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Björn Karlsson
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1 Introduction

For the last many decades industry and insurance companies have been interested in protecting high racked goods from rapid fire growth. This has mainly been done by installing sprinklers of various types and designs in order to either extinguish the fire or control it. The efficiency of such protection measures is, however, very much dependant on the geometry of the stacks, their height, floor area, the flue spacing, etc. and the flammable characteristics of the stored goods.

A research project was initiated by the Swedish Fire Research Board (BRANDFORSK) to throw some light on the aforementioned geometric aspects of the problem. The main part of the project is to be carried out at the Swedish National Testing and Research Institute (SP) but a pilot study was initiated at Lund University, with some participation from scientists at SP.

The work carried out at Lund University consisted of two parts. Firstly, Thomas [1] carried out a litterature survey of earlier experiments and summarized the main findings. Secondly, some experiments were made on reduced scale to examine the effect of the geometry of a pile of inert goods on the flames from a burner. This report describes the work carried out in this second part of the pilot study.

2 Experimental set-up

The most important physical process controlling fire growth on stacked goods is the upward, concurrent flow flame spread velocity. This velocity is in turn determined mainly by the time to ignition of the combustible material and the flame extension at any time. The flame extension is mainly controlled by the total heat release rate (from the ignitor and the combustible material), i.e. the mass release of volitile gases and the entrainment rate of oxygen. The geometry in which the process takes place and the total rate of heat release are thus the dominant physical aspects determining flame extensions in racked storage.

Our intention here is to preliminarily investigate flame heights as a function of heat release rate from a burner in a certain geometry where the flue height and stack width can be altered.

