were discussed in Chapter 8. Two of these were tested for all the above fire flows, with the rotational speed of the exhaust fan doubled and with the fan switched off. The results are presented in Table 9.1.

Table 9.1 Data regarding the examined measures for prevention of smoke spread via exhaust ventilation system

Exhaust fan	Smoke spread	
	To room(s), same branch	To other rooms
Normal	Yes	No
Doubled rotational speed	No	No
Switched off	Yes	Yes (to the whole building)

The case when the rotational speed of the fan is doubled is a very hard measure and can be applied e.g. in ventilation systems with reduced normal capacity. The case when the fan is switched off corresponds to natural ventilation.

9.3.2 Exhaust ventilation system with two terminals in each room

In certain types of buildings another type of exhaust ventilation system can be used. Such systems exhaust air from each of the compartments via two separate terminals, connected to two separate plenums. For example, one terminal is placed in the bathroom and the other one in the kitchen. The layout of the examined exhaust ventilation system is presented in Figure 9.8.

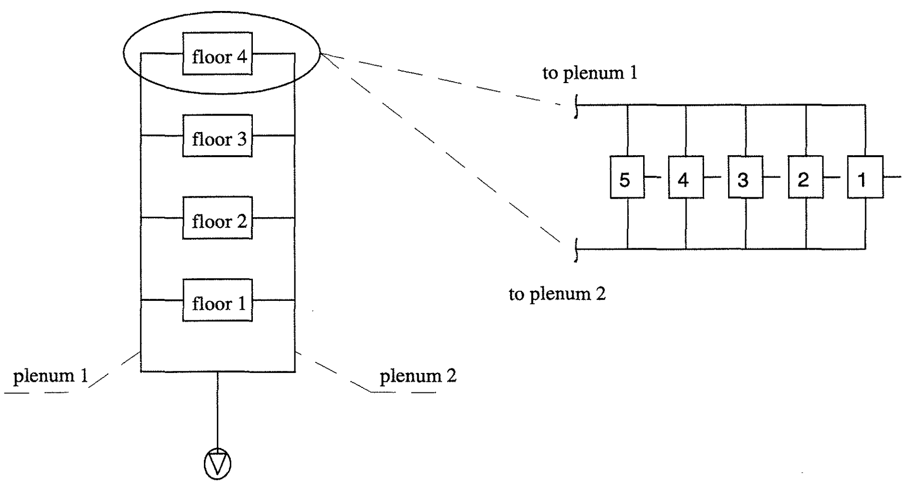


Figure 9.8 Layout of exhaust ventilation system with two plenums for four floors and five rooms on each floor.

Two different cases were studied. In the first case air is exhausted at the rate of 15 l/s from each of two terminals in the room. In the second case air is exhausted at different rates, 10 l/s and 20 l/s, from the terminals. The total exhaust air flow from the room is 30 l/s for both cases. A fan with the same characteristics is installed in all studied cases.

The exhaust fan has the following similar characteristics as the fan in Subsection 9.3.1.

The exhaust ventilation system drives out the total air flow of 600 l/s at 123 Pa pressure, which exhausts via two vertical plenums from four floors, and further via branches from five rooms on each floor.

Different ”fire” cases were studied in order to test the behaviour of ventilation system regarding the risk of smoke spread to the adjacent rooms. ”Fires” were placed in different rooms and the behaviour of the ventilation systems was studied for two major cases with fires in the last but one room and the nearest room with the help of PFS-program. Flows predicted in Section 1 and Table 9.1 were used for the purpose of this study.

For the first ventilation system with equal air flows (symmetrical case), air flows of 1100 l/s from the last but one room and 2350 l/s from the nearest room cause smoke to spread to adjacent room (s).

For the second ventilation system with unequal air flows (asymmetrical case), air flows of 700 l/s from the last but one room and 1450 l/s from the nearest room cause smoke to spread to adjacent room (s).

This example shows that even small changes in the layout of the ventilation system can affect the behaviour of the whole system regarding the risk of smoke spread.

Some measures to prevent smoke spread were discussed in Chapter 8. Two of these, the case with exhaust fan with rotational speed doubled, and the case with the fan switched off, were tested for all the above fire flows. The results are presented in Table 9.2.

Table 9.2 Data for the examined measures to prevent smoke spread via double-plenum exhaust ventilation system

Exhaust fan	Smoke spread	
	To room(s), same branch	To other rooms
Normal	Yes	No
Doubled rotational speed	No	No
Shut down	Yes	Yes (to the whole building)

The case with a fan whose rotational speed is doubled is a very hard measure and can be applied. in e.g. ventilation systems with reduced normal capacity. The case with the fan shut down corresponds to natural ventilation.

9.4 Supply-exhaust ventilation system with a "zero-duct"

Such types of ventilation systems is often used in different office buildings, as described in Subsection 9.1. In these ventilation systems corridors acts as collectors or "zero-ducts". Exhaust air from all rooms in the office is removed through transfer air devices, collects in corridors, and is in turn transported to the exhaust plenum through corridor terminal. The layout of the examined ventilation system is presented in Figure 9.9.

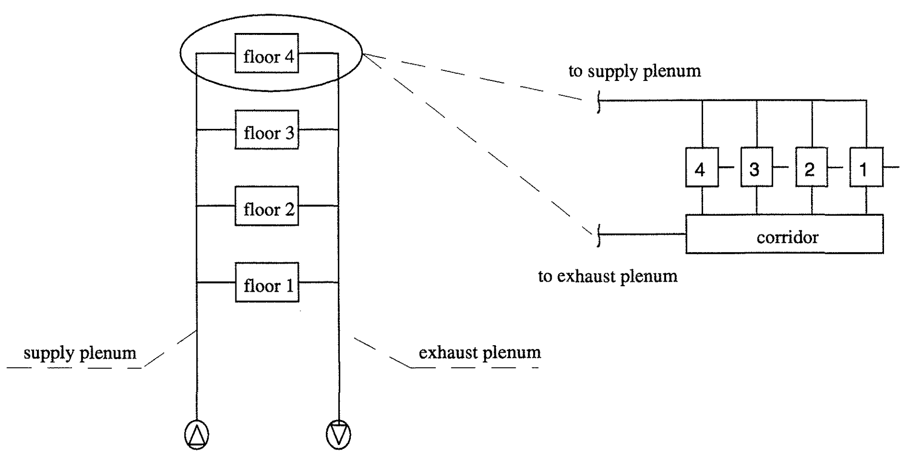


Figure 9.9 Layout of supply-exhaust ventilation system with "zero-duct" for four floors and four rooms on each floor.

Both supply and exhaust fans have similar characteristics as the fan in Subsection 9.3.1.

Different cases were studied in order to figure out boundary fire air flows and corresponding pressures in different rooms. "Fires" were placed in different rooms and the behaviour of the ventilation system was studied with the PFS-program. Though such problems are usually very numerically complex for the majority of ventilation systems with several branches, calculations succeeded in this case. Boundary fire flow for the majority of ”fire” cases was 140 l/s. Smoke spreads to the adjacent rooms via supply ducts, while higher values of gas flows spread directly to the corridor (”zero-duct”) through transfer air devices.

Some measures for the prevention of smoke spread were discussed in Chapter 8. The results of smoke spread evaluations for fire flow of 450 l/s are presented in Table 9.3.

Table 9.3 Data regarding the examined measures for the prevention of smoke spread via supply-exhaust ventilation system with ”zero-duct”

Supply fan	Exhaust fan	Smoke spread	
		To room(s), same branch	To other rooms
Normal	Normal	Yes	No
Doubled rotational speed	Doubled rotational speed	No	No
Closed with by-pass to the exhaust fan	Normal	No	No
Closed	Normal	Yes	Yes
Closed with by-pass to the outside	Closed with bypass to the outside	Yes	Yes
Converts into exhaust fan	Normal	Yes	No

The case when the rotational speed of the fan is doubled is a very hard measure and can be applied e.g. in ventilation systems with reduced normal capacity. The case when the fan is switched off corresponds to natural ventilation.

The studied cases do not cover all possible measures to prevent smoke spread via ventilation ducts, nor do they examine system behaviour with fire dampers.

In all the above cases, part of the smoke produced by a fire spreads directly to the corridor through transfer air devices, where it mixes with ambient air. Evaluation of the degree of dilution can be of great importance in risk assessment. This problem will be discussed in Section 10.

9.5 Supply-exhaust ventilation system

These types of ventilation systems are the most common and are used in all types of examined buildings, as described in Subsection 9.1. Each fire compartment is supplied with air through one or more terminals, and air is exhausted via terminals in the same space. The layout of the examined ventilation system is presented in Figure 9.10.

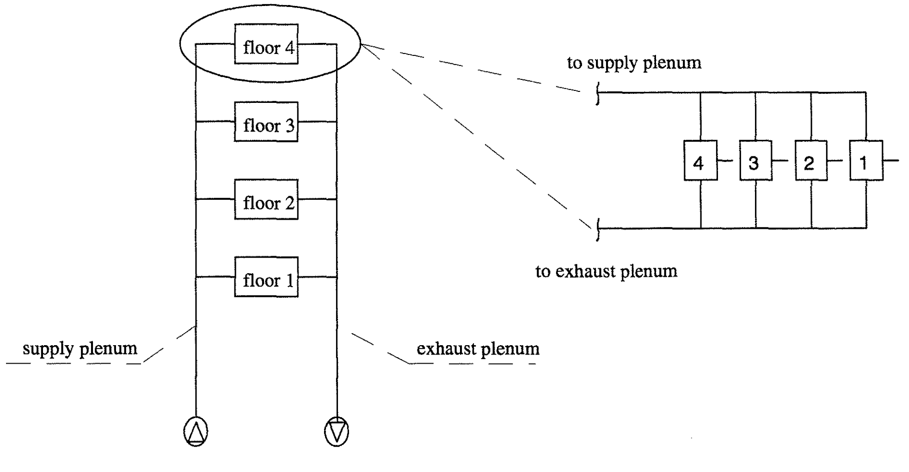


Figure 9.10 Layout of supply-exhaust ventilation system for four floors and four rooms on each floor.

Both supply and exhaust fans have similar characteristics as the fan in Subsection 9.3.1.

Different cases were studied in order to calculate boundary fire air flows and corresponding pressures in different rooms. "Fires" were placed in different rooms and the behaviour of the ventilation system was studied with the PFS program. Though such problems are usually very numerically complex for the majority of ventilation systems with several branches, calculations succeeded in this case. Boundary fire flow for the majority of "fire" cases was 130 l/s. All fire flows which exceed the boundary flow will cause smoke to spread to the adjacent room(s) via supply ducts. According to Table 9.1, fires in all types of buildings with a volume larger then 30 m3 will cause spread of smoke through supply ducts.

Some measures to prevent smoke spread were discussed in Chapter 8. Some of these were tested. The results of smoke spread evaluations for fire flow of 450 l/s are presented in Table 9.4.

Table 9.4 Data regarding the examined measures for the prevention of smoke spread via supply-exhaust ventilation system

Supply fan	Exhaust fan	Smoke spread	
		To room(s), same branch	To other rooms
Normal	Normal	Yes	No
Doubled rotational speed	Doubled rotational speed	Yes	No
Closed with bypass to the exhaust fan	Normal	Yes	No
Closed with bypass to the exhaust fan	Doubled rotational speed	No	No
Closed	Normal	Yes	Yes
Closed with bypass to the outside	Closed with bypass to the outside	Yes	No
Converted into exhaust fan	Normal	No	No

The case when the rotational speed of the fan is doubled is a very hard measure and can be applied e.g. in ventilation systems with reduced normal capacity. Note, that doble speed results in eight times higher moter effect. The case when the fan is switched off corresponds to natural ventilation.

The studied cases do not cover all possible measures to prevent smoke spread via ventilation ducts, nor do they examine system behaviour with fire dampers.

In all the above cases, part of the smoke produced by a fire spreads directly to the corridor through transfer air devices, where it mixes with ambient air. Evaluation of the degree of dilution can be of great importance in risk assessment. This problem will be discussed in Chapter 10.

All the above studied ventilation systems comprise equal spaces with similar air flows. In reality, the air flows in different rooms served by a ventilation system can differ from each other. In such cases the whole behaviour of the system in case of fire in a room can be more complicated and unpredictable than those discussed above. A detailed analysis of such systems is needed to assess the risk of smoke spread via the ventilation system.

10 Evaluation of the toxicity of diluted smoke

10.1 Background

In certain cases, where predictions show that comparatively low volumes of smoke will spread to adjacent rooms, another situation can be discussed. It can be reasonable to look at the degree of dilution of smoke instead of totally forbidding the spread of smoke to adjacent rooms. In this connection, the toxicity of the diluted smoke may have to be evaluated. It is well known that roughly two-thirds of all deaths from enclosure fires can be attributed to the presence of carbon monoxide (CO) which is known to be the dominant toxicant in fire deaths. In the literature, some astonishing facts concerning fatal fires can be found. One of the most extreme cases is the fatal town house fire in Sharon, USA, 1987. Although the fire was essentially localised in the first floor kitchen, deaths occurred on the second floor. One of the victims had an extraordinarily high level of carboxyhaemoglobin, suggesting exposure to very high concentrations of CO. This fact and the later assessment of the highest CO concentration produced by enclosure fires are discussed in [28] and [29]. In these papers very special cases of fire in an enclosure with ceiling and upper walls lined with plywood were studied. The most dramatic effect was the rapid growth and peak level of CO observed. Dry CO concentrations reached 7% at the front sampling position and 14% at the rear 200 s after ignition. The enclosure was fuelled by a natural gas flow corresponding to 400 kW. The above reported levels are extremely high and represent an unusual CO/CO2 ratio. The temperature observed was higher than 500°C. The fire was underventilated (ventilation-controlled fire).

10.2 Evaluation of total volume of spread smoke

The concentration of CO spreading to the adjacent room(s) was evaluated step by step for an exhaust ventilation system.

Assuming that the volume of the room of fire origin is V (m^3) and expansion is characterised by T_e/T_f - *1, (6.1)*, the volume of the hot spread smoke is

$$V_r = (T_e / T_f - 1)V$$

and after cooling down to a normal temperature it is equal to

$$V_r = V(T_e / T_f - 1) / \frac{T_f}{T_e} = V(1 - \frac{T_f}{T_e}) \qquad (10.1)$$

10.3 Evaluation of relative smoke spread to a single room

The share of this smoke volume which reaches another room can be assessed for a simplified ventilation system with the fan shut down. Several rooms are connected to a plenum at the same point. The ductwork can be part of both the exhaust ventilation system and the supply ventilation system.

Assuming, that

n	number of rooms of equal size/volume, connected to the same point before the plenum
a	branch resistance
b	facade resistance
c	total resistance, =1
q_s	flow in the plenum
q_r	flow in other n-1 rooms
q_k	fire flow in the branch
q_f	fire flow through the facade
q_b	total fire flow

The following simple expressions can be drawn up

$$q_b = q_f + q_k \tag{10.2}$$

$$q_k = q_s + (n-1)\, q_r \tag{10.3}$$

The ratio between q_r and q_b expresses the proportion of the smoke volume which spreads from the fire room into the other room. This ratio, r, represents the proportion of smoke volume in the following assessment. A simple way to calculate this ratio is to assign some flow value to the other rooms as q_r and then calculate backwards. First of all the pressure in the common junction, p_g, is calculated as

$$p_g = (a+b)\, q_r^2 \tag{10.4}$$

The flow q_s in the plenum is calculated with the help of pressure p_g

$$p_g = c\, q_s^2 = 1 q_s^2 \tag{10.5}$$

Fire flow in the branch is calculated according to (10.2) and the fire pressure p_b is then calculated

$$p_b = p_g + a\, q_k^2 \tag{10.6}$$

The next step is to calculate facade flow with the help of fire pressure and the following expression

$$p_b = b\, q_f^2 \tag{10.7}$$

The proportion of smoke volume r

$$r = q_r \,/\, q_b = q_r \,/\, (q_f + q_s + (n-1)\, q_r) \tag{10.8}$$

The proportion of smoke volume r as a function of parameters a, b and n

$$r = \frac{1}{\left(\dfrac{(n-1+(a+b)^{0.5} + ((a+b+a((a+b)^{0.5}+n-1)^2}{b} \right)^{0.5}} \tag{10.9}$$

The proportion of smoke volume r can be calculated for several combinations of parameters.

Table 10.1 shows that the proportion of smoke volume, *r,* reaching one of the rooms decreases with increasing number of rooms, *n*, and decreasing airtighteness of the facade, *b*.

Table 10.1 Proportion *r* of smoke volume which spreads to the one of the *n* rooms according to (10.9)

		r			
a	b	n=2	n=5	n=10	n=20
5	1.0	0.212	0.047	0.027	0.014
5	0.5	0.163	0.037	0.021	0.011
5	0.2	0.111	0.026	0.014	0.008
5	0.1	0.082	0.020	0.011	0.006

The above expressions can also be used to evaluate the proportion of smoke volume reaching another room in the case when both fans in a supply-exhaust system are shutdown. Perfect symmetry is assumed and the above expressions each describe half of the ventilation system. The only parameters which must be changed is *b*. The parameter *b* in this case describes only one half of the total facade. This means that the previously defined *b* is replaced by *4b* because one half of the total flow gives the same pressure drop as before.

The proportion *r* of smoke volume can be calculated for the case with double spread for several combinations of parameters.

Table 10.2 shows that the proportion *r* of smoke volume reaching one of the rooms decreases with increasing number of rooms, *n*, and decreasing airtighteness of the facade, *b*. In general, more smoke spreads to the adjacent room in this case that that in Table 10.1.

Table 10.2 Proportion of smoke volume *r* according to (10.9) , which spreads to one of the *n* rooms (double spread)

		r			
a	b/4	n=2	n=5	n=10	n=20
5	1.0	0.344	0.200	0.118	0.064
5	0.5	0.273	0.153	0.088	0.047
5	0.2	0.195	0.106	0.060	0.032
5	0.1	0.149	0.080	0.045	0.024

10.4 Evaluation of CO - concentration in a single room

Assuming that

c_b CO-concentration in the fire room and in spreading smoke (average value)

c_r CO- concentration in other rooms

$$c_r = (\frac{T_e}{T_f} - 1) / (1 + (\frac{T_e}{T_f} - 1))\, r\, c_b \frac{V_b}{V_r} = (1 - \frac{T_f}{T_e}) r\, c_b \frac{V_b}{V_r} \qquad (10.10)$$

or for room of the same volume, $V_b = V_r$

$$c_r = (\frac{T_e}{T_f} - 1) / (1 + (\frac{T_e}{T_f} - 1))\, r\, c_b = (1 - \frac{T_f}{T_e}) r\, c_b \qquad (10.11)$$

The expansion $(T_e / T_f - 1)$ can vary from 1 to 2, which corresponds to temperature change from 20°C to 313°C and 606°C, respectively. Note that all rooms are assumed to be equal. It is also possible, of course, to calculate the case with rooms of different size.

10.5 Dangerous levels of CO - concentration

Different recommendations can be drawn up concerning acceptable and dangerous CO concentrations in diluted smoke. Different concentrations of CO cause different human reactions.

Table 10.3 Dangerous levels if CO-concentrations

	CO concentration, ppm	Type of fire	Other compounds, % O_2	Other compounds, % CO_2	CO-dose, ppm* min	Time to Incapacitation, min	Ref
Death	10000	-	-	-	-	1	30
Dangerous	3000	-	-	-	-	30	30
Unconsciousness	1500-2000	-	-	-	-	60	30
Unconsciousness	1000-8000	-	-	-	27000	-	7
-	1500	smoldering	15-21	-	-	hours	7
-	10000	flaming	10-21	0-10	-	a few	7
-	0-30000	fully developed	-	HCN 0-1500 ppm	-	< 1 if possible	7
Acceptable	2000	-	>15	<5	-	-	4

Information about the toxic effects of CO in respiration air varies a lot both in terms of concentration and dose. Thus it seems difficult to draw unequivocal conclusion concerning the risk due to CO-concentration.

10.6 Evaluation of CO - dose

The CO concentration calculated according to (10.10) may be found not to be dangerous in itself. It is the CO dose or the product of CO concentration, duration of exposure and the type of activity during which exposure takes place which determines the toxic effects. According to [7] it is not concentration in the smoke that directly determines how someone will be affected, but the concentration that has accumulated in the blood in the form of carboxyhaemoglobin. Direct measurements are not feasible and indirect measurements of exposure involve a certain degree of uncertainty. A high level of activity and, as a result, intensive respiration is more dangerous than slow level of activity, e.g. a sleeping person.

The fatal dose of CO is around 27000 ppm*min at concentrations of max. 8000 ppm [7].

There is another criterion, IDLH (immediately dangerous to life and health), limited to 1500 ppm during 30 min, which gives a total of 45000 ppm*min. The concentrations presented in Table 10.3, converted into CO dose, show a significant spread.

