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SIMPLE CEILING JET CORRELATION DERIVED FROM NUMERICAL EXPERIMENTS

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ABSTRACT

Numerical experiments, constituting of 90 simulations in FDS, were used in this paper for two purposes. Firstly an evaluation of previously derived correlations for ceiling jet excess temperatures and velocities was performed. Secondly the numerical experiments were used to demonstrate how computer simulations could be used as a complement to actual fire experiments in fire science research.

The evaluation indicates that the existing correlations will give a good estimate of the average temperature in a ceiling jet. However, it seams like the correlations will not give a good estimate of the maximum excess temperature or velocity. Consequently, a new correlation to estimate the maximum temperature was developed. The novelty of this research is primarily the method that includes an outline of how numerical experiments can be used in fire science research.

INTRODUCTION

Correlations to estimate temperatures and velocities in the hot gases beneath a ceiling in a fire, a so-called ceiling jet, have existed for at least four decades[1]. These types of correlations are often used in fire safety engineering in order to get an estimate of sprinkler and/or heat detector activation in enclosure fires [2]. Such correlations can also be used to estimate damage if a ceiling material will ignite or if structures will be affected. A ceiling jet is created when a buoyancy driven plume impinges on a flat un-obstructed ceiling and the hot gases spreads radially under the ceiling. As the ceiling jet moves radially from the outward air will be entrained and the temperature cools down due to entrainment of cold air and heat losses to the ceiling[2] [3]. If the ceiling jet is unconfined it will have a maximum thickness of about 5-13% of the total room height and the maximum temperature will be at a distance of 1% of the room height below the ceiling[3]. The thickness of the ceiling jet has been defined as the distance to where the excess of gas temperature drops to 1/e of (1/2.72) the maximum excess temperature[4]. In a normal compartment fire this type of unconfined ceiling jet will only exist in the earliest stages of fire development before the hot gases will accumulate in the compartment[2]. Alpert[1] presented ground-breaking correlations for flow velocities and excess temperatures for steady and unconfined celling jets, which are widely used because of its easy use. The correlations have also been implemented in computer software, like DETACT-QS [5] and CFAST [6], and used as a part of the traveling fires concept [7]. Presently, there are a range of ceiling jet correlations available for different applications, e.g. for transient fires and confined ceilings [2].

Alpert assumed an axisymmetric fire induced flow beneath a flat, horizontal ceiling that was unobstructed by walls [1] and the ceiling jet was divided into two regions. Thus were two sets of correlations, for the maximum excess temperature ($T_g - T_a$) and maximum velocity (u_{max}), presented; the first one is valid in the turning region where the plume impinges the ceiling (r/H<0.18 for equation 1 and r/H<0.15 for equation 2) and is independent of the radial distance of the plume.

$$T_g - T_a = 16.9\frac{\dot{Q}^{2/3}}{H^{5/3}} \qquad [1]$$

$$u_{max} = 0.947\left(\frac{\dot{Q}}{H}\right)^{1/3} \quad [2]$$

The second set of correlations is valid in the far field (r/H>0.18 for equation 3 and r/H>0.15 for equation 4) and is dependent on the radial distance from the plume centreline.

$$T_g - T_a = 5.38\frac{\dot{Q}^{2/3}/H^{5/3}}{(r/H)^{2/3}} \quad [3]$$

$$u_{max} = 0.197\frac{(\dot{Q}/H)^{1/3}}{(r/H)^{5/6}} \quad [4]$$

Where H is the ceiling height, r is the radial distance from the plume centreline and $\dot{Q}$ is the heat release rate of the fire. These original correlations where found with the help of qualitative curve fit of experimental data. A range of different types of fuels was used in the experiments but no regard was taken to the size of the convective part of the heat release rate, which later has been showed to control the properties of fire plumes [8]. Alpert also conducted a numerical study of ceiling jets [4]. It was, among other things, studied how heat transfer to the ceiling affects the ceiling jet and it was seen that there was no large effect on the ceiling jet temperature and thickness within a radial distance of less than 1 ceiling height (r/H<1). However, at distances of 3 to 5 ceiling heights, the effects were significant.

The correlations for the far field have been modified lately[9] by introducing the virtual origin concept and the actual heat release rate ($\dot{Q}$) has been substituted with the convective heat release rate ($\dot{Q}_c$).

$$T_g - T_a = 6.72\frac{\dot{Q}_c{}^{2/3}}{(z_H - Z_v)^{5/3}}\left(\frac{r}{z_H - Z_v}\right)^{-0.65} \quad [5]$$

$$u_{max} = 0.25\frac{\dot{Q}_c{}^{1/3}}{(z_H - Z_v)^{1/3}}\left(\frac{r}{z_H - Z_v}\right)^{-1.07} \quad [6]$$

Where z_v is the virtual origin and $z_H$is the ceiling height. The updated correlations show a good fit to the experimental data and a high coefficient of determination. The theoretical background is well founded but the experimental data that the original and updated correlations are based on are considered limited and the fact that the heat transfer to the ceiling is ignored makes it desirable to study the validity of these correlations further with more data.