The experimental arrangement is shown in Figure 1

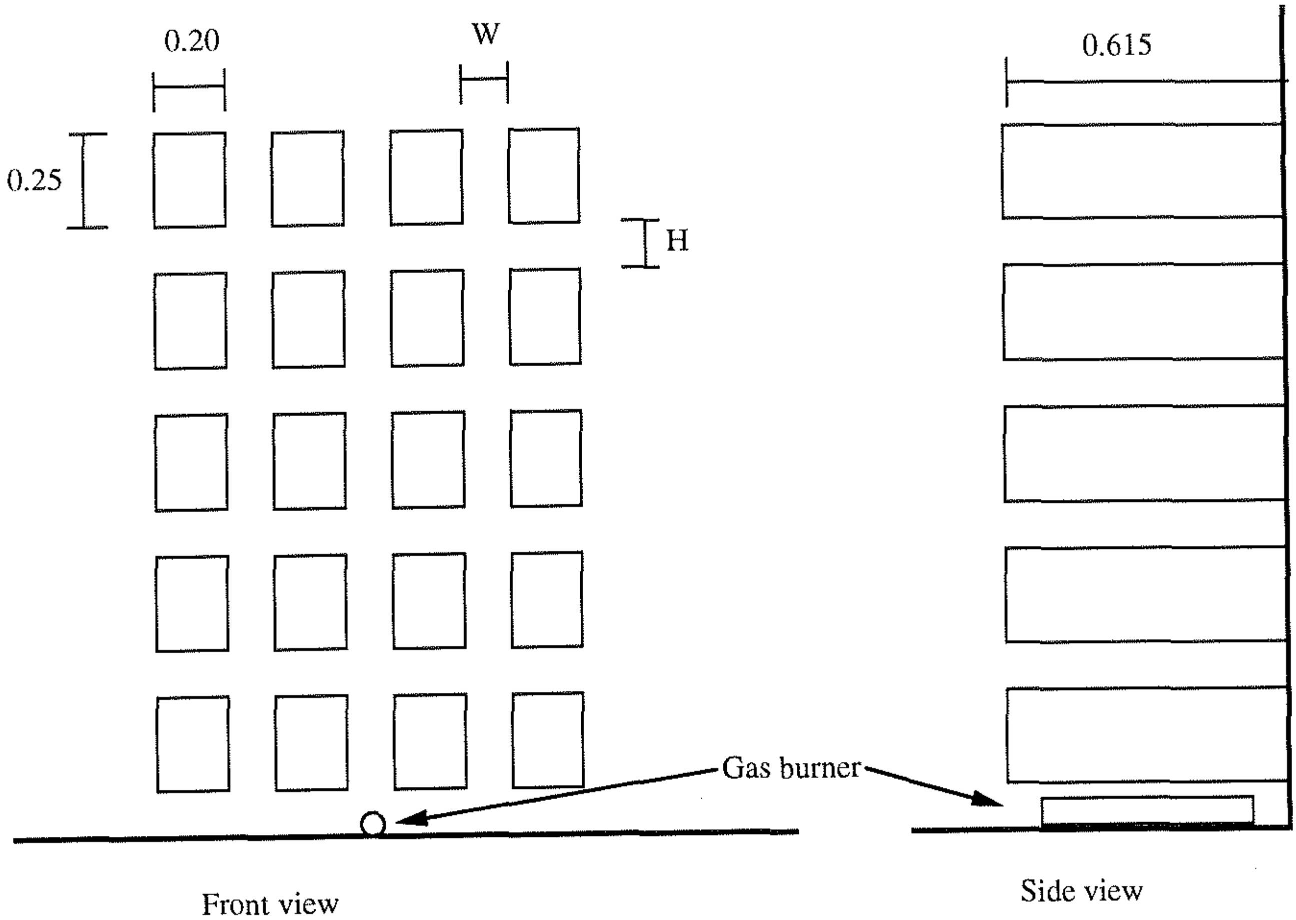

Figure 1. Experimental set-up

A gas burner of length 0.4 m (see Figure 1) was intended to produce a two-dimensional flow system. In the initial experiments described here three sides of the stack were open, in later experiments two sides or two ends were closed (as summarily described in section 4 of this paper). The inert blocks were of the same dimension throughout. The experiments consisted of measuring the flame height L for various values of the gas flow rate, which is proportional to the heat release rate, Q, and various combinations of the horizontal and vertical separations, respectively W and H. The floor gap was kept constant in their first series of experiments. The results are given in Table I.

3 Dimensional analysis

We use conventional Froude Number treatment with the addition of a term to accommodate the frictional effect of the wall and the narrow gaps.

Thus $$\frac{L}{D} = F_1\left(\frac{Q}{\rho_o C_p T_o D^2\sqrt{gD}}, \quad \frac{D\sqrt{gD}}{\upsilon}\right)$$

where L is a flame height or a distance to a given isotherm and D is a dimension, such as the width of the gap, to which all other dimensions are proportional. If there are some lengths, e.g. W and H (see Figure 1) which are not proportional to D, other ratios such

as $\frac{W}{D}$ or $\frac{H}{W}$ etc need inclusion.

Velocities scale as

$$\omega \sim \left(\frac{gQ}{\rho_o C_p T_o D}\right)^{1/3} F_2\left(\frac{Q}{D^2\sqrt{gD}\rho_o C_p T_o}, \quad \frac{Z}{D}, \frac{D\sqrt{gD}}{\upsilon}\right)$$

If the system is two-dimensional Q is replaced by Q′ D, where Q′ is heat release per unit length, to obtain a functional relationship in terms of Q′ instead of Q. We can consider a simplified two-dimensional system using a simplified hydraulic model.

In two-dimensional buoyancy driven flow with little change in density, the characteristic lengths are those of the geometry, the burner, stack, gaps and one based on the buoyancy i.e.

$$\frac{1}{g}\left(\frac{gQ'}{\rho_o C_p T_o}\right)^{2/3}$$

where	g	is the acceleration due to gravity
	ρ_o	the gas density
	C_p	its specific heat
and	T_o	the ambient temperature

A three-dimensional system would produce a characteristic buoyancy length of $\frac{Q'^{2/5}}{(\rho C T_o)^{2/5} g^{1/5}}$

i.e. for a given burner length. Thus $Q'^{2/3}$ and $Q'^{2/5}$ respectively are the variable parts of the characteristic lengths.