If the time for one air change, T, is known, the CO dose can be easily calculated

$$CO_{dose} = Tc_r \tag{10.12}$$

It is assumed. that the CO-concentration is achieved during a few minutes, after which fire "chokes", or pressure relieves in the fire room. The CO-concentration decreases exponentially according to

$$c(t) = c_r\, e^{-t/T} \tag{10.13}$$

Integrating of *c(t)* from 0 to infinity gives expression (10.12) for the CO-dose. The time of one air change can be simply calculated for case of mechanical ventilation, but it is more difficult for the case of only infiltration and exfiltration.

This case is suitable for exhaust ventilation systems with a distribution chamber and shut down fan, and even for supply ventilation systems with shut down fan. A distribution chamber in a supply ventilation system can provide protection against a dangerous CO dose, but at the expense of the risk of several rooms being subjected to equal smoke spread.

10.7 Application

CO concentrations of smoke reaching a single room can be calculated according to (10.10) and Table 10.1 for rooms of different degrees of airtighteness and different CO concentrations in the smoke itself. Assuming expansion $(T_e/T_f\text{-}1)$ equal to 1, which corresponds to temperature change from 20°C to 313°C, we have

$$c_r = 0.5 r c_b$$

An average value of parameter c_b as can be assessed at 1%. Corresponding values converted into ppm are set out in Table 10.4. Note that all rooms are assumed to be equal.

Table 10.4 CO concentration in ppm which spreads to one of n rooms at an average value c_b = 1%

	CO, ppm			
b	n=2	n=5	n=10	n=20
1.0	1060	235	135	70
0.5	815	185	105	55
0.2	555	130	70	40
0.1	410	100	55	30

All values are acceptable according to IDLH since CO concentration level does not exceed 1500 ppm (shaded area).

Values of mean CO concentration c_b other than 1% result in higher values. Corresponding CO concentrations reaching a single room, for 14% CO in the smoke from the fire room, are presented in Table 10.5.

Table 10.5 CO concentration in ppm which spreads to one of *n* rooms at an average value c_b = 14%

	CO, ppm			
b	n=2	n=5	n=10	n=20
1.0	14840	3290	1890	980
0.5	11410	2590	1470	770
0.2	7770	1820	980	560
0.1	5740	1400	770	420

All values which do not exceed CO concentration level of 1500 ppm are acceptable according to IDLH (shaded area).

11 Evaluation of visibility of diluted smoke

11.1 Background

As discussed in Subsection 10, it may be reasonable in certain cases where the predicted spread of smoke to adjacent rooms has comparatively low values to look at the degree of dilution of the smoke instead of totally forbidding the spread of smoke to adjacent rooms. In this connection, evaluation of risk due not only to the toxicity of diluted smoke but also to visibility may be necessary. Visibility through smoke can be of great importance for the survival of an individual in a fire. Visibility depends on many different factors, such as wavelength of the light, whether the sign is emits or reflects light, illumination of the room(s), the visual acuity of the individual, the absorption coefficient of the smoke, etc. However, there are methods for smoke visibility estimation. One of them, for safe level, is presented in Swedish Buildings Codes [8]; the height of the smoke layer above the floor must not be less than 1.6 m + 10% of room height. This smoke visibility can be regarded as safe if it is combined with other limiting parameters, such as level of heat radiation and air temperature. Another method is presented in [5]; visibility s can be described as

$$s=\begin{cases}\dfrac{k}{8} & \textit{for light - emitting sign}\\[2ex] \dfrac{k}{3} & \textit{for light - reflecting sign}\end{cases} \qquad (11.1)$$

where k is the smoke extinction coefficient and is a product of an extinction coefficient per unit mass, k_m, and mass concentration of the smoke, m.

$$k = k_m \; m \tag{11.2}$$

For example, Seader and Einhorn obtained k_m values of 7.6 m^2/g for smoke produced during flaming combustion of wood and plastics and a value of 4.4 m^2/g for smoke produced during pyrolysis of these materials. There are a lot of uncertainty factors in such smoke visibility assessment. The data is based e.g. on the subjects viewing the smoke through glass (the irritant effect was eliminated). The value k_m is based on a limited number of small-scaled experiments with a polychromatic light source, etc.

Another method for estimating the visibility uses the empirical mass optical density data. Optical density per meter, D, describes as

$$D = \frac{D_m \, \Delta M}{V_c} \tag{11.3}$$

where D_m is the empirical mass optical density, m^2/g, ΔM is the mass loss of the sample, g, and V_c is the volume of the fire room, m^3. This method is regarded to be more reliable and more direct.

According to [32], [33] lowest visibility value in familiar spaces is 3-5 m, but never less then 2 m, and in unfamiliar spaces it is 15-20 m.

11.2 Evaluation of visibility in diluted smoke spread to a single room

The evaluation of visibility in smoke in another room as a result of smoke spread via ventilation ducts is analogous to evaluation of CO-concentration in smoke, presented in Subsection 10.

Assuming that the smoke in the fire room and also in the other room which it reaches is well mixed, that some limit of weakness of the comfort conditions is common for all rooms and that

s_b is visibility in the fire room
s_r is visibility of diluted smoke reaching one of the rooms
r_b is smoke concentration in the fire room
r_r is concentration of diluted smoke reaching one of the rooms,
we have

$$s_b \, r_b = s_r \, r_r \tag{11.4}$$

$$s_r = s_b \, r_b \, / \, r_r \tag{11.5}$$

Visibility will in actual fact be greater because smoke concentration will be higher near the ceiling and will gradually decrease downwards.

12 "Cold" case assessment

The whole study assumes that all flows have ambient parameters, "cold flows". In fact, according to results obtained in Section 1, flow temperatures can exceed 300 °C. Although all evaluations of smoke spread via ventilation ducts take the temperature factor into consideration in dealing with volume flows, the problem of calculating pressure drop in ventilation systems can be discussed further. According to [31], Fanning friction factor f for fully developed tube flow is inversely proportional to the Reynolds number based on mean velocity and tube diameter. At the same time, the Darcy - Weisbach friction factor f_D is four times as large as f.

$$f_D = 4f \tag{12.1}$$

Different degree of flow turbulence show different empirical relations between f_D and Re_D, where $Re_D = UD/\nu$. Kinematic viscosity is $\nu = \eta/\rho$, m^2/s, where η is viscosity.

$$f_D \cong 4 \cdot 0.079 \, \mathrm{Re}_D^{-0.25} \qquad 2 \cdot 10^3 < \mathrm{Re}_D < 2 \cdot 10^4 \tag{12.2}$$

Pressure drop per unit length, l, is

$$\frac{\Delta P}{l} = \frac{f_D}{d} \cdot \frac{\rho U^2}{2} \qquad \text{Pa/m} \tag{12.3}$$

Substituting (12.2) into (12.3) gives

$$\frac{\Delta P}{l} \cong 0.158 \frac{\eta^{0.25} \rho^{0.75} U^{1.75}}{d^{1.25}} \qquad 2 \cdot 10^3 < \mathrm{Re}_D < 2 \cdot 10^4 \tag{12.4}$$

or

$$\frac{\Delta P}{l} \cong 0.158 \frac{\nu^{0.25} \rho \, U^{1.75}}{d^{1.25}} \qquad 2 \cdot 10^3 < \mathrm{Re}_D < 2 \cdot 10^4 \tag{12.5}$$

or, as a function of flow

$$\frac{\Delta P}{l} \cong 0.158 \frac{\eta^{0.25} \rho^{0.75} q^{1.75}}{d^{4.75}} \qquad 2 \cdot 10^3 < \mathrm{Re_D} < 2 \cdot 10^4 \qquad (12.6)$$

$$2.5 \cdot 10^3 < q/dv < 2.5 \cdot 10^4$$

and

$$\frac{\Delta P}{l} \cong 0.158 \frac{v^{0.25} \rho \, q^{1.75}}{d^{4.75}} \qquad 2 \cdot 10^4 < \mathrm{Re_D} < 10^6 \qquad (12.7)$$

$$2.5 \cdot 10^4 < q/dv < 1.3 \cdot 10^6$$

An empirical relation that holds at high Reynolds numbers is

$$f_D \cong 4 \times 0.046 \mathrm{Re}_D^{-0.2} \qquad 2 \cdot 10^4 < \mathrm{Re_D} < 10^6 \qquad (12.8)$$

Substituting (12.8) into (12.3) gives

$$\frac{\Delta P}{l} \cong 0.092 \frac{\eta^{0.2} \rho^{0.8} U^{1.8}}{d^{1.2}} \qquad 2 \cdot 10^4 < \mathrm{Re_D} < 10^6 \qquad (12.9)$$

or

$$\frac{\Delta P}{l} \cong 0.092 \frac{v^{0.2} \rho \, U^{1.8}}{d^{1.2}} \qquad 2 \cdot 10^4 < \mathrm{Re_D} < 10^6 \qquad (12.10)$$

or, as a function of flow

$$\frac{\Delta P}{l} \cong 0.092 \frac{\eta^{0.2} \rho^{0.8} q^{1.8}}{d^{4.8}} \qquad 2 \cdot 10^4 < \mathrm{Re_D} < 10^6 \qquad (12.11)$$

$$2.5 \cdot 10^4 < q/dv < 1.3 \cdot 10^6$$

and

$$\frac{\Delta P}{l} \cong 0.092 \frac{v^{0.2} \rho \, q^{1.8}}{d^{4.8}} \qquad 2 \cdot 10^4 < \mathrm{Re_D} < 10^6 \qquad (12.12)$$

$$2.5 \cdot 10^4 < q/dv < 1.3 \cdot 10^6$$

Expressions (12.11) and (12.12) describe fully developed turbulent flow with high Reynolds numbers, which is characteristic for high temperature flows.

For fully developed turbulent flows through ducts with cross sections other than round, provided Re_D should be replaced by the Reynolds number based on hydraulic diameter, Re_{Dh}.

The relationship between temperature, density ρ and $\nu^{0.2}$ ρ-term from (12.12) and (12.10) is illustrated in Figure 12.1

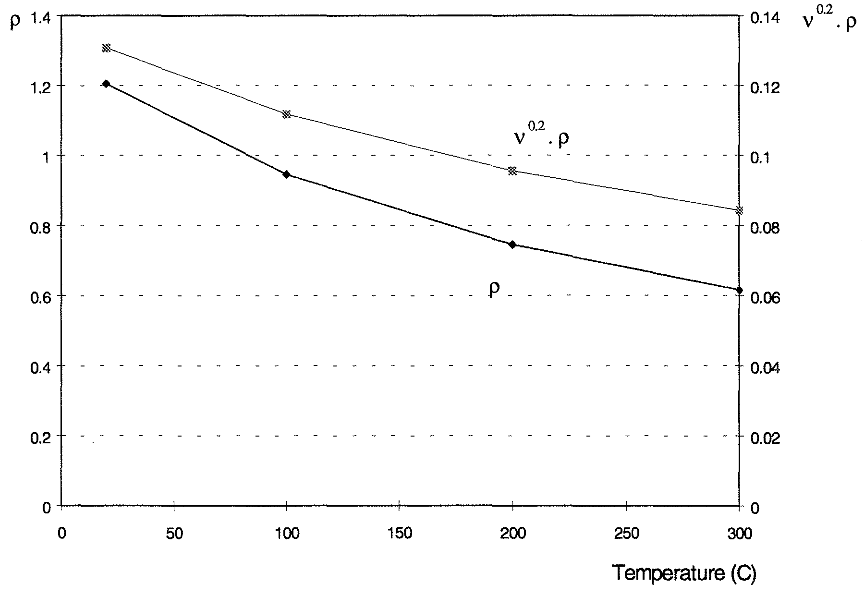


Figure 12.1 Density ρ and the $\nu^{0.2}$ρ-term vs. temperature for fully developed turbulent flows.

Figure 12.1 shows that density ρ and the $\nu^{0.2}$ ρ-term decrease by approximately a factor of two as temperature in K doubles. This means that the pressure drop per meter length of duct (friction pressure drop in straight ducts) also decreases by a factor two.

This seems to indicate that all ventilation system calculations for the "cold" case are overestimated. At the same time, as smoke is diluted downstreams in the main duct, flow temperatures decrease and "cold" flows are the default values.

The pressure drop in wyes and junctions is more difficult to evaluate, as data is not available.

13 The "Alexander"-method

Another method for evaluating the ability of a ventilation system to ventilate a burning room without smoke spread to adjacent room(s) via the ventilation ducts is developed by Lars Jensen and is presented in [16]. It is a method for manual calculations and is named "Alexander" method after Alexander the Great and myth of the Gordian knot. The method is based on the "cut-off" principle. A branch(es) with zero pressure (boundary conditions), serving the burning room, is cut off and the rest of the ventilation system is calculated once more regarding the new pressure/flow proportions. This calculation results in new total pressure loss and flow values. On the bases of these new parameters and the fan curve, new total pressure and flow for the abridged ventilation system are assessed. The fire flow for such a system can be calculated.

The algorithm of this method is shown for an exhaust ventilation system with six equal branches. The schematic layout of the examined ventilation system is presented in Figure 13.1.

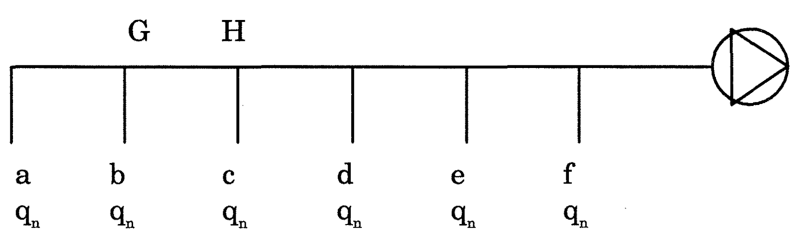


Figure 13.1 Layout of exhaust ventilation system.

where

q_n is a normal ventilation flow

a-f rooms
G,H junctions.

In the ordinary case the present ventilation system is regulated and the pressure loss in branch a-G is equal to pressure loss in branch b-G. In the case of fire, pressure in the burning room, e.g. in room a, rises and affects pressure in branch a-G. The boundary or limit condition, when smoke from room a starts to spread to the adjacent room b, is reached when pressure in junction G becomes equal to zero. The described method uses this phenomena and replaces the layout presented above with an abridged ventilation system layout, shown in Figure 13.2

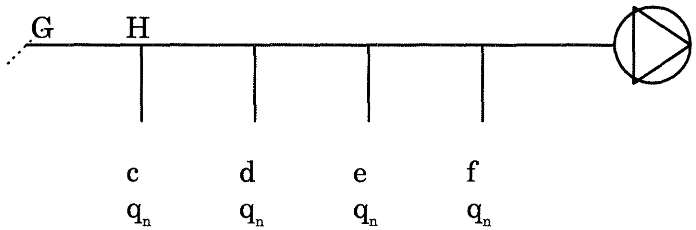


Figure 13.2 Layout of abridged exhaust ventilation system.

Part of the main duct a-G and branch G-b is cut off in G and is replaced by some fictitious "room" with atmospheric pressure and flow of $2q_n$. If the pressure loss in branch G-H is p_1, the "new" flow from room c is

$$q = q_n \left(p_1 / p_{c-H}\right)^{0.5}$$

where p_{CHn} is pressure loss in G-H determined for the normal case.

This principle is used to calculate "new" flows in each branch for the abridged ventilation system. The resulting total flow q_a and the resulting total pressure loss p_a are plotted in Figure 13.3.

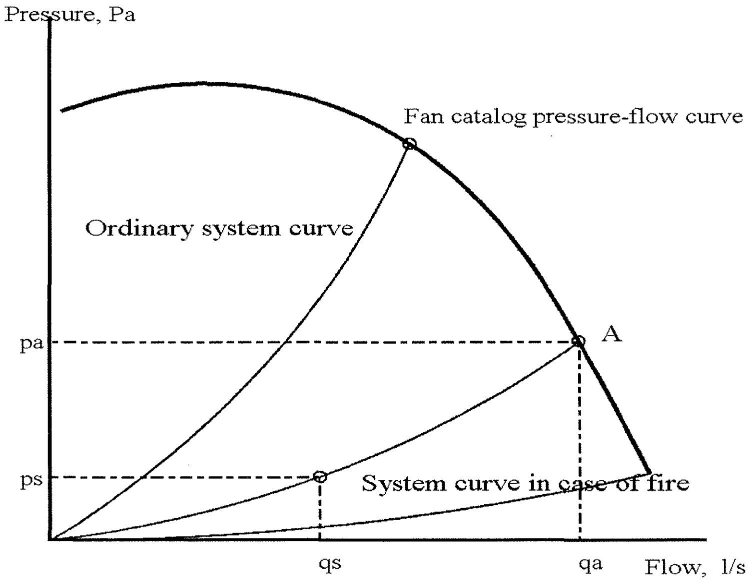


Figure 13.3 Pressure-flow diagram.

Pressure p_s and flow q_s are new fan values for this abridged ventilation system. The corresponding boundary fire flow in branch G-H (instead of assumed flow of $2q_n$) can be calculated

$$q_b = 2q_n\, q_s \,/\, q_a$$

where

q_b is boundary fire flow.

The corresponding boundary fire pressure can be calculated

$$p_b = p_{a-G}\ (q_b \,/\, q_n)^2$$

where

$p_{a\text{-}G}$ is pressure loss in branch a-G at the normal ventilation flow, q_n.

14 Discussions and conclusions

Introduction

The theoretical studies along with computer simulations have provided knowledge regarding smoke production of different typical fires in certain types of buildings, as well as knowledge regarding spread of smoke to adjacent room(s) via ventilation ducts. Application of this basic knowledge largely depends on the characteristic parameters estimated for different types of buildings. The main building types chosen for this work are dwelling houses, hospitals, offices and hotels. The study is interdisciplinary and comprises different fields of knowledge: fire protection engineering, building science and building services.

Whether or not smoke spread will occur is determined by factors such as the typical fire scenario in the above types of buildings, the airtightness of the construction, window breakage as a result of heat stress and the layout of the ventilation system.

Fire scenario and rooms geometry

Summing up statistical data presented in different sources regarding the danger of fire in the analysed buildings, it was assumed that fire is limited to the room of fire origin and to the object in which the fire started. The most probable objects where the fire starts are bedclothes and sofas in the dwelling houses.

In order to evaluate fire behaviour in the analysed types of rooms, a fire growth curve is used which is based on the results of full-scale tests in which different items were burnt in the laboratory and heat release rate as a function of time was measured.

The following items were assumed to initiate fires: sofa and bed in dwelling houses, bed in hospitals, equipment and furnishing in offices and bed in hotels. Data provided by these fire growth curves is used as basic fire data in evaluating fire progress in the examined rooms with the help of computer programs.

The geometry of the studied types of rooms is chosen in diapason of 30 -224 m^3 for the standard room areas and room heights for each type of buildings. Doors and windows are closed and undamaged, and the only vents are leakage paths.

Computer programs for predicting compartment fires

Fire simulations are made with the help of the computer program CFAST (Consolidated Model of Fire Growth and Smoke Transport), which is part of the computer program HAZARD1. It is based on the two-layer fire model. A comparison of parameters obtained by CFAST for single-room fires, with measured values, shows that pressures, O2-concentrations and mass flows are slightly underpredicted, while there is good agreement regarding temperatures.

In order to compare the magnitude of parameters obtained with CFAST with those predicted with the two-layer fire model computer program DSLAYV and with the field model program SMAFS, a special case of a compartment medium fast αt^2-fire in a single room of 6×5×2.5 m is simulated. Both mass and volume flows predicted by SMAFS are 32% higher than those predicted by CFAST, which is in turn 35% higher than those predicted by DSLAYV. Flows obtained with SMAFS cannot be considered as determining values because they are very approximate.

Owing to the scarcity of experimental data and simulation results, and the complexity of comparing the numerous variables in a complex fire model, true validation of the CFAST model is not possible in this study (true validation of a model would involve proper statistical analysis of a variety of compared variables). A special study of the issue is required. Different locations of burning items are also tested.

Airtightness

Validation of the magnitude of internal and external leakage paths in the studied buildings is an important issue for evaluation of both fire progress in the room and predicted parameters.

The study of relevant literature has shown that the air leakage according to the Swedish Building Regulations BBR 94 (1.25 cm^2/m^2 for dwellings and 2.5 cm^2/m^2 for other types of studied buildings), applied to the whole building envelope, can be accepted as a suitable and probable value.

The analysed data are not sufficient for less robust validation as they cover mostly dwellings, while this study comprises different types of buildings. In particular, there are no data for older buildings. At the same time, due to Swedish construction traditions and airtightness requirements which are different from those in other countries, the information from international scientific documents published abroad cannot be used as straightforward data.

Window breakage

As the CFAST fire model assumes that the envelope of the fire room is perfectly airtight during the entire fire progress, except for the leakage paths, the evaluation of the time and ambient conditions at which window breakage occurs seems important.

A study of the literature, together with the simple window breakage model presented in this work, shows that the temperature difference of 58-100°C in the glass itself can be assumed to be dangerous for glass cracking. The most probable temperatures in the fire room which cause this phenomenon vary between 200 and 400°C.

For this study, the temperature of 350°C in the fire room is accepted as the limiting temperature value. The uncertainty of such assumptions is aggravated by lack of data on window breakage as a result of the simultaneous effect of both high pressure and high temperature in the enclosure.

Further research on the issue appears necessary.