Fire experiments in real scale are very costly and with very large experimental setups it will be very hard to control all important parameters, such as air movement due to weather conditions outside the laboratory or due to a HVAC system that could affect the experiment. An alternative could be reduced scale experiments, where different parameters can possible be control better. However, it is not possible to comply the scaling laws for all the mechanisms of importance in fire science that might introduce faults. There are of course also uncertainties in measurements. When it comes to measuring gas temperatures in a ceiling jet it is commonly done with bare bead thermocouples and these can be associated with significant systematic errors[10]. It was for example found by Pitts et al [10] that the absolute thermocouple measurements error due to radiation could be as high as 75% in the cold layer and about 7% in the hot layer. The relative expanded uncertainty associated with measured ceiling jet temperatures was, among other things, studied by NUREG[11] for two specific experimental tests and it was found to be in the range 4-12%. Another issue is that the measurement equipment it self might affect the experiment, e.g. the hot gases might be affected by a large number of bi-directional probes used to measure the hydrodynamic pressure.

An alternative or complement to laboratory experiments can be numerical experiments. The term numerical experiment has previously been used in fire science research [12,13] but it is not well defined. However, the fundamental research procedure is consistent with actual experiments, i.e. the experiment is conducted in a systematic manor to study how the system responds to a strategic manipulation in order to answer a specific question[14]. Even though the term numerical experiment is seldom used in fire science, computer-aided numerical models have been used for a relatively long time in the fire research field, e.g. Magnusson and Thelandersson [15] used numerical models along with actual fire experiments.

There are of course both advantages and disadvantages with using numerical experiments. The main advantage is the possibility to gather a large amount of empirical data due to the low cost of doing numerical experiments compared to actual experiments. The obvious disadvantages of the numerical experiments are the limitations in the numerical model, because it can partly be based on assumptions and empirical relations, and this can of course introduce errors and uncertainties in the results. Therefore, it is of great importance that the model used is validated to a satisfying extent for the intended use. Also, it is necessary that the researcher knows how the model works, its limitations and most importantly that the researcher has an understanding of the relevant fire science theories and physics implemented in the model.

Numerical experiments with the CFD model FDS6[16] is performed in this paper in order to ceiling jets and the ceiling jet correlations further. FDS have been validated[17] for different types of ceiling jet applications, e.g. the sprinkler activation experiments performed by Vettori[18] and in a study of two different experiments it was found that predictions of ceiling jet temperatures with FDS fell within the experimental uncertainty of the experiment[19]. The Alpert ceiling jet correlation is based on a simple plume correlation, while FDS determines the temperature and velocity of fire plumes and ceiling jets using a large eddy simulation technique. This means that FDS has no explicit ceiling jet model; consequently, temperatures are computed directly from the governing conservation equations[16].

OBJECTIVE

This paper holds two objectives. The first objective is to see how well the existing ceiling jet correlations for the far field presented by Alpert, fits to some to data from the numerical experiments. The second objective is to develop an alternative correlation for ceiling jet temperatures based on a simplified theory and numerical experiments. The primary goal of the second objective is to further illustrate the practical use of numerical experiments.

SIMPLIFIED CEILING JET THEORY

In this simplified theory the ceiling jet is considered to be a homogenous layer of gases that spreads radial under the ceiling from the plume centreline. Assuming that there are no heat losses due to radiation or convection from the ceiling jet the energy flow rate in the gases can be expressed as:

$$\dot{Q} = \dot{m}_r \cdot c_p \cdot T_g - T_a \qquad [5]$$

Where $\dot{Q}$ is the heat release from the fire, $\dot{m}_r$ is the mass flow at a distance r from the plume centreline, c_p is the specific heat and $T_g - T_a$ is the difference between the gas temperature and the ambient temperature. The mass flow, $\dot{m}_r$ is dependent on a range of temperature dependent parameters. To avoid using these parameters the mass flow is assumed to be proportional to the plume mass flow $\dot{m}_p$ and the relative distance from the plume. There is a range of expressions available for calculating plume mass flows[3]. Here the ideal plume equation[3] is used to find the plume mass flow ($\dot{m}_p$) and the plume radius (b) as it hits the ceiling,

$$\dot{m}_p = 0.20 \left(\frac{\rho_a \cdot g}{c_p \cdot T_a}\right)^{1/3} \cdot z^{5/3} \cdot \dot{Q}^{1/3} \qquad [7]$$

$$b = \frac{6}{5} \cdot \alpha \cdot z \qquad [8]$$

Where z is the height over the fuel and α is a constant that equals 0.15 [3]. The excess temperature in the ceiling jet can be expressed as in equation 9 with the help of equation 7 and 8 and the assumption that $\dot{m}_r$ is equal to $\dot{m}_p$, the relative distance from the plume (r/b) and the constants k and n. The expression $k.(r/b)^n$ in equation 9 expresses the entrainment into the ceiling jet. If entrainment would not occur it would cause the ceiling jet thickness to decrease with increasing distance to the plume centreline, which is not the case.

$$T_g - T_a = \frac{\dot{Q}}{\dot{m}_p \cdot k \cdot (r/b)^n \cdot c_p} \qquad [9]$$