Peak fire flows

The assumption in predicting peak fire volume flows by CFAST simulations is that leakage paths are located at the sills of doorways. Mass flows with leakage paths at the sill of the doorway were somewhat larger then those with leakage paths at the other locations (5-20%) (due to the differnce in air density). At the same time temperature, pressure, rate of heat release and interface position were insignificantly affected by the location of leakage paths. For the purpose of generalisation, the fire locations chosen were those which give the highest fire flow values in these cases.

A regression analysis of these flows made with the statistical program Minitab shows good agreement with the regression line in the case of fires in dwellings and fires in hotels, while the agreement with fire flows in hospitals and offices, predicted in such a way, was not good enough.

A simple model which approximates fire curves as a linear segment function and is based on evaluation of fire flow, which depends directly on the heat release effect, accumulated into released energy, which in turn corresponds to the given volume of consumed room air, gives peak fire flow values in good agreement with the regression line over the whole range of the studied types of buildings. Although there is an uncertainty in such an assessment, it seems reasonable to use reported fire flows as default peak flow values in the described rooms, as they are evaluated with a margin for overestimation. Peak fire flows are at least ten times higher than ordinary ventilation flows.

Characteristic flow curves for the chosen buildings, of volumes ranging from 30 m^3 to 240 m^3, are presented. These volumes are assumed to be those most usual for the described types of buildings.

For the purpose of comparison, both the presented flows and flows obtained with DSLAYV for t^2 - fires are plotted in the same diagram. It shows that flows obtained for offices agree very well with those predicted for the medium fast t^2 - fires. Flows obtained for hospitals have values between those predicted for medium and fast t^2 - fires over the whole range of volumes. Flows obtained for hotels up to approximately 100 m^3 are insignificantly lower than those predicted for fast t^2 - fires, while flows in hotels larger than 100 m^3 have values between those predicted for fast and ultrafast t^2 - fires. Flows obtained for dwellings up to approximately 100 m^3 are lower than those predicted for ultrafast t^2 - fires. In contrast, flows in dwellings larger than 100 m^3 have higher values than those predicted for ultrafast t^2 - fires.

Other parameters predicted with fire simulations

All compartment fire simulations show that only the ignition and growth stages of a fire occur.

Values of oxygen in the rooms studied at the time when the corresponding peak fire flows were obtained vary quite a lot even in the same room depending on fire location.

Peak fire flow occurs shortly after ignition. The time after ignition varies between 1 and 5 min. Exceptions are fires in dwellings with a bed as ignition item, where this period can be as long as 7 min 30 sec.

The peak temperature in the upper layer of the majority of the examined rooms does not exceed 340°C.

The pressure in the majority of rooms is relatively low, except for dwellings with a sofa as the burning item where the pressure is considerably higher, up to 2057 Pa. "Real" pressures, obtained in rooms with terminals, do not exceed 647 Pa.

Ventilation system design

In natural ventilation systems which serve each separate room with a separate duct, smoke spread will never occur except due to leakage of the duct itself.

The risk of smoke spread via mechanical ventilation systems depends mainly on the type of ventilation system.

General theoretical methods show that the highest risk of smoke spread to the adjacent room(s) via ducts can be expected in open supply-exhaust ventilation systems, while the lowest risk can be expected in exhaust ventilation systems with the pressure drop in branches larger than in the main duct.

In mechanical ventilation systems designed according to given pressure drop relations, in which prevention of smoke spread relies only on shutting down the ventilation system, some smoke spread to the adjacent room(s) will always occur.

The proportion of smoke which reaches adjacent room(s) in mechanical systems in which the supply fan or both fans are switched off depends on the number of rooms and their sizes. The maximum amount of smoke spreads to the adjacent room(s) from the burning room in cases where there are two equal rooms (with fire in one of them), a lot of smoke spreads from a small burning room to the rest of the building, and little smoke spreads from a large burning room (or several burning rooms) to the small room. The magnitude of fire flow is not discussed here. The term "adjacent room(s)" in this study can refer to any fire compartment on the same floor or on another floor nearest to the burning room, served by the same ventilation system.

Boundary conditions

Exhaust and supply-exhaust (open and closed) systems and supply-exhaust systems with "zero"-duct ventilation are studied with the help of the semi-graphical computer program PFS which treats arbitrary flow systems of any structure and layout, any media, and any problem, design and investigation.

Boundary conditions, e.g. boundary fire flows when smoke from the burning room starts spreading via ducts to the adjacent room (zero air flow in the adjacent room(s)), are in good agreement with values expected according to the general models.

As this study is interested in "abnormal" flow behaviour, i.e. changes in flow directions and consequent decrease in flow in certain parts of junctions to zero value, it is not obvious how wyes would respond.

PFS provides the opportunity to describe the resistance properties of wyes and junctions in two different ways: with a quadratic function and with the help of empirical equations. Both types are tested, and the resulting boundary fire flows are different. Pressure loss as a quadratic function, which takes account of high Reynolds numbers in duct flows in case of fire, is chosen as the default. More detailed research into the behaviour of wyes under such conditions seems important.

"Real-case"

The types of buildings examined in this study are equipped, as usual, with ventilation systems, the degree of complexity of which can be different. Evaluation of boundary fire flows in these ventilation systems is very numerically complex. Assessment of the risk of smoke spread via ducts seems more manageable when fire flows typical for the studied buildings presented in this work are used.

Measures to prevent the spread of smoke

Different solutions for the prevention of smoke spread to the adjacent room(s) via the ventilation system are analysed; these are shutting down the fan(s), doubling the speed of rotation of the fan(s), converting the supply fan into exhaust fan, bypassing the support plenum to the exhaust plenum, and a combination of these measures with ordinary fan function and with each other.

These measures do not cover the entire range of measures for the prevention of smoke spread via ducts, nor do they examine the behaviour of systems with fire dampers. There is no total solution of the problem. Different measures have shown different results for different ventilation system layouts. Each must be tested separately for the actual type of ventilation system and layout. Doubling the speed of rotation of ordinary fan(s) is a very hard measure and can be applied e.g. in ventilation systems with reduced normal capacity. Shutting down the fan(s) corresponds to natural ventilation, and spread of smoke occurs in all the examined systems.

Toxicity and visibility of the diluted smoke

In certain cases, where predicted spread of smoke to adjacent rooms shows comparatively low values, another situation can be discussed.

It can be reasonable to look at the degree of dilution of the smoke instead of totally forbidding the spread of smoke to adjacent rooms. In this connection, the risk of toxicity and visibility of diluted smoke may have to be evaluated. Evaluation of the concentration of CO in the smoke spread is then important. In certain underventilated fires, with the ceiling and upper walls lined with plywood, dry CO concentrations are reported to reach 14%. These reported levels are extremely high and represent an unusual CO/CO_2 ratio. Generally, CO concentrations increase dramatically in underventilated fires.

Evaluation of the concentration of CO which spreads to the adjacent room(s), made step by step for exhaust and supply-exhaust ventilation systems, comprises evaluation of the total volume of smoke spread, evaluation of the proportion of this smoke volume which reaches another room, evaluation of the concentration of CO in a single room, and evaluation of the CO - dose.

The CO-dose is a product of CO-concentration, the duration of exposure, and the type of activity during which exposure takes place.

There are different criteria which determine the fatal dose of CO. Information about the toxic effects of CO in respiration air varies a lot both in terms of both concentration and dose. Thus it seems difficult to draw unequivocal conclusions about the risk rate due to CO-concentrations. IDLH (immediately dangerous to life and health), limited to 1500 ppm during 30 min, is used as the default value in this study.

Visibility through smoke can be of great importance to an individual attempting to survive a fire. The evaluation of the visibility of smoke in another room, as a result of smoke spread via ventilation ducts, is analogous to evaluation of the concentration of CO in the spread smoke. In actual fact, visibility will be higher than assessed, because the concentration of smoke will be higher near the ceiling and will gradually decrease downwards.

"Cold" case assessment

The whole study assumes that all flows have ambient parameters, "cold flows". In fact, according to results obtained in fire simulations, flow temperatures can exceed 340°C. Although all evaluations of smoke spread via ventilation ducts take into consideration the temperature factor in dealing with volume flows, the pressure drop per meter length of duct (friction pressure drop in straight ducts) at such temperatures seems to decrease to one half of ordinary values. This statement seems to indicate that all ventilation system calculations made for the "cold" ventilation systems are over estimated. The pressure drop in wyes and junctions is more difficult to evaluate due to the paucity of data.

Further research in this field is needed. At the same time, along with smoke dilution downstream from the main duct, flow temperatures decreases and "cold" flows become the default ones.

Manual methods

One more method for evaluating of possibility og smoke spread via ducts is presented in the study. The "Alexander" method is a method for manual calculations, based on the" cut-off" principle. The "cut-off" principle means that a branch(es) at the boundary conditions with zero pressure is cut off and the rest of the ventilation system is calculated once more with respect to the new pressure/flow conditions. This calculation results in new total pressure loss and flow values. On the bases of these new parameters and the fan curve, the new total pressure and flow are assessed for the abridgedventilation system. The fire flow for such a system can be calculated. The method is named after Alexander the Great and myth of the Gordian knot.

Application

To evaluate smoke spread via ventilation systems in case of fire, the following procedures can be applied.

For ventilation systems of all types, the risk of smoke spread via ducts can be evaluated step by step with the help of computer programs as follows:

"Boundary" fire flow:

step 1 the ventilation system studied is described with the help of a computerprogram,

step 2 the "boundary" fire flow in the room studied or in one of the rooms connected with the branch located furthest away from the fan are evaluated. It means that the supply flow to the room studied in the case of supply and exhaust ventilation system is replaced by the zero flow. In the case of exhaust ventilation system, the flow(s) in the exhaust branch calculated upwards from the "fire" room is replaced by the zero flow,

step 3 the "boundary" flow(s) is compared with a fire flow(s) (Figure 4.13) for the room of corresponding volume in the corresponding type of building. If the "boundary" flow is higher than the fire flow from the Figure 4.13, smoke does not spread via the ventilation system. If the "boundary" flow is lower than the fire flow from the Figure 4.13, smoke spread occurs via the ventilation system.

"Real" fire flow:

step 1 the ventilation system studied is described with the help of a computer program,

step 2 the fire flow in the room of certain volume studied in the type of building studied is evaluated with the help of Figure 4.13,

step 3 the ventilation system studied is tested for risk of smoke spread with the help of those fire flows replacing normal ventilation flows in the room(s) studied.

"Alexander" method

This method for manual calculations, described for the exhaust ventilation systems in Section 13, can be applied for smoke spread evaluations via ventilation systems with lower degree of complexity.

Note that smoke spread via ventilation systems should be evaluated separately for each ventilation system of actual layout and properties.

Different measures preventing smoke spread via ventilation ducts can then be tested separately for the ventilation system studied in conjunction with Subsection 8.3.

In certain cases, when toxicity of assessed smoke spread via exhaust ventilation system and supply and exhaust ventilation system are of interest, it can be rapidly evaluated using Table 10.4 and Table 10.5 respectively.

Future research

This work along with other reports [1], [2], [3] and [27] is a pioneering research attempts in regard to the evaluation of smoke spread via ventilation ducts in ventilation systems in operation. Owing to the great uncertainty of the assumptions made, the paicity of experimental data and lack of knowledge regarding certain fire processes, it is necessary to investigate the problem further.

The fire scenario in the buildings studied, with more than one burning item involved, is of interest as such fires can produce fire flows different from those predicted in this work.

The issue of the reliability of the parameters predicted by CFAST, along with true validation of the model, should be analysed in a proper way.

The problem of flashover in smoke in ventilation ducts or terminals, i.e. ignition of unburned fuel in fire gases, must be studied properly, probably with the help of field model computer programs.

Window breakage phenomena as a result of both high temperatures and the influence high pressures must be studied.

The "cold" case as against the real high temperature smoke flow in ventilation systems must be examined in greater detail, since no examination has been made as yet of pressure drop in junctions and wyes in cases with "abnormal" flow behaviour, i.e. changes in flow directions and consequent decrease in flow in certain parts of junctions to zero value.

The problem of smoke spread via ventilation ducts in other types of buildings, e.g. in industrial buildings and stores, seems important. The possibility of using ordinary ventilation systems along with other safety measures (smoke venting, sprinklers, etc.) in the event of fire in such buildings can improve safety, and the economic consequences of it are far from negligible.

The problem of eliminating or reducing smoke spread via ducts to the adjacent room(s) is connected with evaluation of the toxicity and visibility of the diluted smoke. This matter needs further research.

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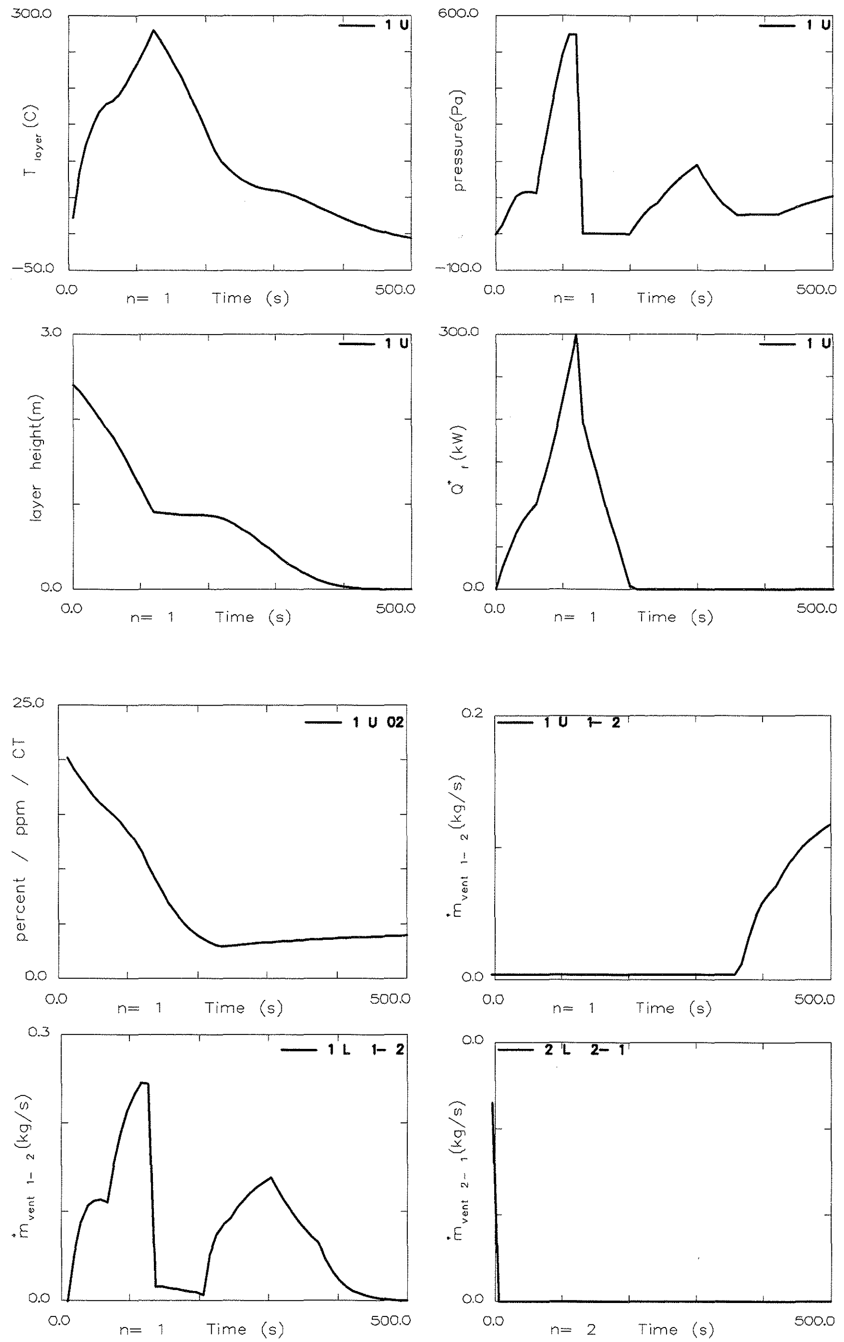
Appendix

The following figures correspond to Table 4.5, Subsection 4.3.



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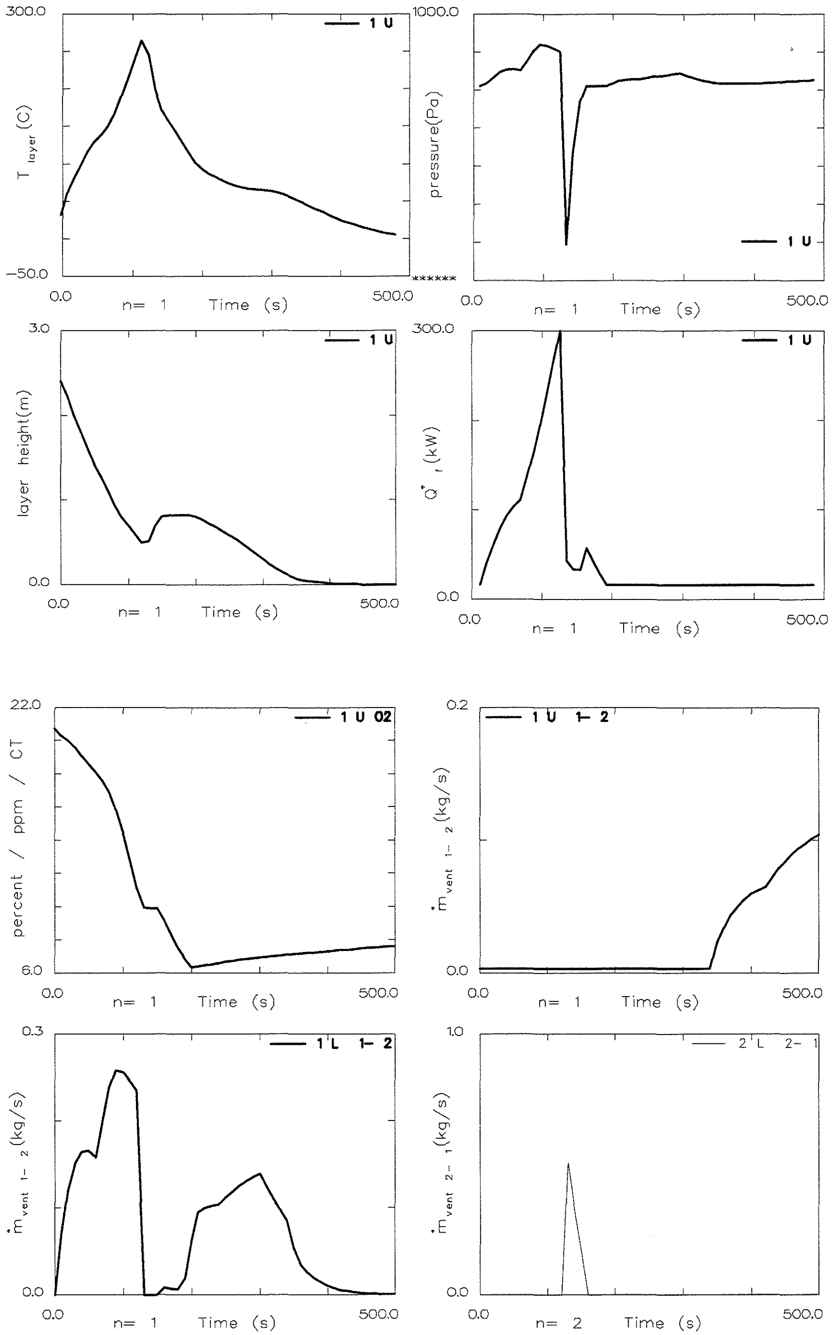

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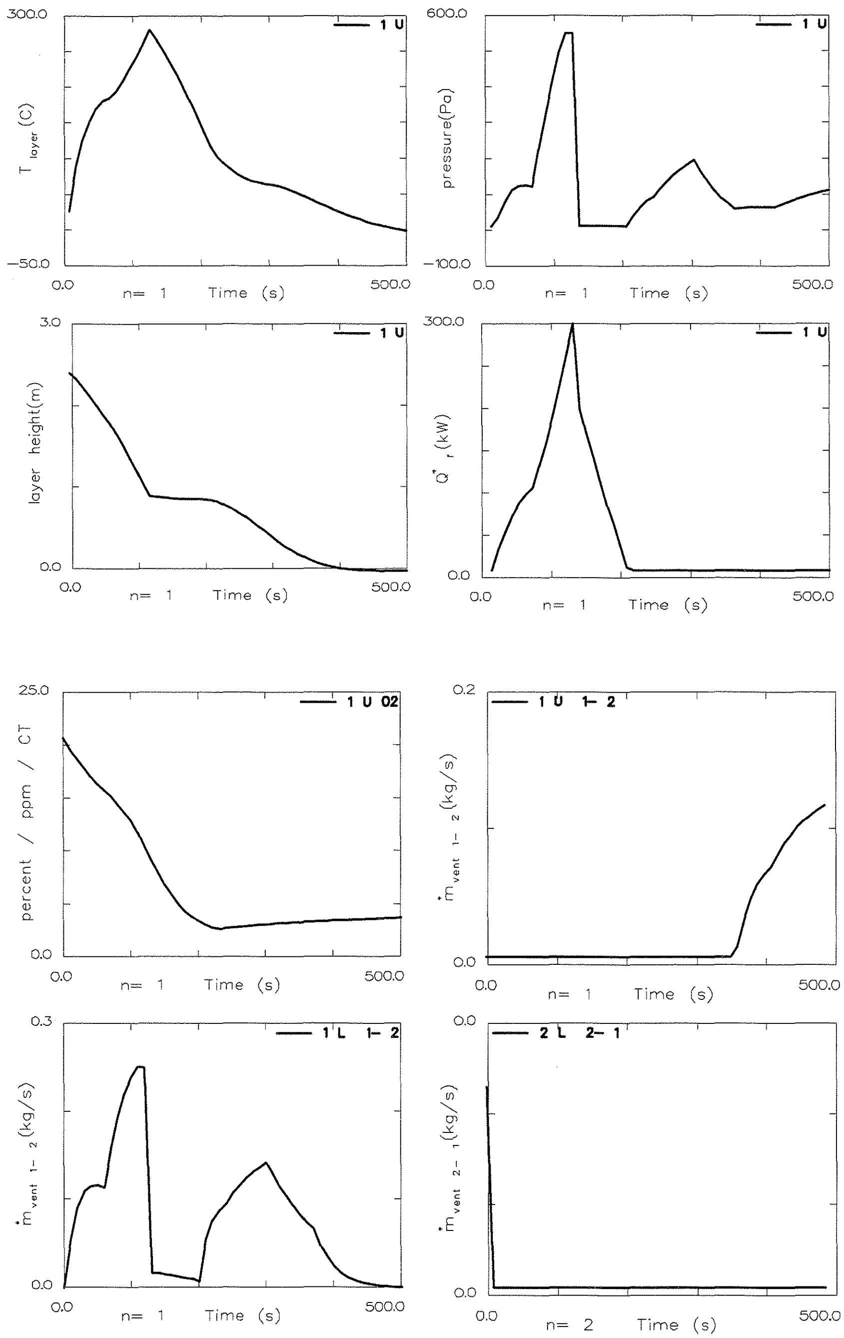

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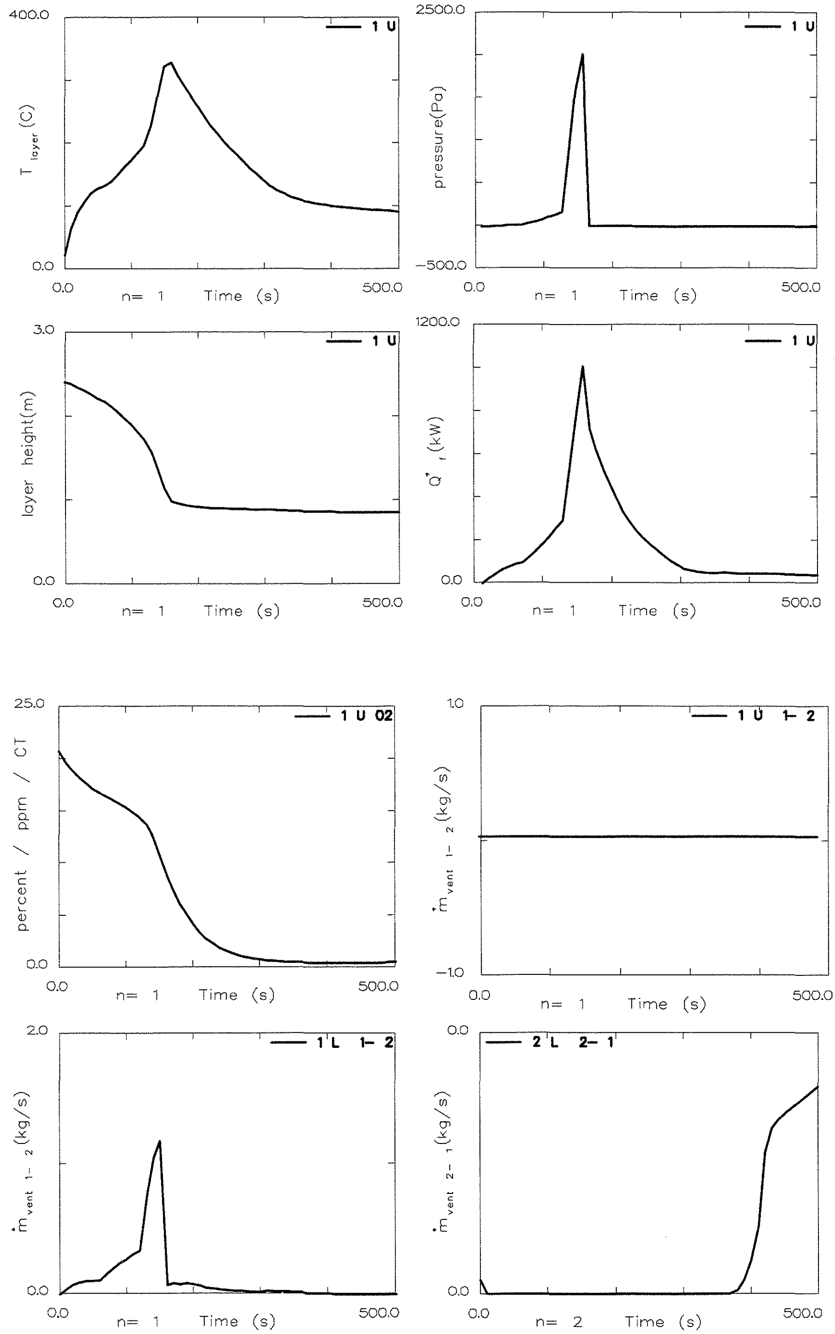

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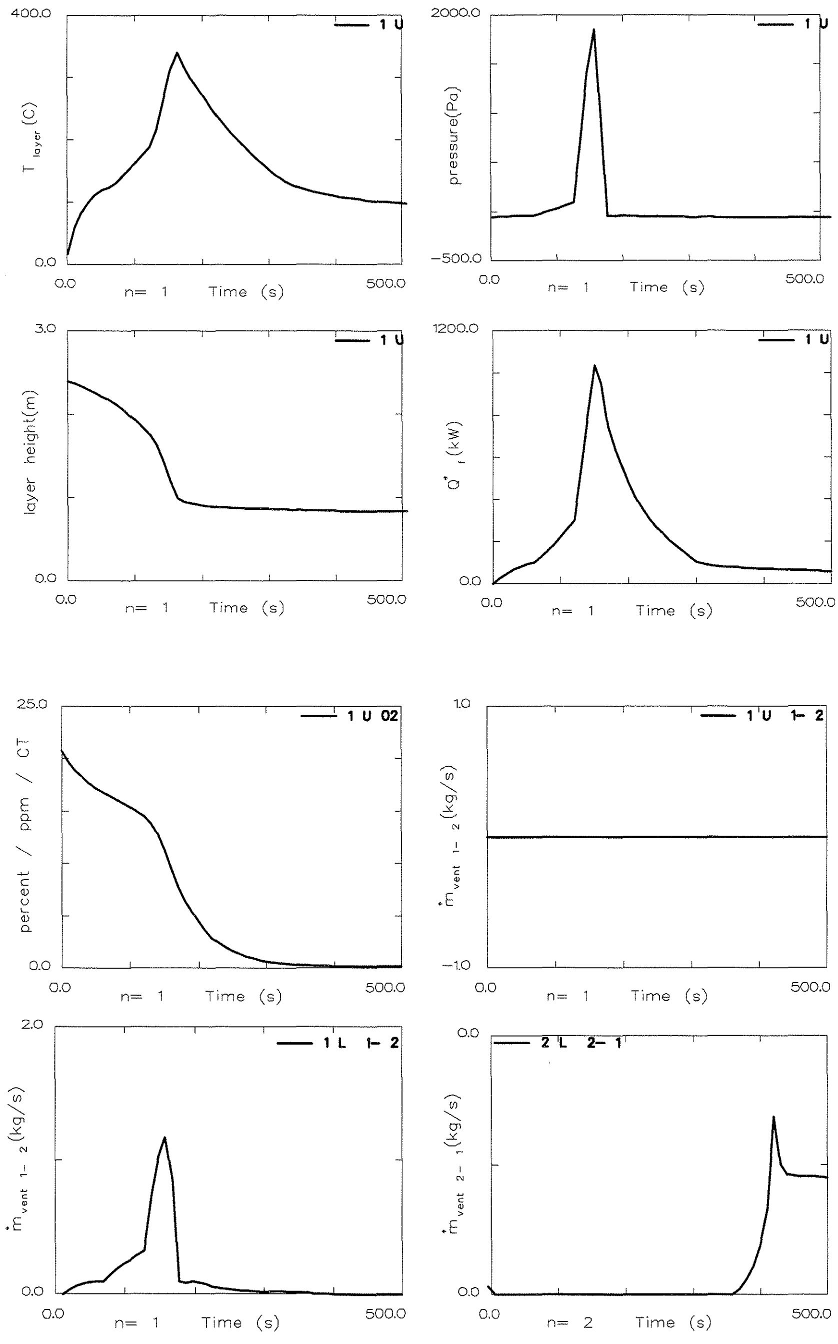

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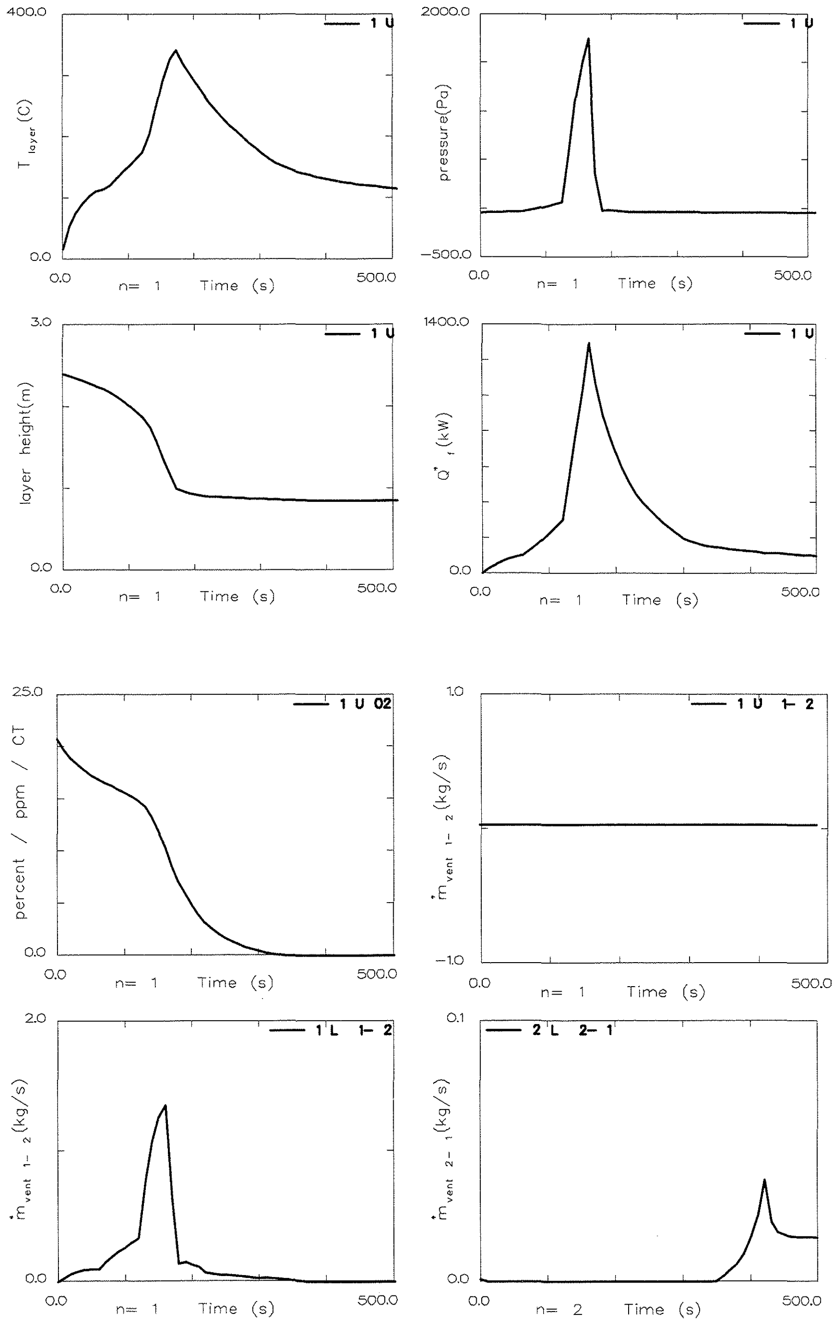

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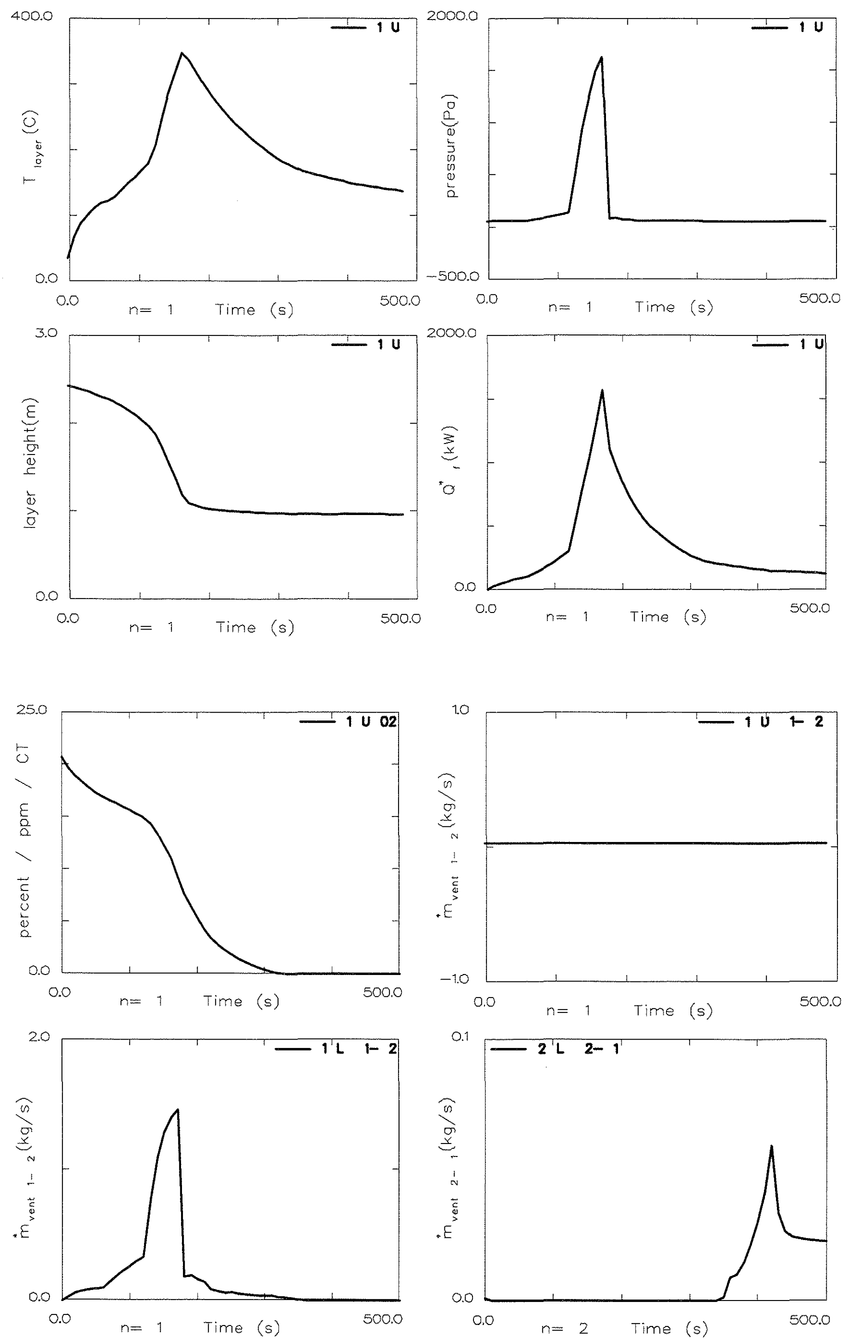

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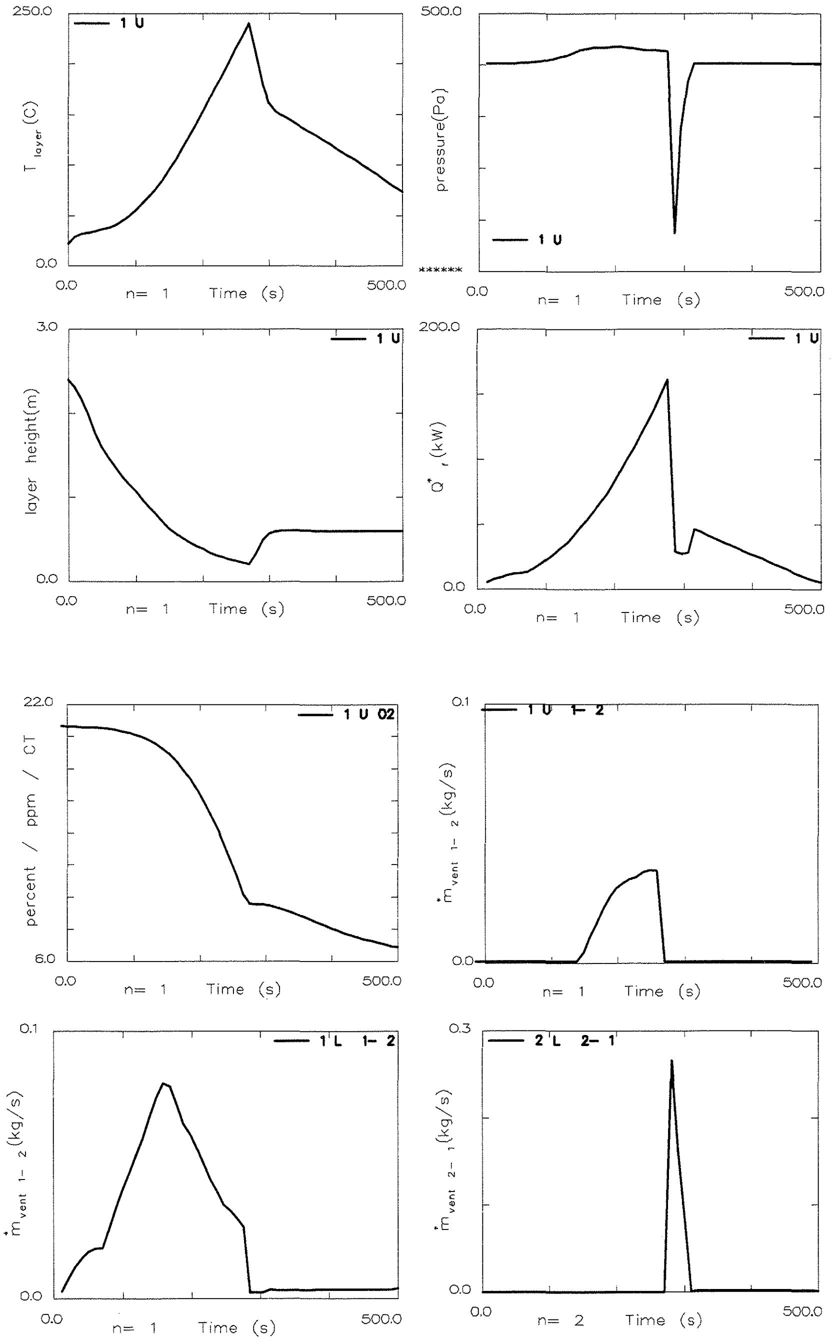
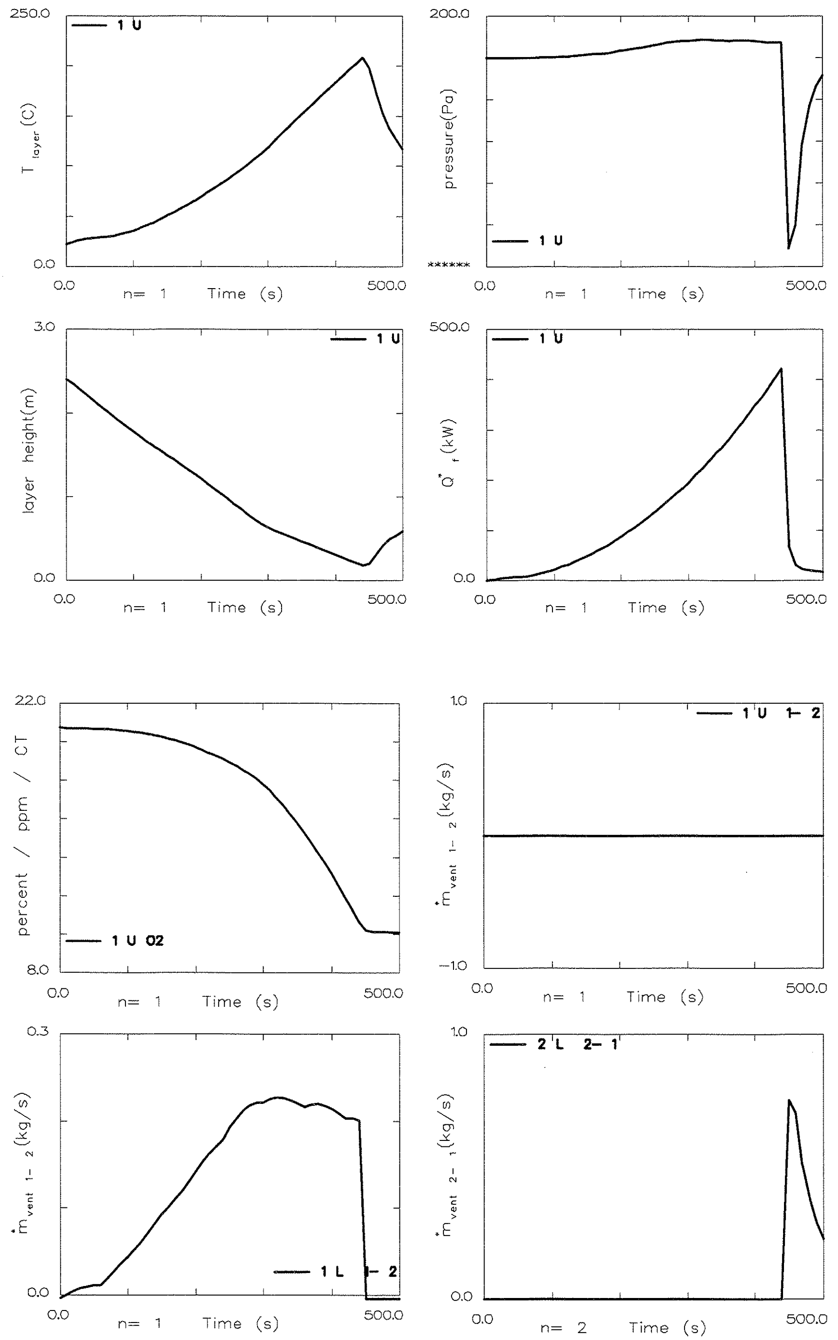