METHOD

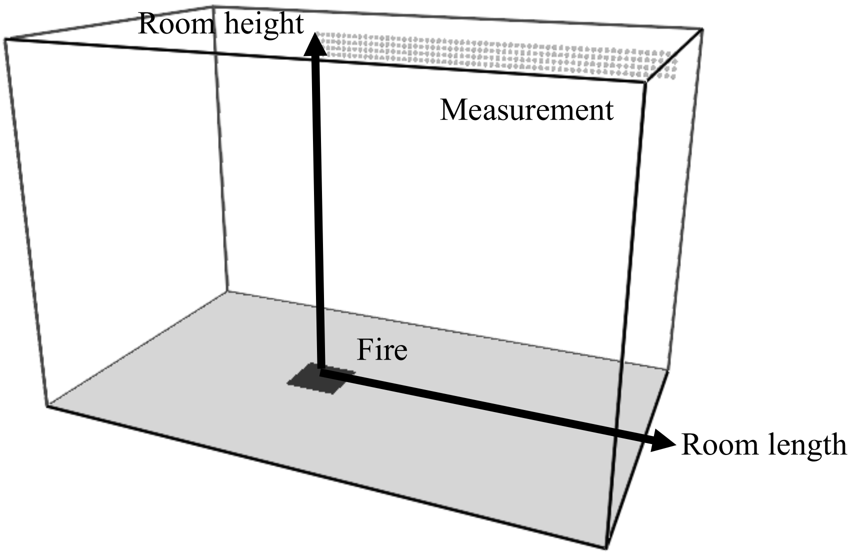
The method of this paper consists of two steps. In the first step computer simulations are performed as numerical experiments and it is compared to the predictions of equation 3 and 4. In the second step the numerical experiment is used to find the constant n in equation 9.

Numerical experiments

A total of 90 numerical experiments have been carried out in order to gather data. The numerical experiments were performed with the CFD model FDS6 RC3 (SVN 14299) [16]. The heat release rate, room height and ceiling surface properties were varied in the numerical experiments.

The heat release per unit area was kept constant to 2000 kW/m^2 but the fuel area varied which created 12 different constant heat release rates ranging from 250 to 18000 kW. The radiation fraction was kept constant at 0.35 in all the simulations. Seven different room heights ranging from 3 to 18 m were also used. The unobstructed and unconfined ceiling surface was either inert (a non-reacting solid boundary whose temperature is constantly fixed at initial ambient temperature[16]) or adiabatic (a non-reacting solid boundary with a calculated wall temperature so that the sum of the net convective and radiative heat flux is zero[16]) to illustrate effect of extreme values of heat losses to the ceiling on the proprieties of the ceiling jet. The domain extended from the fire source as far as the height to the ceiling in the positive x-direction and half of the height to the ceiling in the positive and negative y-direction. In the negative x-direction the domain extended four times the side of the burner (see Figure 1). Spacing of heat detectors and sprinkler bulbs are generally not greater than 6 m and that makes this domain reasonable. All vertical sides of the domain were modelled as open to the surroundings.

Figure 1: A typical layout of the domain used in one of the numerical experiments.



In each experiment D*/dx = 16 was used as a criteria in order to determine a grid size that would resolve the relevant phenomena to an acceptable degree. This criterion has been used in previous studies as it is considered to give good results at a moderate computational cost [19]. Since only one mesh was used to ensure computational robustness, simulations with more than 4 million cells were excluded, which resulted in the 90 simulations. In the simulations the mean flame height (L_f), estimated with the Heskestad mean flame height correlation[8], ranged from 30 to 99% of the ceiling height.

A mean value during 20 seconds, after the gas flow had stabilized, of the temperatures and horizontal velocities in the four cells just below the ceiling in the positive x-direction was used as output. These four cells cover about 3 to 9% of the total ceiling height depending on the cell size in each simulation. The data was compared with the predictions made using equation 3 and 4.

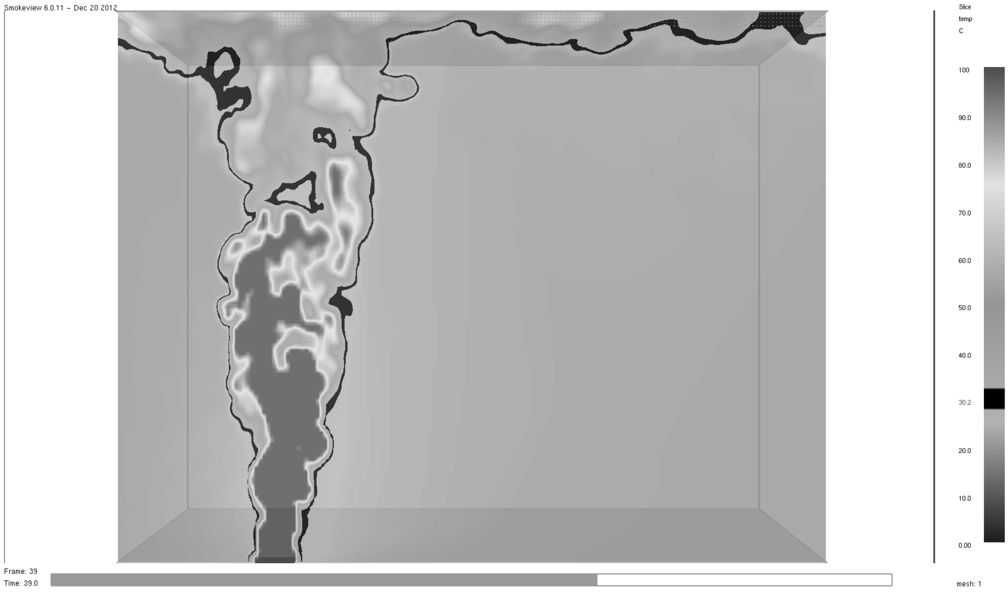
Simple ceiling jet correlation

In the second step a regression analysis was performed in order to find a fit of equation 9 to the empirical data from the numerical experiments.

RESULTS

A total of 90 simulations were performed in FDS and an example of the flow field of the fire, plume and ceiling jet in one of the simulations are presented in Figure 2.

Figure 2: Flow field of the fire, plume and ceiling jet in one of the FDS simulations.



Different properties of ceiling

Two different properties of ceiling were used, inert or adiabatic, in the numerical experiments. The predicted temperature is presented in order to compare these two boundary conditions.

Figure 3: Comparison of excess temperature in FDS of inert and adiabatic ceiling at first (left figure) and second (right figure) cell from the ceiling.

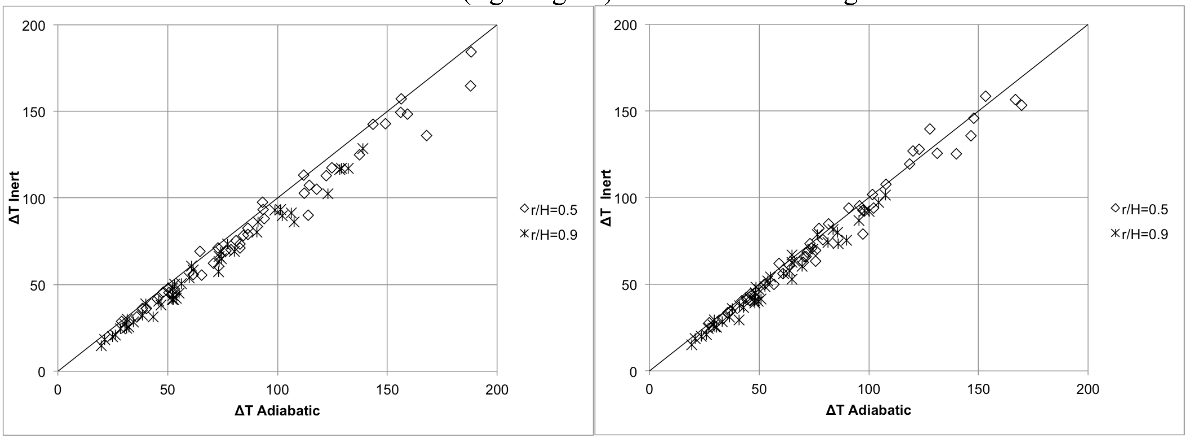
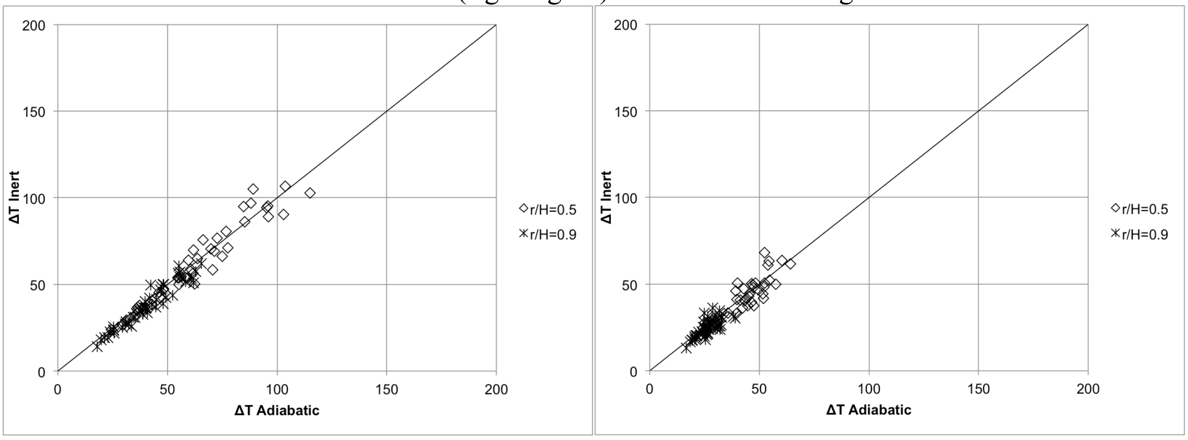


Figure 4: Comparison of excess temperature in FDS of inert and adiabatic ceiling at third (left figure) and fourth (right figure) cell from the ceiling.