Dwelling house (bed) 8



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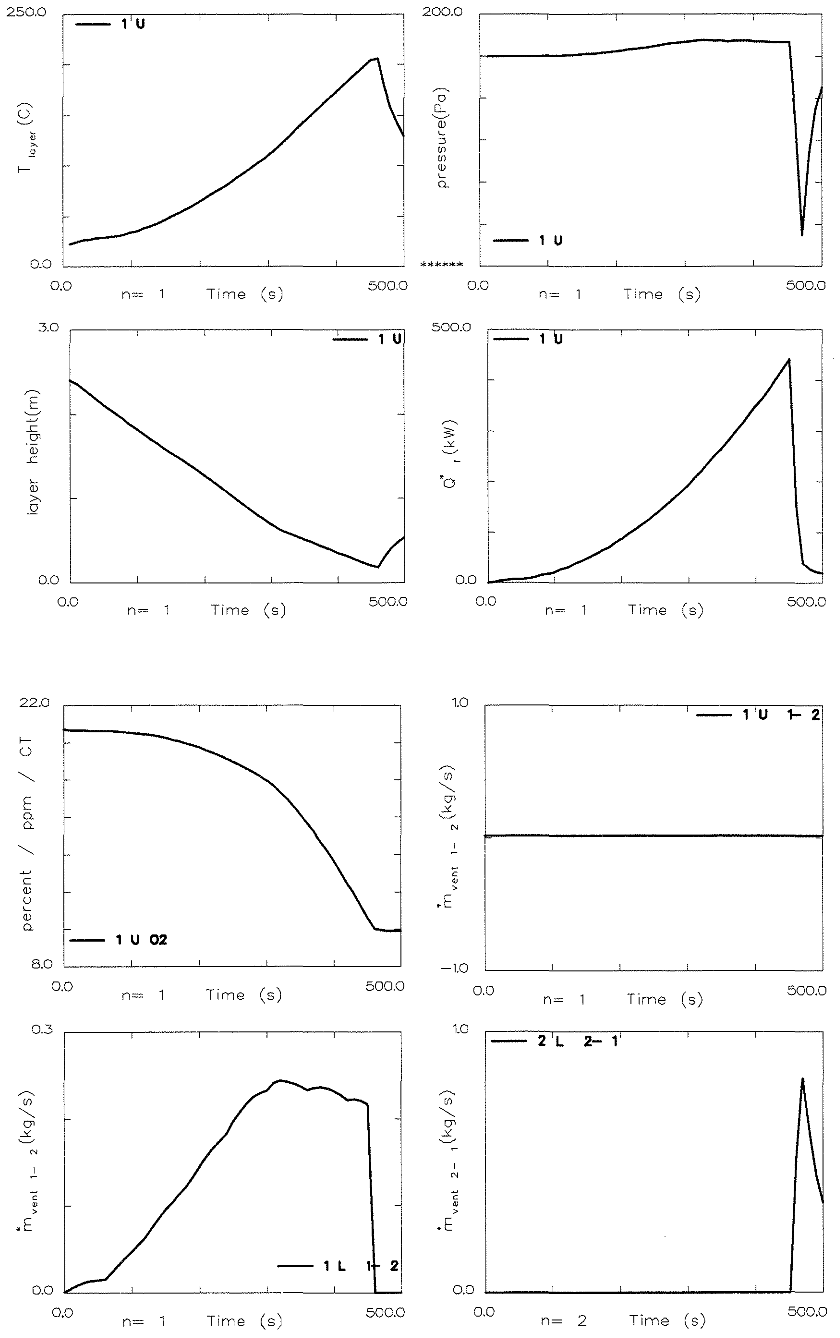

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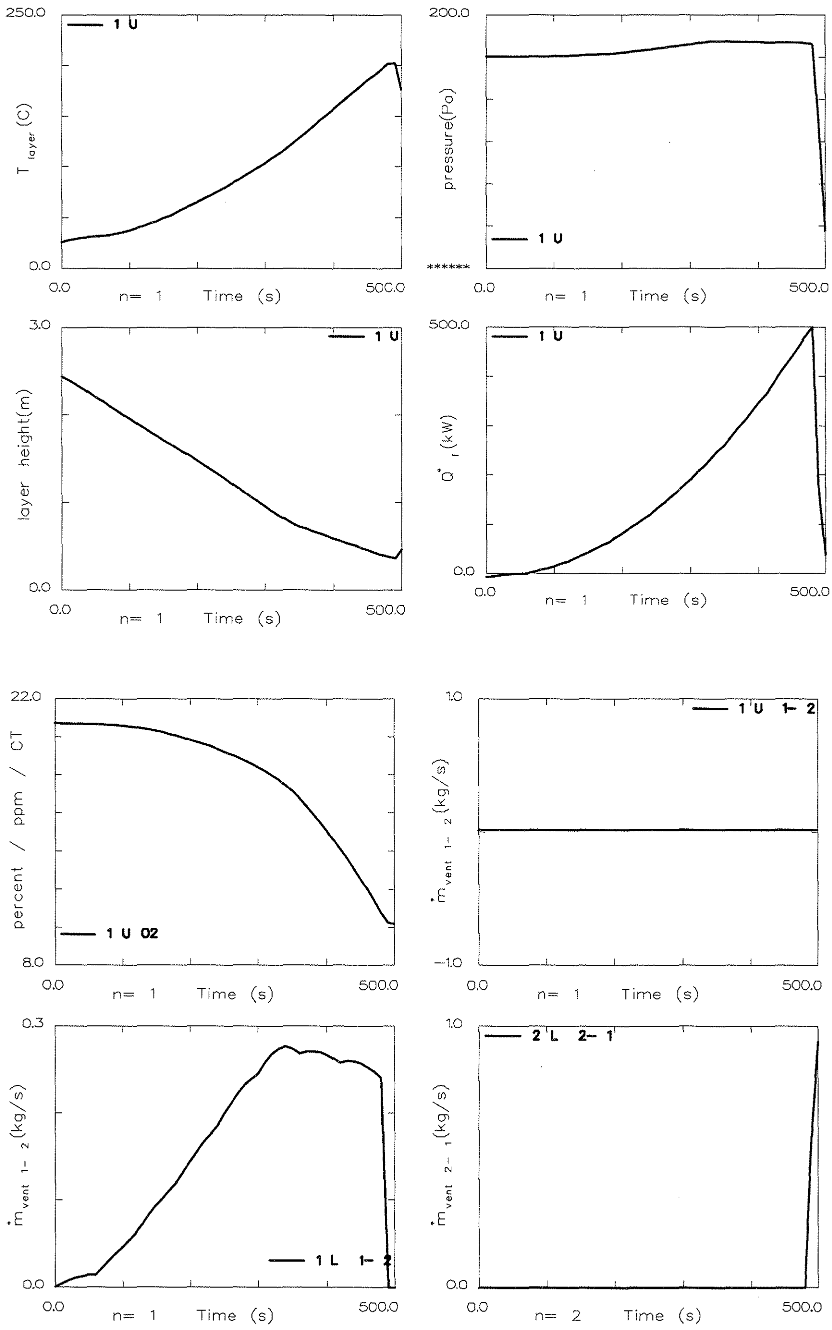

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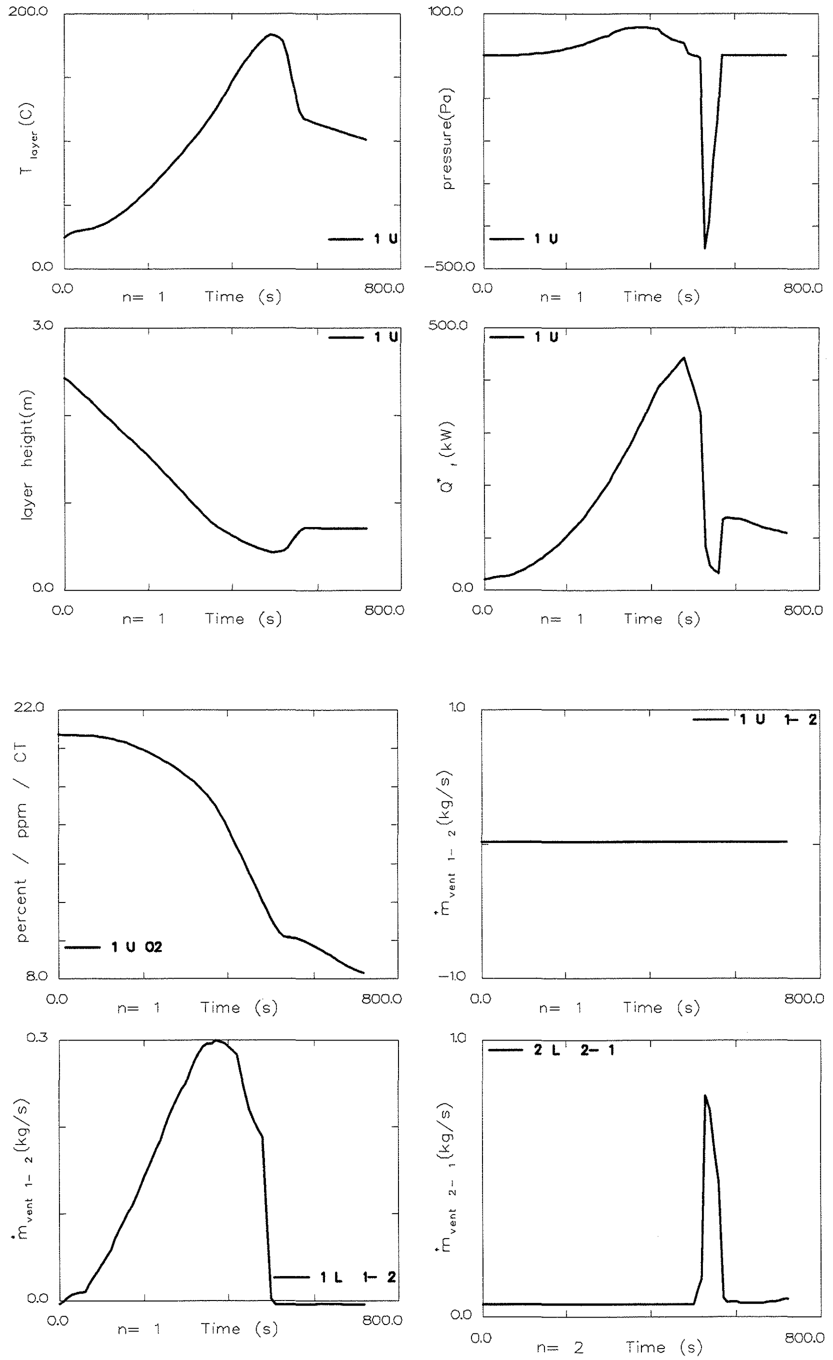

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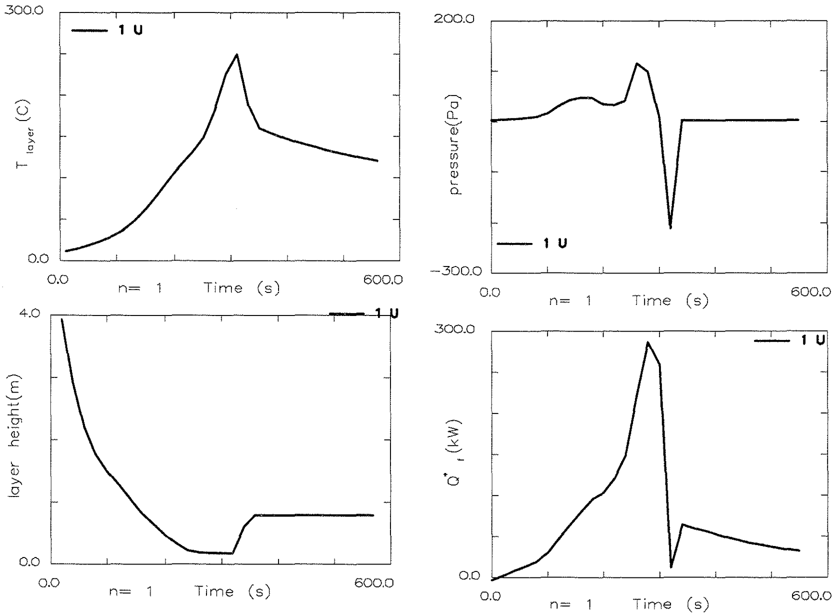

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-300.0
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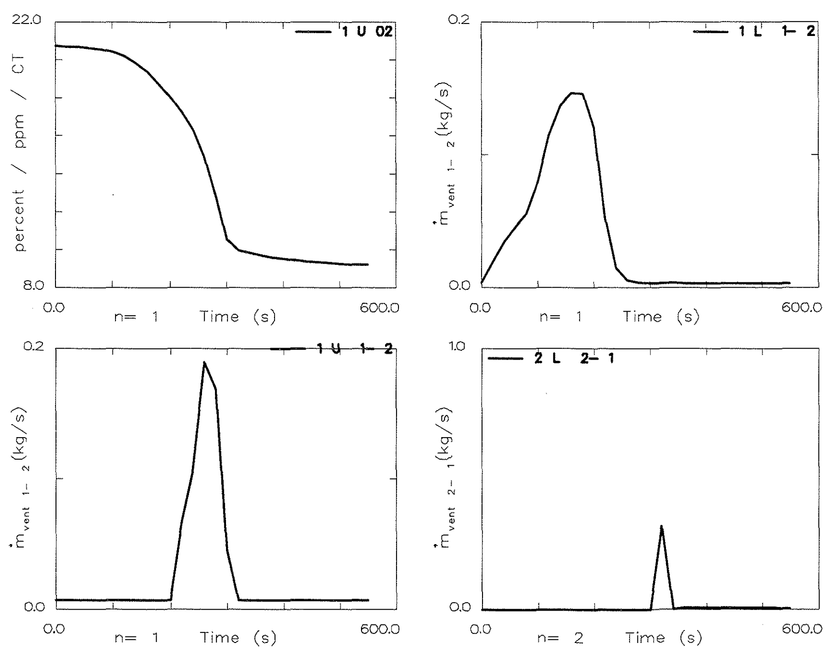
layer height(m)
300.0
Q̇ f (kW)



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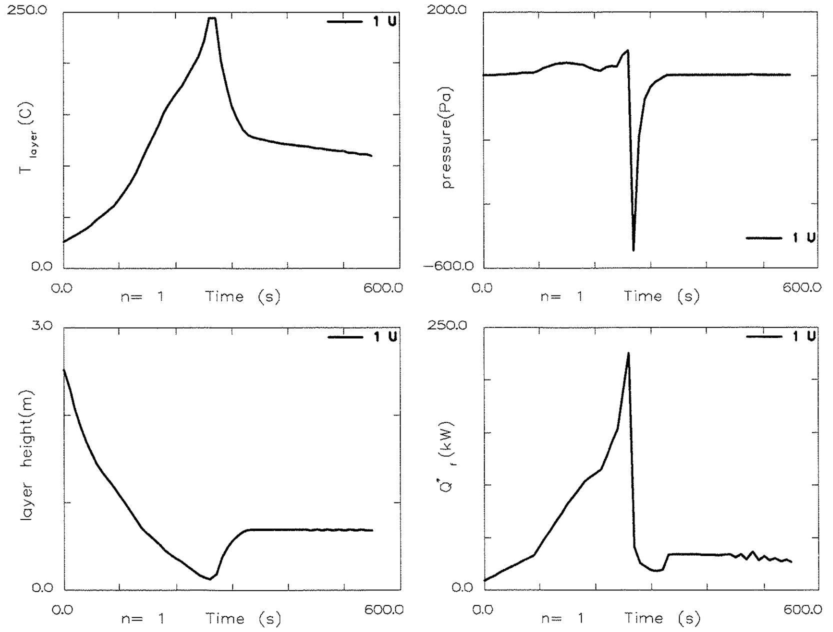
1 L 1- 2
ṁ vent 1- 2 (kg/s)
1 U 1- 2
1.0
2 L 2- 1
ṁ vent 2- 1 (kg/s)
n= 2

Hospital 13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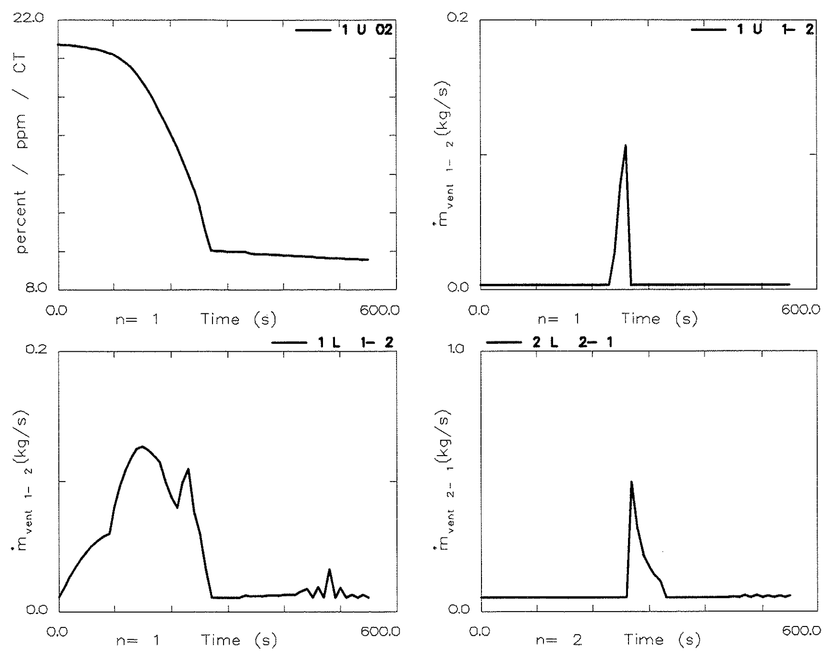
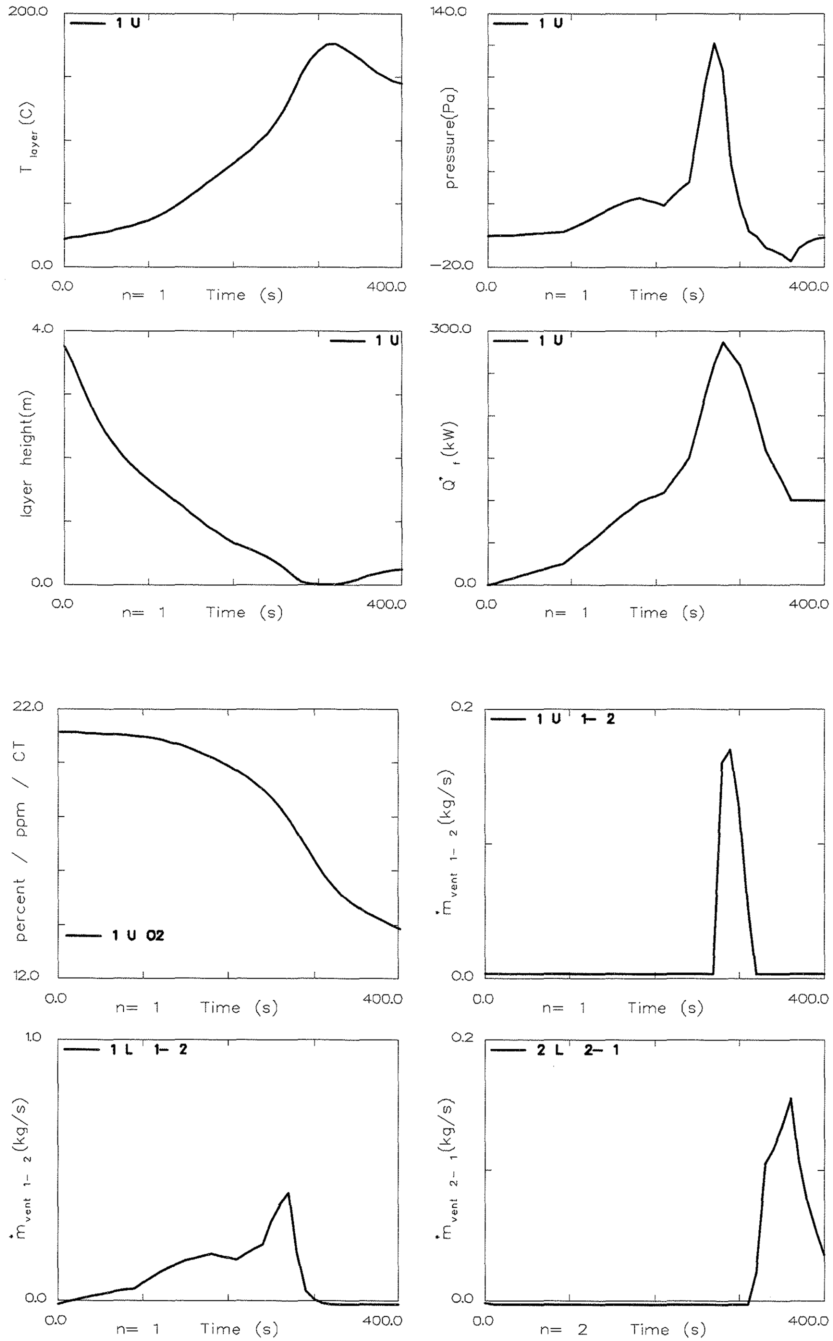
pressure(Pa)
−600.0
0.0 n= 1 Time (s) 600.0
1 U
3.0
layer height(m)
0.0
0.0 n= 1 Time (s) 600.0
1 U
250.0
Q*f (kW)
0.0
0.0 n= 1 Time (s) 600.0
1 U