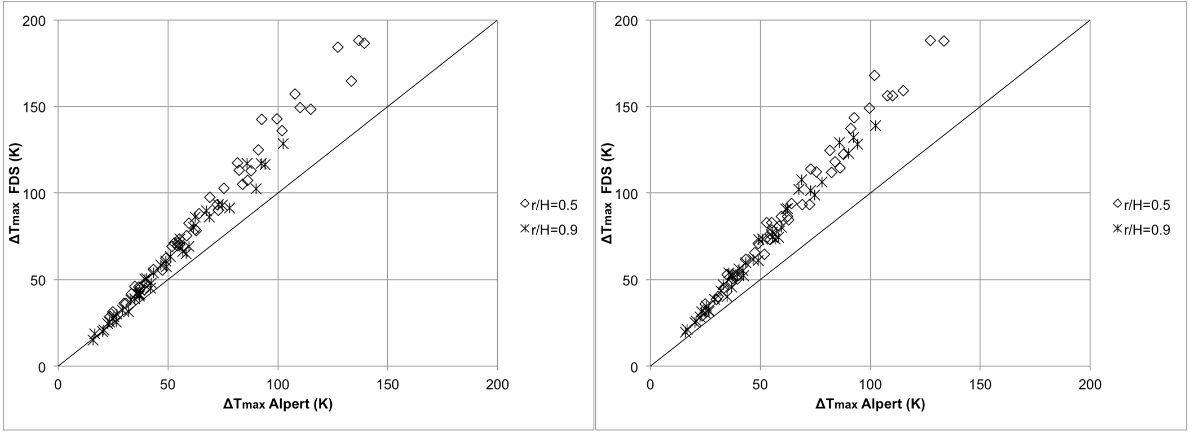


In Figure 3 and Figure 4 it can be seen that the temperature difference in the adiabatic case will be somewhat higher (10-15%) in the cell closest to the ceiling, but in the cells further below the ceiling there was an ineligible difference.

Temperature

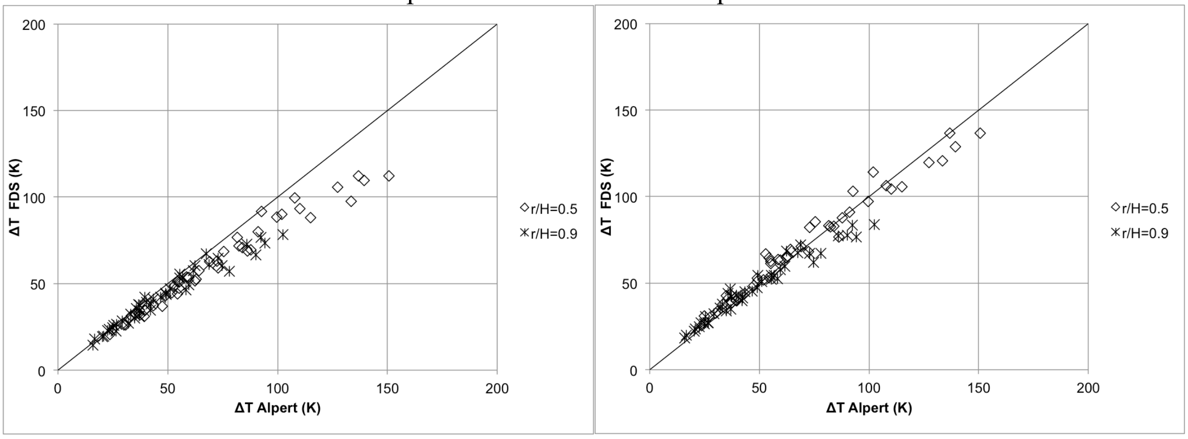
A comparison of the temperature calculated with equation 3 and the maximum and average temperature in FDS is done at two distances (r/H=0.5 and 0.9) from the plume centreline. The average temperature is derived as the mean of the temperature in the four cells just below the ceiling. The temperature gradient in the ceiling jet is also studied.

Figure 5: Maximum excess temperature in FDS in the inert (left) and adiabatic (right) case compared to excess temperature calculated with equation 3.