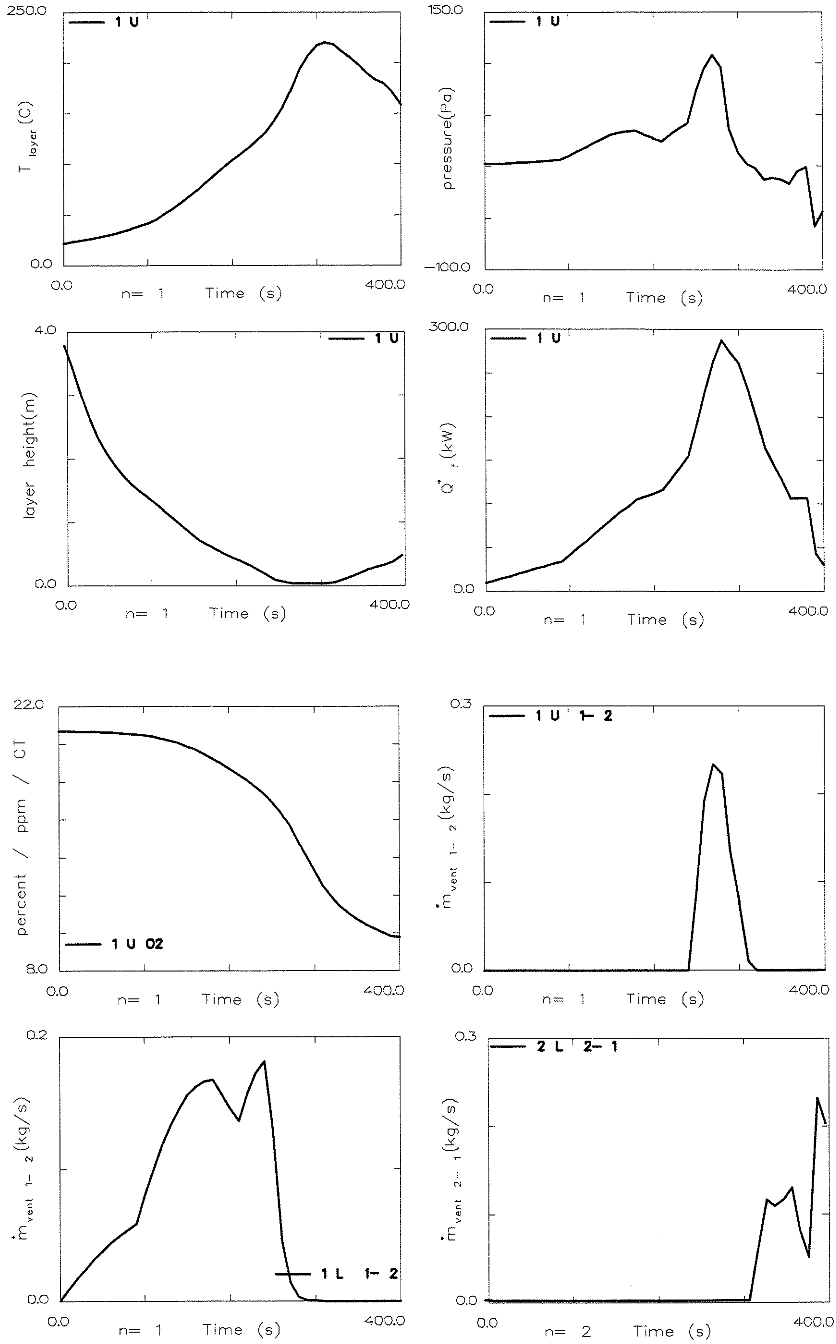

22.0
percent / ppm / CT
8.0
0.0 n= 1 Time (s) 600.0
1 U O2
0.2
ṁvent 1- 2(kg/s)
0.0
0.0 n= 1 Time (s) 600.0
1 U 1- 2
0.2
ṁvent 1- 2(kg/s)
0.0
0.0 n= 1 Time (s) 600.0
1 L 1- 2
1.0
ṁvent 2- 1(kg/s)
0.0
0.0 n= 2 Time (s) 600.0
2 L 2- 1

Hospital 14



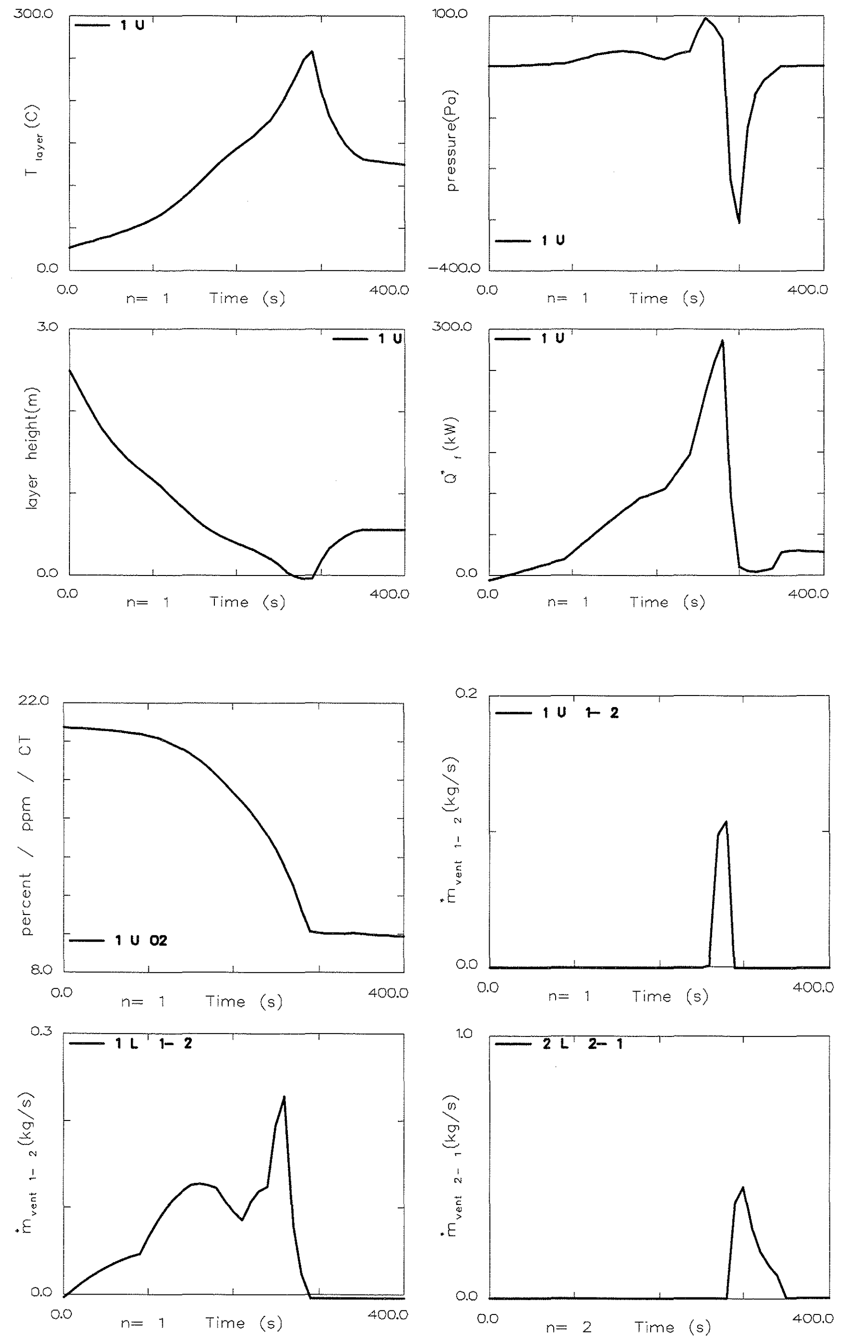
200.0
1 U
T layer (C)
0.0
0.0
n= 1
Time (s)
400.0
140.0
1 U
pressure(Pa)
−20.0
0.0
n= 1
Time (s)
400.0
4.0
1 U
layer height(m)
0.0
0.0
n= 1
Time (s)
400.0
300.0
1 U
Q̇ f (kW)
0.0
0.0
n= 1
Time (s)
400.0
22.0
percent / ppm / CT
1 U O2
12.0
0.0
n= 1
Time (s)
400.0
0.2
1 U 1– 2
ṁ vent 1– 2 (kg/s)
0.0
0.0
n= 1
Time (s)
400.0
1.0
1 L 1– 2
ṁ vent 1– 2 (kg/s)
0.0
0.0
n= 1
Time (s)
400.0
0.2
2 L 2– 1
ṁ vent 2– 1 (kg/s)
0.0
0.0
n= 2
Time (s)
400.0

Hospital 15

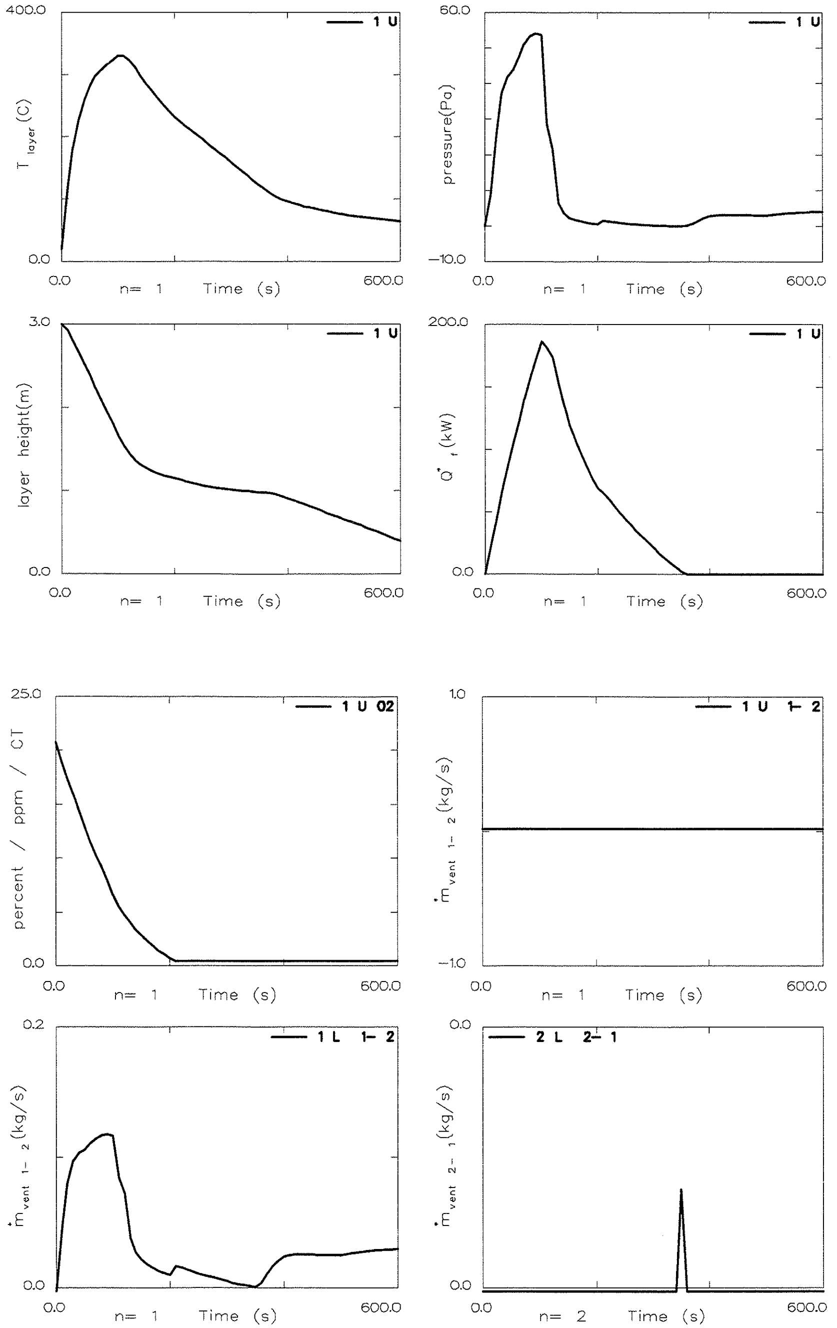


250.0
0.0
T layer (C)
1 U
0.0
n= 1
Time (s)
400.0
150.0
-100.0
pressure(Pa)
1 U
4.0
0.0
layer height(m)
300.0
Q f (kW)
22.0
8.0
percent / ppm / CT
1 U O2
0.3
0.0
m vent 1- 2 (kg/s)
1 U 1- 2
0.2
1 L 1- 2
m vent 2- 1 (kg/s)
2 L 2- 1
n= 2

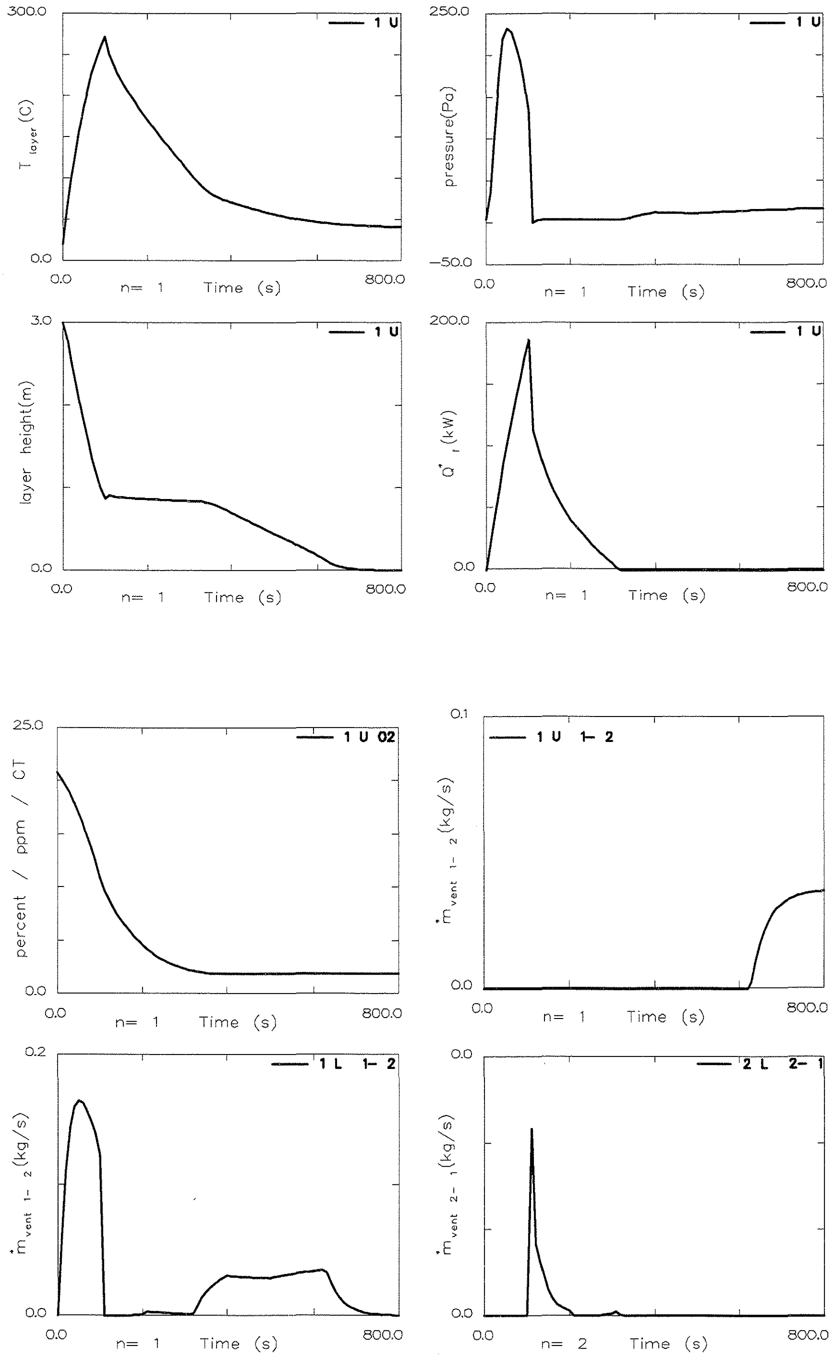
Hospital 16


300.0
1 U
T layer (C)
0.0
0.0
n= 1
Time (s)
400.0
100.0
pressure(Pa)
1 U
-400.0
0.0
n= 1
Time (s)
400.0
3.0
1 U
layer height(m)
0.0
0.0
n= 1
Time (s)
400.0
300.0
1 U
Q' f (kW)
0.0
0.0
n= 1
Time (s)
400.0
22.0
percent / ppm / CT
1 U O2
8.0
0.0
n= 1
Time (s)
400.0
0.2
1 U 1- 2
ṁ vent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
400.0
0.3
1 L 1- 2
ṁ vent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
400.0
1.0
2 L 2- 1
ṁ vent 2- 1 (kg/s)
0.0
0.0
n= 2
Time (s)
400.0