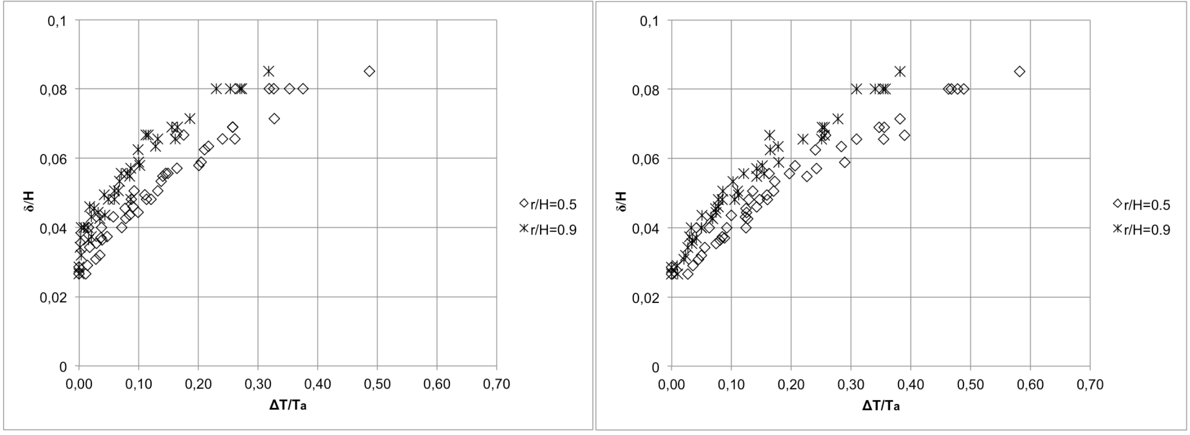
The maximum temperature in FDS is roughly 30-50% higher than predicted with equation 3. The difference is a bit less for the inert case. The maximum temperature was almost always located in the cell closest to the ceiling. This is regarded reasonable in regard to previous research on the location of the maximum temperature [2] because the cell closest to the ceiling covers 1-2%, depending on simulation, of the ceiling height.

Figure 6: Average temperature in FDS in the inert (left) and adiabatic (right) case compared to gas temperature calculated with equation 3.



Equation 3 gives a reasonable estimate of the average temperature below the ceiling in FDS. There is a noticeable better agreement in the case were adiabatic surface is used in FDS. In the inert case it is clear that the difference is larger closer to the plume and that the difference increases with hotter gases. This is expected since the heat exchange is proportional to the temperature difference.

Figure 7: Temperature gradient between cell 1 and 4 in the ceiling in FDS in the inert (left) and adiabatic (right) case.

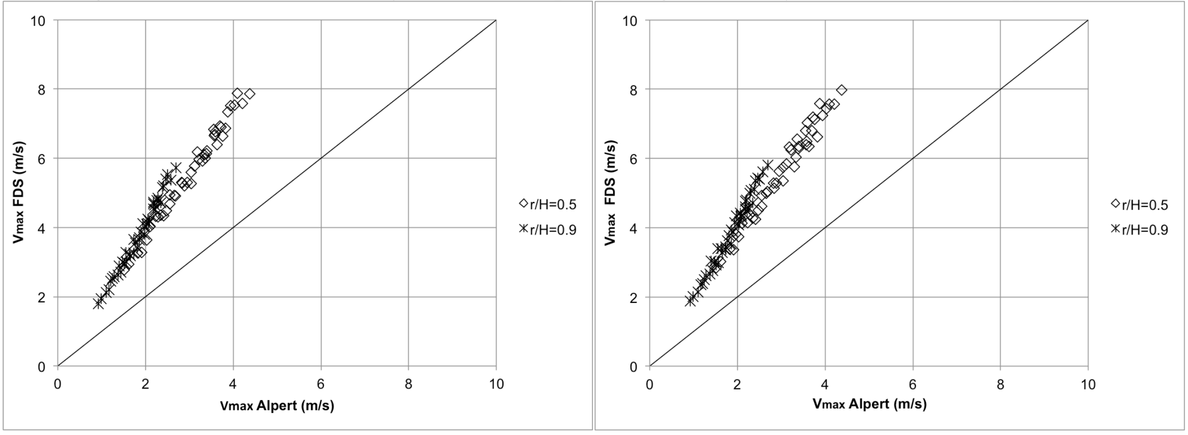


In Figure 7 the temperature gradient is expressed as a dimensionless number of the temperature difference between the cell closest to the ceiling and the fourth cell from the ceiling is plotted against the distance between these two cells divided by the total height of the ceiling. In Figure 7 it is clear that the temperature gradient increases with increasing distance to the ceiling. The shape of the increase resembles a Gaussian profile.

Velocity

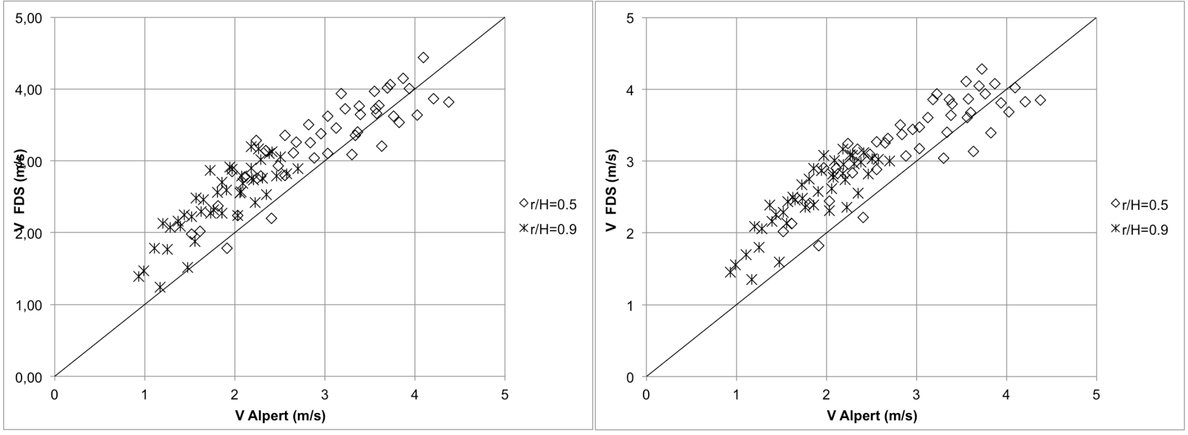
A comparison of the velocity calculated with equation 4 and the maximum and average velocity in FDS is done at two distances (r/H=0.5 and 0.9) from the plume centreline. The average velocity is derived as the mean of the velocity in the four cells just below the ceiling. The velocity gradient in the ceiling jet is also studied.