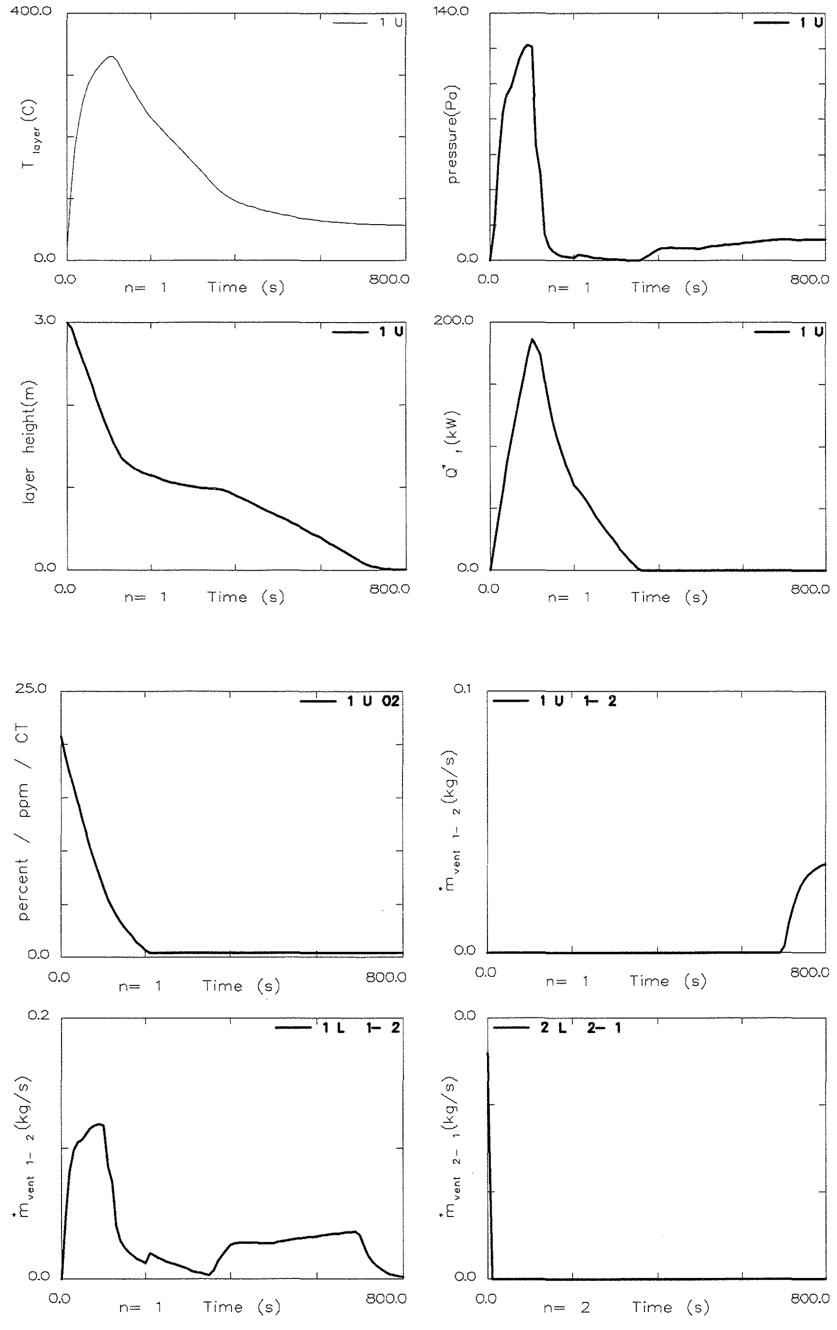
Hospital 17


400.0
0.0
T layer (C)
— 1 U
0.0
n= 1 Time (s)
600.0
60.0
−10.0
pressure(Pa)
— 1 U
0.0
n= 1 Time (s)
600.0
3.0
0.0
layer height(m)
— 1 U
0.0
n= 1 Time (s)
600.0
200.0
0.0
Q̇ f (kW)
— 1 U
0.0
n= 1 Time (s)
600.0
25.0
0.0
percent / ppm / CT
— 1 U 02
0.0
n= 1 Time (s)
600.0
1.0
−1.0
ṁ vent 1− 2 (kg/s)
— 1 U 1− 2
0.0
n= 1 Time (s)
600.0
0.2
0.0
ṁ vent 1− 2 (kg/s)
— 1 L 1− 2
0.0
n= 1 Time (s)
600.0
0.0
0.0
ṁ vent 2− 1 (kg/s)
— 2 L 2− 1
0.0
n= 2 Time (s)
600.0

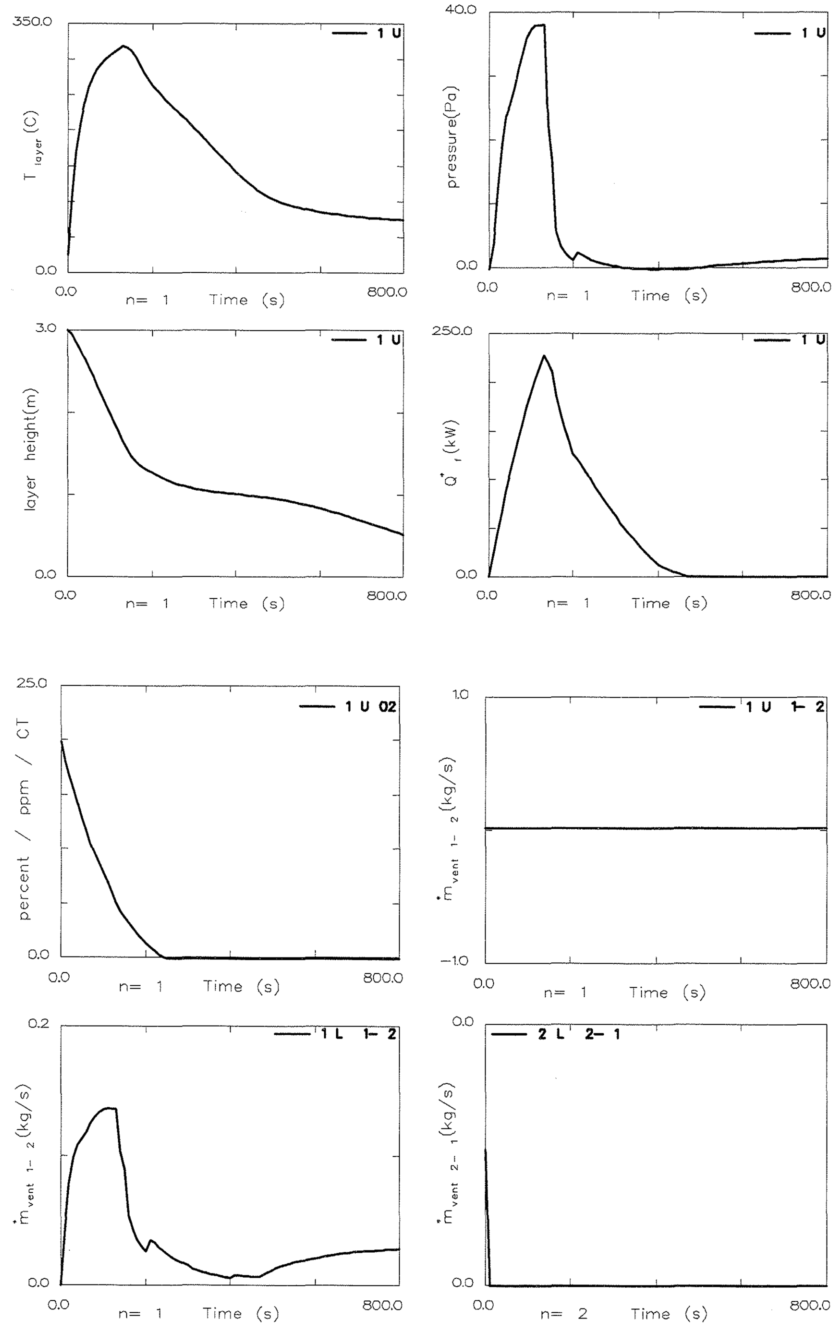
Office 18


300.0
1 U
T layer (C)
0.0
0.0
n= 1
Time (s)
800.0
250.0
1 U
pressure(Pa)
-50.0
0.0
n= 1
Time (s)
800.0
3.0
1 U
layer height(m)
0.0
0.0
n= 1
Time (s)
800.0
200.0
1 U
Q' 1 (kW)
0.0
0.0
n= 1
Time (s)
800.0
25.0
1 U 02
percent / ppm / CT
0.0
0.0
n= 1
Time (s)
800.0
0.1
1 U 1- 2
m vent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
800.0
0.2
1 L 1- 2
m vent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
800.0
0.0
2 L 2- 1
m vent 2- 1 (kg/s)
0.0
0.0
n= 2
Time (s)
800.0

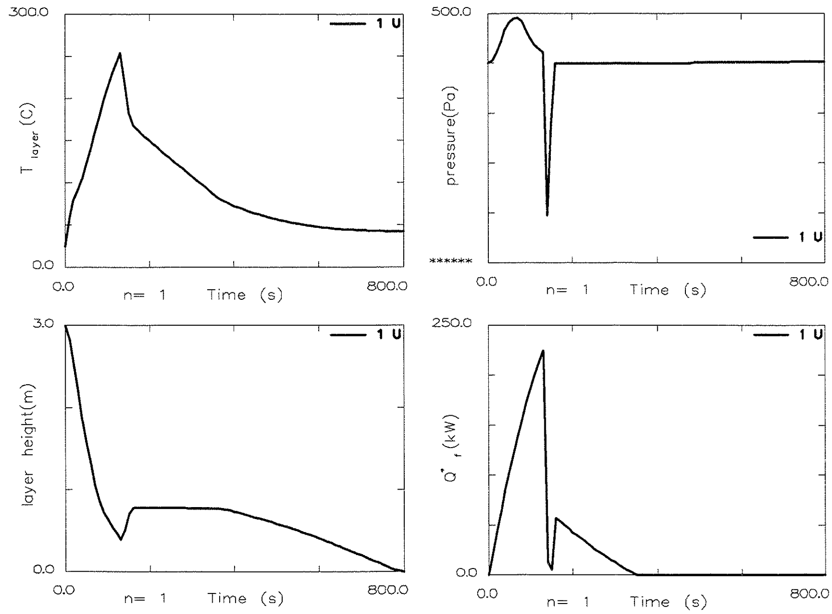
Office 19

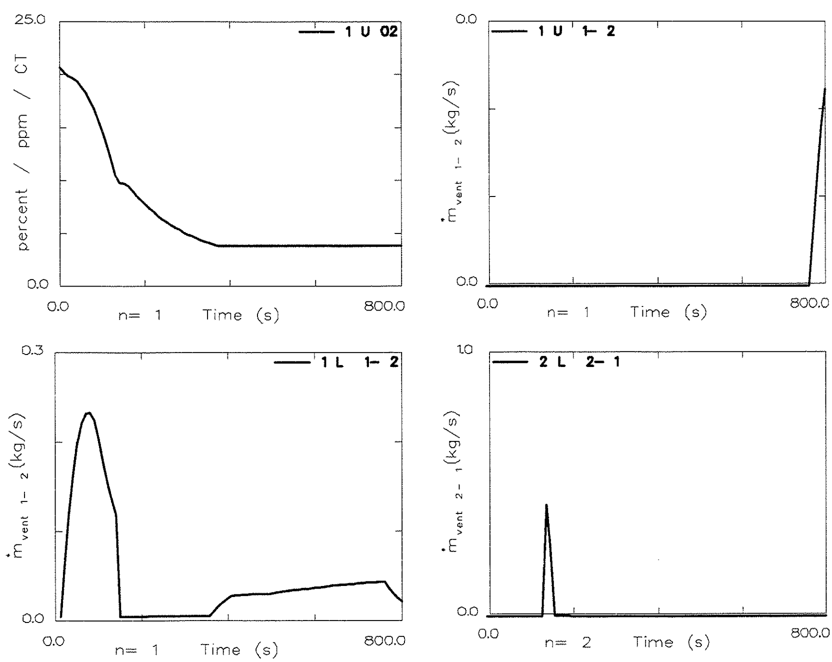

400.0
0.0
T layer (C)
1 U
0.0
n= 1
Time (s)
800.0
140.0
0.0
pressure(Pa)
1 U
0.0
n= 1
Time (s)
800.0
3.0
0.0
layer height(m)
1 U
0.0
n= 1
Time (s)
800.0
200.0
0.0
Q 1 (kW)
1 U
0.0
n= 1
Time (s)
800.0
25.0
0.0
percent / ppm / CT
1 U O2
0.0
n= 1
Time (s)
800.0
0.1
0.0
m vent 1- 2 (kg/s)
1 U 1- 2
0.0
n= 1
Time (s)
800.0
0.2
0.0
m vent 1- 2 (kg/s)
1 L 1- 2
0.0
n= 1
Time (s)
800.0
0.0
0.0
m vent 2- 1 (kg/s)
2 L 2- 1
0.0
n= 2
Time (s)
800.0

Office 20

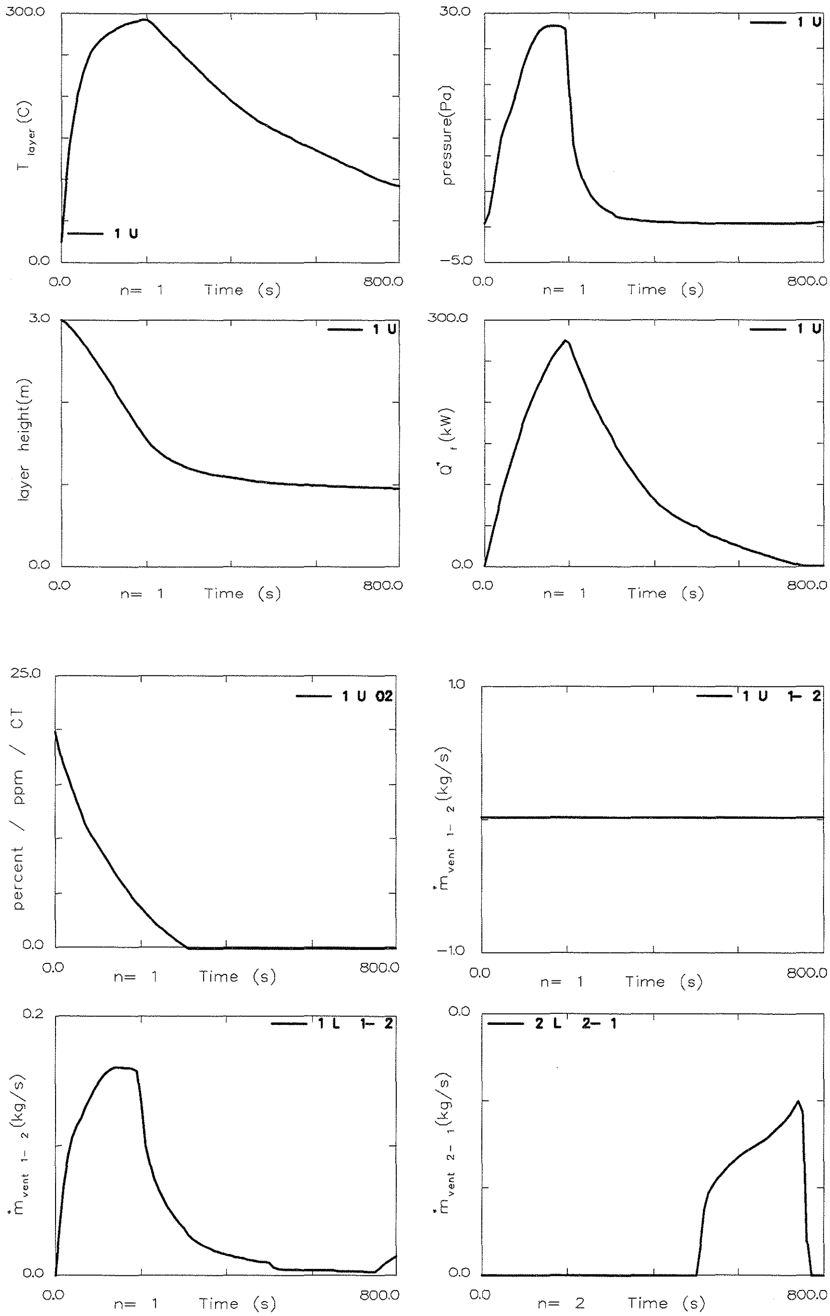

350.0
0.0
1 U
T layer (C)
0.0
n= 1
Time (s)
800.0
40.0
0.0
1 U
pressure(Pa)
n= 1
Time (s)
800.0
3.0
0.0
1 U
layer height(m)
n= 1
Time (s)
800.0
250.0
0.0
1 U
Q f (kW)
n= 1
Time (s)
800.0
25.0
0.0
1 U 02
percent / ppm / CT
n= 1
Time (s)
800.0
1.0
-1.0
1 U 1- 2
m vent 1- 2 (kg/s)
n= 1
Time (s)
800.0
0.2
0.0
1 L 1- 2
m vent 1- 2 (kg/s)
n= 1
Time (s)
800.0
0.0
2 L 2- 1
m vent 2- 1 (kg/s)
n= 2
Time (s)
800.0

Office 21

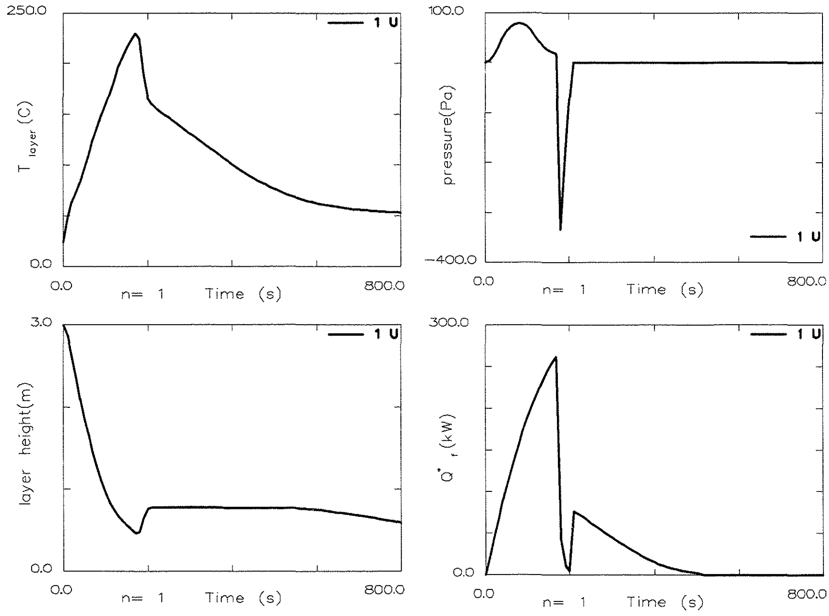

300.0
0.0
T layer (C)
1 U
0.0
n= 1 Time (s)
800.0
500.0
pressure(Pa)
******
1 U
0.0
n= 1 Time (s)
800.0
3.0
0.0
layer height(m)
1 U
0.0
n= 1 Time (s)
800.0
250.0
0.0
Q˙ f (kW)
1 U
0.0
n= 1 Time (s)
800.0


25.0
0.0
percent / ppm / CT
1 U O2
0.0
n= 1 Time (s)
800.0
0.0
0.0
ṁ vent 1- 2 (kg/s)
1 U 1- 2
0.0
n= 1 Time (s)
800.0
0.3
0.0
ṁ vent 1- 2 (kg/s)
1 L 1- 2
0.0
n= 1 Time (s)
800.0
1.0
0.0
ṁ vent 2- 1 (kg/s)
2 L 2- 1
0.0
n= 2 Time (s)
800.0

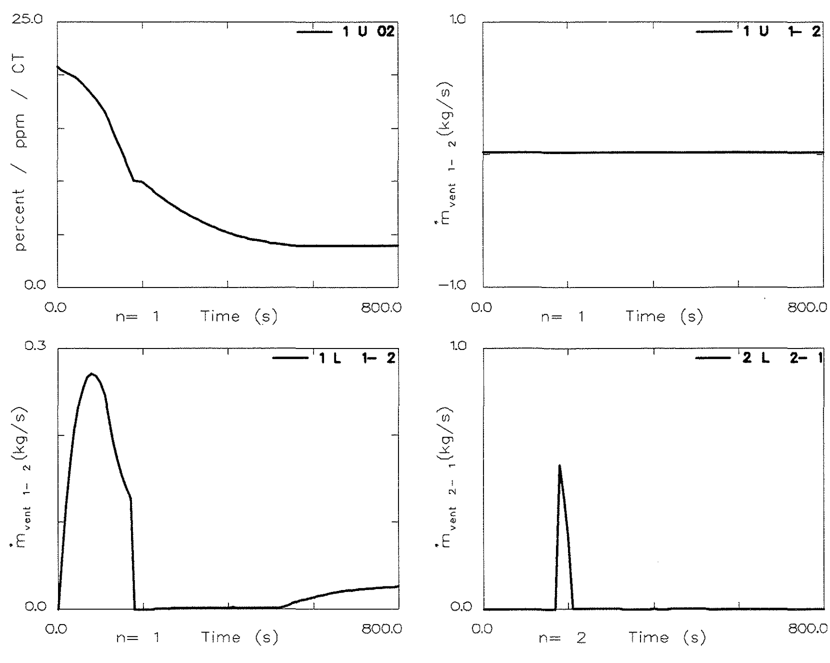
Office 22


T layer (C)
1 U
n= 1 Time (s)
pressure(Pa)
layer height(m)
Q' f (kW)
percent / ppm / CT
1 U 02
m vent 1- 2 (kg/s)
1 U 1- 2
1 L 1- 2
m vent 2- 1 (kg/s)
2 L 2- 1
n= 2 Time (s)

Office 23

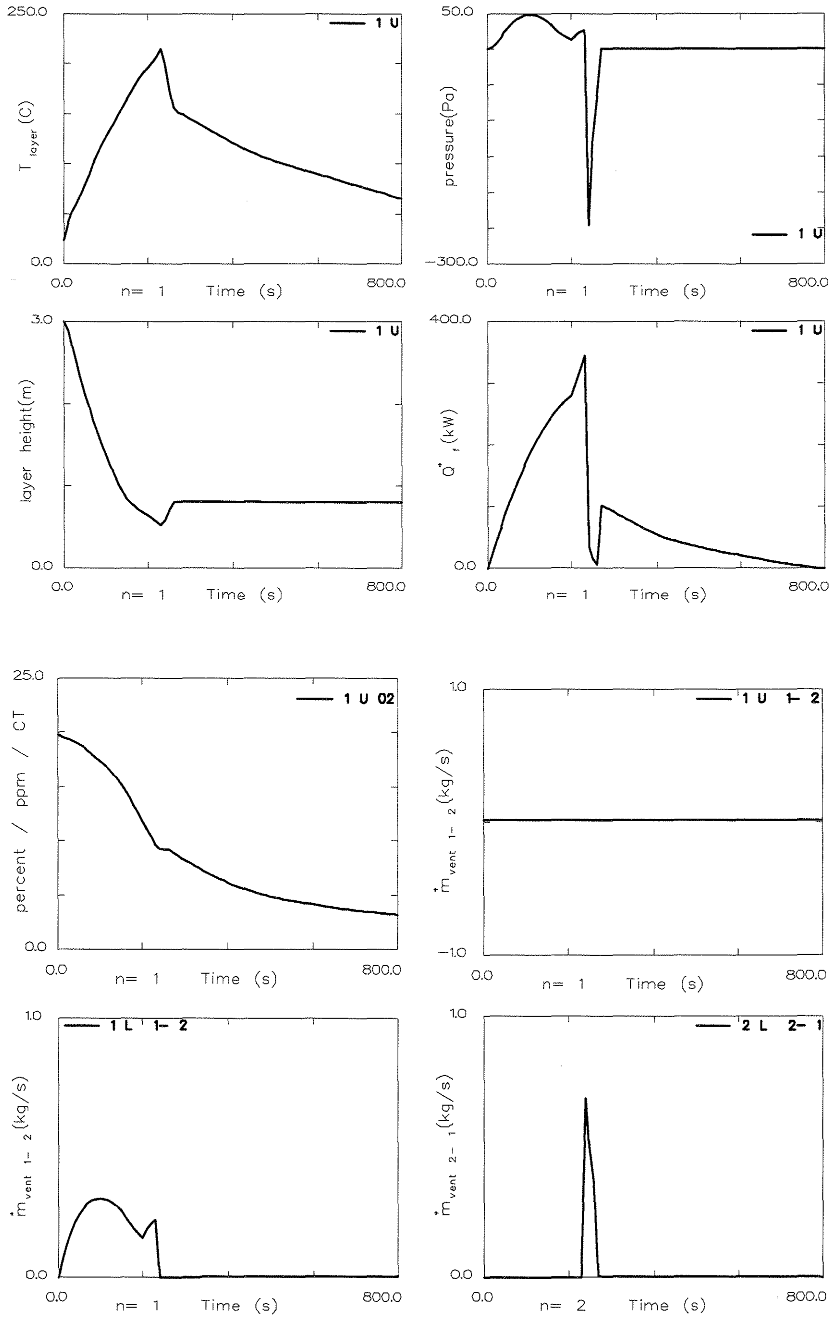


250.0
0.0
T layer (C)
1 U
0.0
n= 1 Time (s)
800.0
100.0
-400.0
pressure(Pa)
1 U
0.0
n= 1 Time (s)
800.0
3.0
0.0
layer height(m)
1 U
0.0
n= 1 Time (s)
800.0
300.0
0.0
Q f (kW)
1 U
0.0
n= 1 Time (s)
800.0



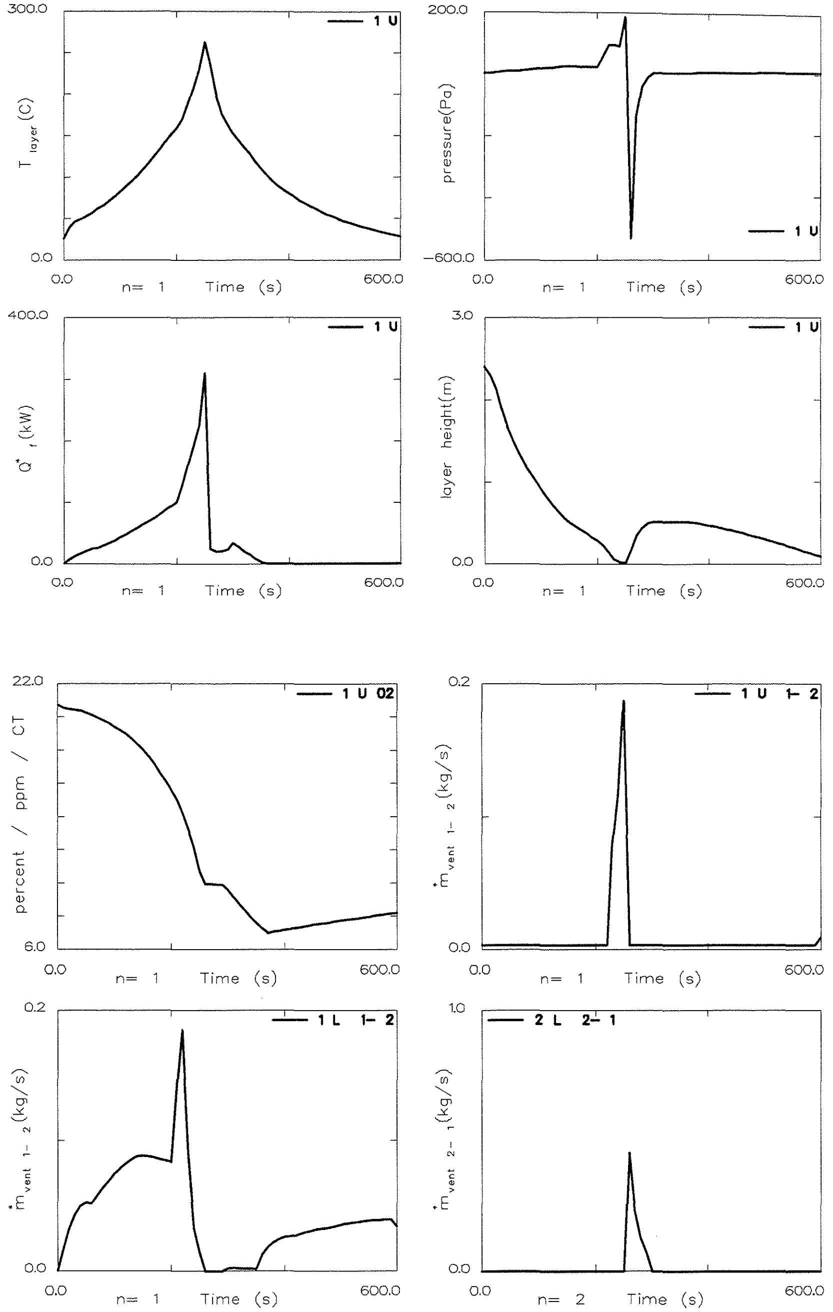
25.0
0.0
percent / ppm / CT
1 U O2
0.0
n= 1 Time (s)
800.0
1.0
-1.0
m vent 1- 2 (kg/s)
1 U 1- 2
0.0
n= 1 Time (s)
800.0
0.3
0.0
m vent 1- 2 (kg/s)
1 L 1- 2
0.0
n= 1 Time (s)
800.0
1.0
0.0
m vent 2- 1 (kg/s)
2 L 2- 1
0.0
n= 2 Time (s)
800.0

Office 24

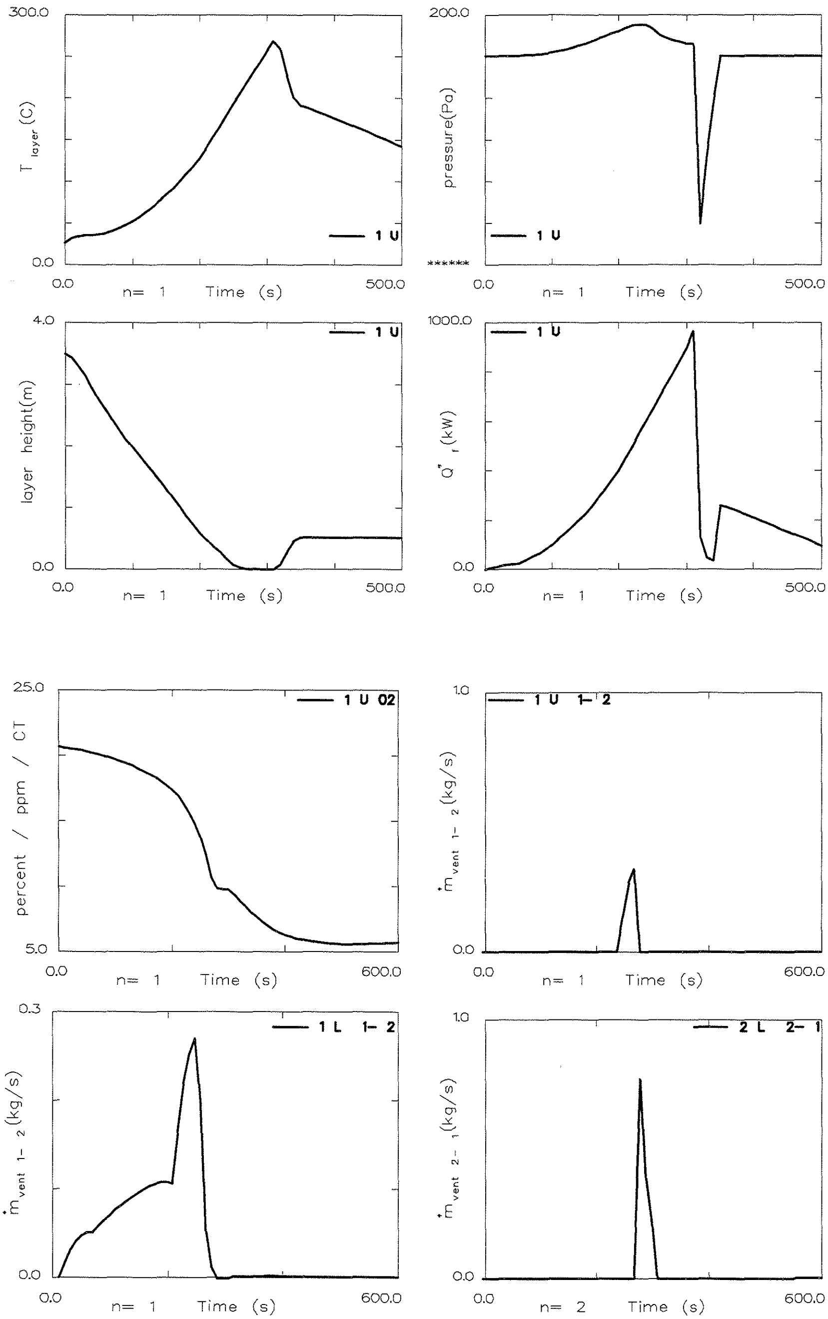


250.0
0.0
T layer (C)
1 U
n= 1 Time (s)
800.0
50.0
-300.0
pressure(Pa)
3.0
layer height(m)
400.0
Q̇ f (kW)
25.0
percent / ppm / CT
1 U 02
1.0
-1.0
ṁ vent 1- 2 (kg/s)
1 U 1- 2
1 L 1- 2
ṁ vent 2- 1 (kg/s)
2 L 2- 1
n= 2 Time (s)

Office 25

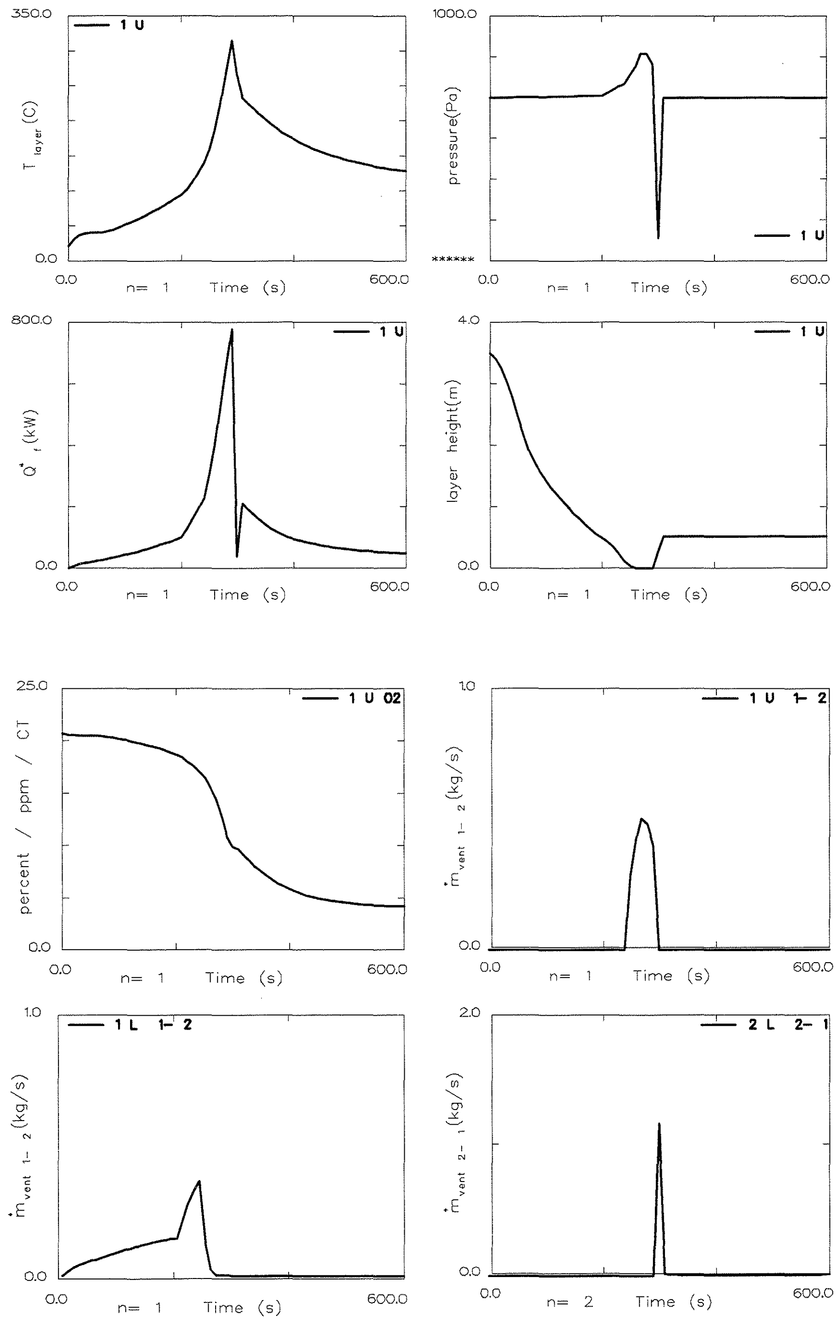

300.0
T layer (C)
0.0
0.0
n= 1
Time (s)
600.0
1 U
200.0
pressure(Pa)
-600.0
0.0
n= 1
Time (s)
600.0
1 U
400.0
Q f (kW)
0.0
0.0
n= 1
Time (s)
600.0
1 U
3.0
layer height(m)
0.0
0.0
n= 1
Time (s)
600.0
1 U
22.0
percent / ppm / CT
6.0
0.0
n= 1
Time (s)
600.0
1 U 02
0.2
m vent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
600.0
1 U 1- 2
0.2
m vent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
600.0
1 L 1- 2
1.0
m vent 2- 1 (kg/s)
0.0
0.0
n= 2
Time (s)
600.0
2 L 2- 1

Hotel 26

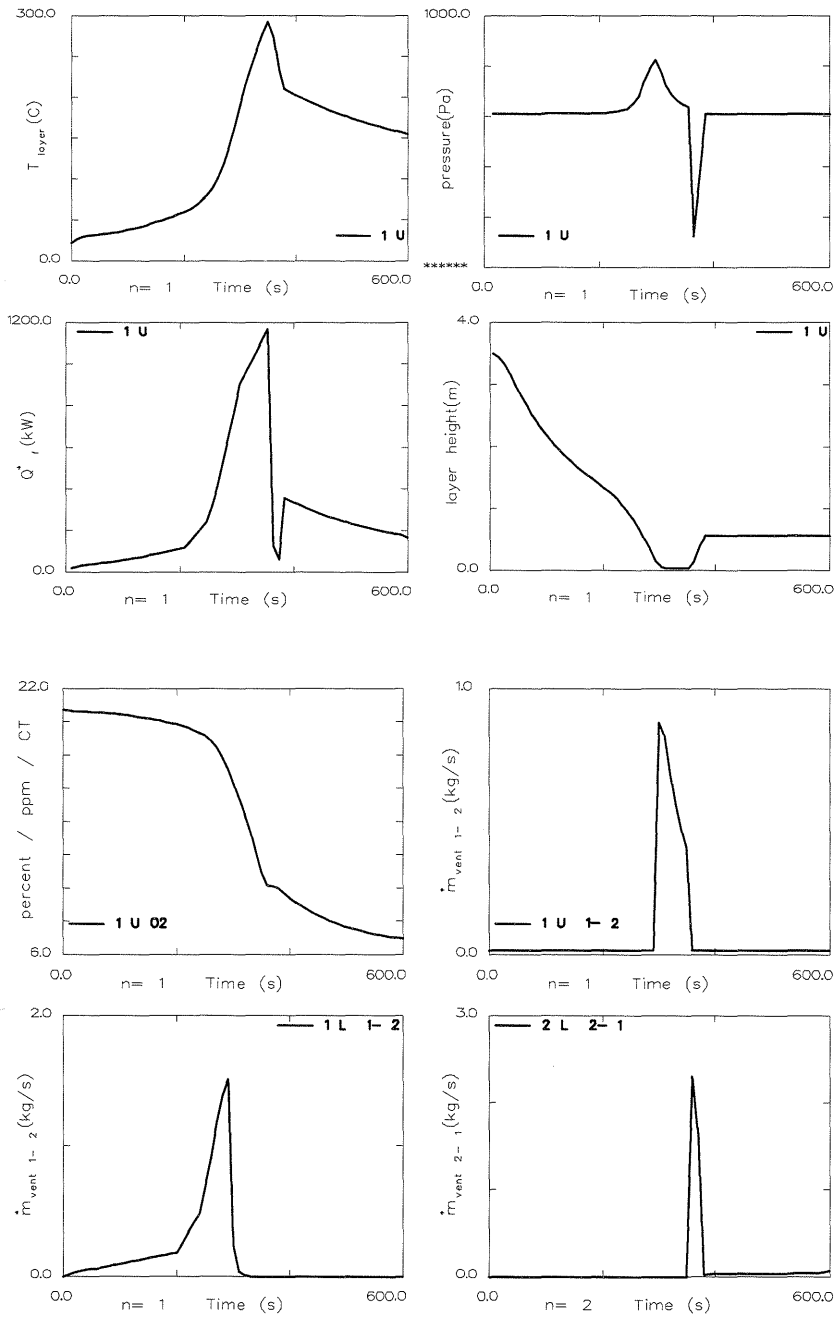


300.0
0.0
T layer (C)
1 U
n= 1
Time (s)
500.0
200.0
pressure(Pa)
4.0
layer height(m)
1000.0
Q̇ f (kW)
25.0
5.0
percent / ppm / CT
1 U O2
600.0
1.0
ṁ vent 1- 2 (kg/s)
1 U 1- 2
0.3
1 L 1- 2
ṁ vent 2- 1 (kg/s)
2 L 2- 1
n= 2

Hotel 27


350.0
1 U
T layer (C)
0.0
0.0
n= 1
Time (s)
600.0
1000.0
pressure(Pa)
1 U
******
0.0
n= 1
Time (s)
600.0
800.0
1 U
Q' f (kW)
0.0
0.0
n= 1
Time (s)
600.0
4.0
1 U
layer height(m)
0.0
0.0
n= 1
Time (s)
600.0
25.0
1 U 02
percent / ppm / CT
0.0
0.0
n= 1
Time (s)
600.0
1.0
1 U 1- 2
ṁvent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
600.0
1.0
1 L 1- 2
ṁvent 1- 2 (kg/s)
0.0
0.0
n= 1
Time (s)
600.0
2.0
2 L 2- 1
ṁvent 2- 1 (kg/s)
0.0
0.0
n= 2
Time (s)
600.0

Hotel 28


300.0
T layer (C)
0.0
— 1 U
0.0
n= 1
Time (s)
600.0
1000.0
pressure(Pa)
******
— 1 U
0.0
n= 1
Time (s)
600.0
1200.0
Q̇ , (kW)
— 1 U
0.0
n= 1
Time (s)
600.0
4.0
layer height(m)
— 1 U
0.0
n= 1
Time (s)
600.0
22.0
percent / ppm / CT
— 1 U O2
6.0
0.0
n= 1
Time (s)
600.0
1.0
ṁ vent 1- 2 (kg/s)
— 1 U 1- 2
0.0
n= 1
Time (s)
600.0
2.0
ṁ vent 1- 2 (kg/s)
— 1 L 1- 2
0.0
n= 1
Time (s)
600.0
3.0
ṁ vent 2- 1 (kg/s)
— 2 L 2- 1
0.0
n= 2
Time (s)
600.0

Hotel 29

ISSN 1103-4467
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