Figure 8: Maximum velocity in FDS compared to gas velocity calculated with equation 4.



The maximum velocity in FDS is roughly 70-80% higher than predicted with equation 4. There is a negligible difference between the inert and adiabatic case.

Figure 9: Average gas velocity in FDS in the inert (left) and adiabatic (right) case compared to gas velocity calculated with equation 4.



Close to the plume there is a reasonable correspondence of the gas velocities. However, further way from the plume the average gas velocity was calculated with FDS roughly 10-25% higher than predicted with equation 4.

Simple correlation for maximum temperature

The numerical experiments have been used in order to find the constants *n* and *k* in equation 9 that was derived from a simplified theory. The constants have been estimated with the help of a regression analysis of the inert case in the numerical experiments. Equation 9 can be rewritten as:

$$T_g - T_a = 1.6\frac{\dot{Q}}{\dot{m}_p\cdot(r/b)^{0.72}\cdot c_p} \qquad [9b]^1$$

Equation 8 can be incorporated in equation 9b, yielding in the following:

$$T_g - T_a = 0.47\frac{\dot{Q}}{\dot{m}_p\cdot(r/H)^{0.72}\cdot c_p} \qquad [9c]^1$$

Equation 9b are compared to the FDS data and equation 4 for to different cases in Figure 10.

Figure 10: Calculated maximum temperature in FDS in the inert case in simulation 2 (left) and simulation 43 (right) compared to calculated temperatures with equation 4 and 9b.

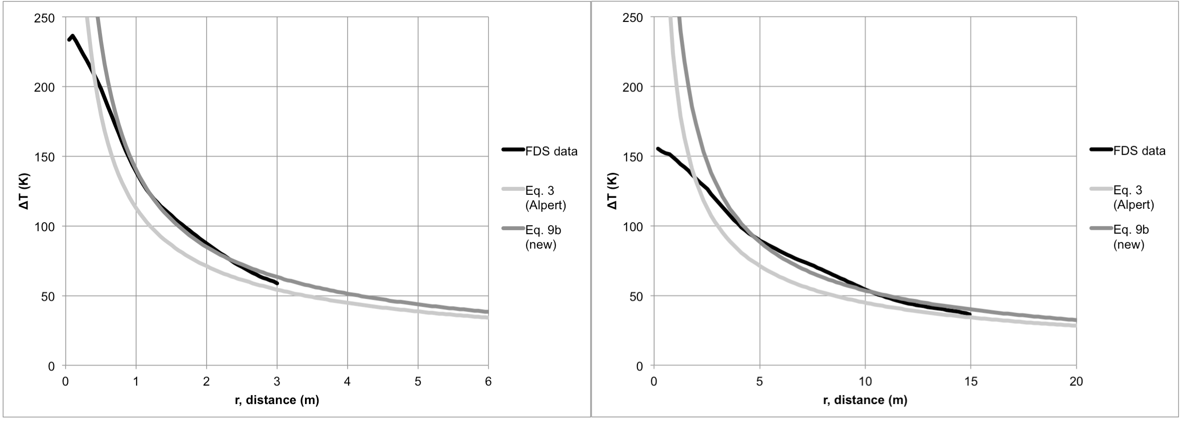


Figure 10 shows a good agreement between the maximum temperatures from the numerical

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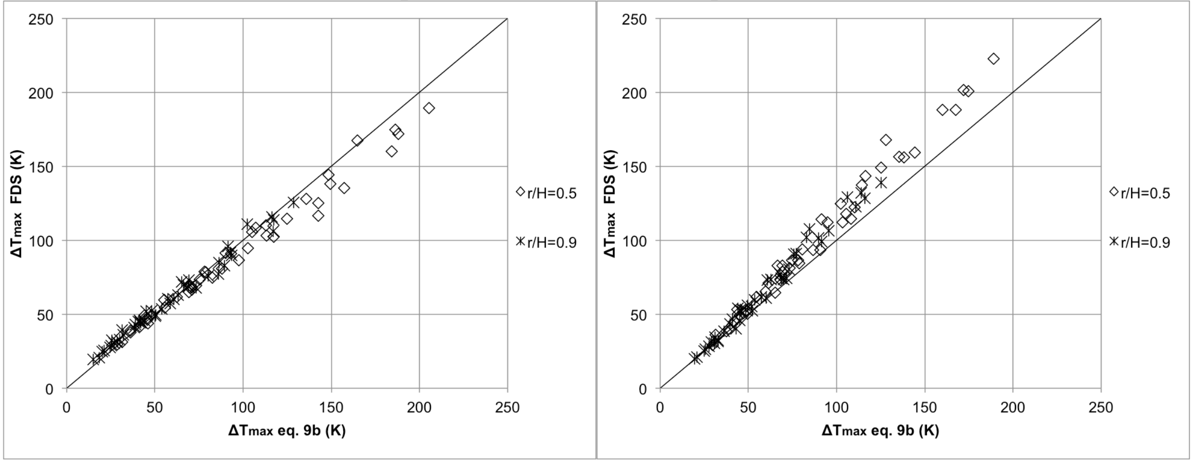
[1] Equation revised in this manuscript due to misprint in original.

experiments and equation 9b in the range where heat-sensing devices usually are placed.

Figure 11: Maximum temperature in FDS in the inert (left) and adiabatic (right) case compared to gas temperature calculated with equation 9b.



Equation 9b will gave a slightly lower estimate of the temperature in the adiabatic case and a higher estimate in the inert case (see Figure 11). This is considered reasonable since no account is taken for the ceiling material in the correlation.

DISCUSSION

The equations presented by Alpert are applicable for the unconfined ceiling jet produced by a weak fire and this is the situation that can be expected in the early stages of a compartment fire and within the time frame of when heat sensing devices are supposed to activate. The results from the numerical experiments indicate that the equation 3 will give a good estimate of the average temperature of a ceiling jet. The average radial velocity of the gases will be somewhat underestimated with the original correlation for gas velocities (equation 4). However, it has been seen in the numerical experiments that the correlations will not give a good estimate of the maximum temperature and velocity. The results from the simulations in FDS are approximately 30-50% and 70-80% higher for the temperature and velocity respectively. Previous validation exercises of FDS5 have shown that FDS might overestimate the temperature somewhat, but just in the order of 10-15% and indications from work done with FDS 6 shows both under- and overestimation.

In all simulations, included in the numerical experiments, the heat release rate per unit area was kept constant to 2000 kW/m^2, as well as the radiative fraction (0.35) and soot yield. These are properties that might affect the generalizability of the results. However the values have been chosen in regard to what can be expected in a compartment fire.

The temperature gradient in the ceiling jet was studied with the numerical experiments. It can be seen from Figure 7 that the temperature will decrease with an increasing distance from the ceiling and that the decrease seams to follow a Gaussian profile. This confirms the current understanding[3].

A simple model to estimate the maximum temperature was developed with the help of a heat balance and data form the numerical experiments. The model is based on the ideal plume model, since the assumptions associated with the ideal plume are considered to be acceptable when studying ceiling jets and especially for high room heights. No attempt has been made to use the virtual origin concept or to only use the convective part of the heat release. The new model will overestimate the temperature close to the fire plume but will give a very good estimate of the maximum temperature predicted with FDS6 in the area where heat-sensing devices usually are placed. No account is taken to heat transfer to the ceiling in the new model, since it does not seam to have any large affected on the ceiling jet near the plume (r/H<1).

The novelty of this research is not primarily the derived correlation, but the method that includes an outline of how numerical experiments can be used in fire science research. Ceiling jets have been studied with CFD models before but to the knowledge of the authors, not in the sense of developing simple correlations for engineering purposes. In order to further validate the derived correlation it would be desirable to use actual experimental data.

There are both advantages and disadvantages with this type of numerical experiment approach. The obvious disadvantages of the numerical experiments are the limitations in the numerical model, because it can partly be based on assumptions and empirical relations, and this can of course introduce errors and uncertainties in the results. Therefore, it is of great importance that the model used is validated to a satisfying extent for the intended use. Also, it is necessary that the researcher knows how the model works, its limitations and most importantly that the researcher has an understanding of the relevant fire science theories and physics. The advantages include the possibility to gather a large amount of data to a low cost compared to actual experiments and to easily be able to re-run tests, which is forgiving in regard to errors that may be included in the original experimental design. Another advantage is the possibility to control all the important variables in order to find some causal relationship. In an actual real-scale experiment the results can be very sensitive to weather conditions and material properties might not be correctly defined. Measuring equipment in a real-scale fire might also interfere with the experiment; an example could be measurements with a large number of bi-directional probes of the gas flow from a weak fire.

There is no experimental method that can be recommended for use for all types of research tasks in fire science. A combination of methods can be both efficient and good and numerical experiments are considered to play a more important roll in fire science in the future.

CONCLUSION

Numerical experiments, which included 90 different simulations in FDS, were used in this paper to study ceiling jets under an unconfined and unobstructed ceiling. They were compared to the correlations presented by Alpert in 1972. The results from the numerical experiments indicate that the correlations will give a good estimate of the average temperature of a ceiling jet. However, it has been seen in the numerical experiments that the correlations will not give a good estimate of the maximum excess temperature and velocity. Therefore, a simple model to estimate the maximum temperature was developed and presented in this paper.

The novelty of this research is not primarily the derived correlation, but the method that includes an outline of how numerical experiments can be used in fire science research. However, the numerical experiments represent a model of reality and there are several advantages and disadvantages with using this type of method.

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