Accordingly the results in Table I, calculated as $\frac{L}{Q'^{n}}$ and $\frac{W}{Q'^{n}}$ are plotted in Figure 2 for n = 2/3. A plot with n = 2/5 produces systematic unacceptable scatter.

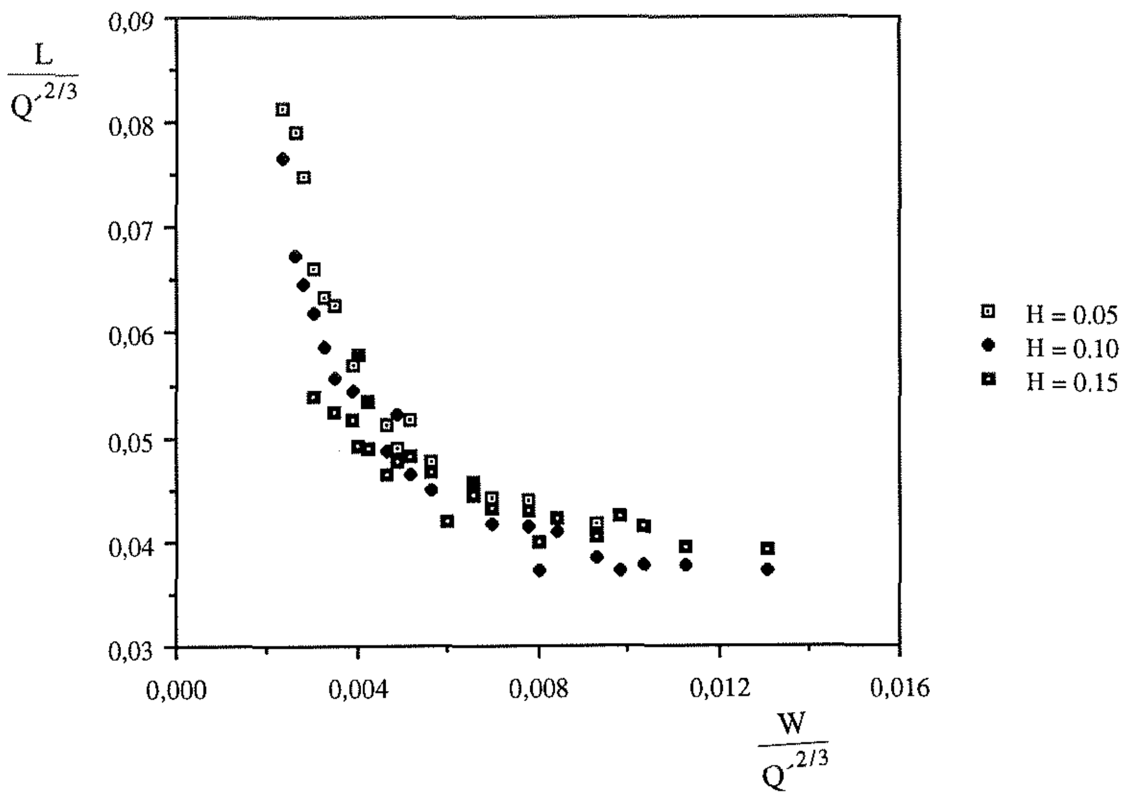

Fig 2 $L/Q'^{2/3}$ plotted against $W/Q'^{2/3}$

The results for large $W/Q'^{2/3}$ tend to $L/Q'^{2/3} = 0.038$. Thomas [2] gave a correlation for two-dimensional flames $L = 18.6 m'^{2/3}$ (1)

where L is in m

m′ in kg/ms, the mass loss rate of wood per meter per second

For heat release equal to 65 % of the calorific value of wood volatiles

i.e. $0.65 \cdot 16500 kJ/kg$ then

$$L = 0.038\, Q'^{2/3} \qquad (2)$$

This is close to a recent correlation by Hasemi [3] obtained directly in terms of Q.

We seek to analyse the data where L is clearly influenced by W and H and we therefore omit the data approaching the horizontal limit seen in Figure 2.

A power law regression confined to results for $W/Q'^{2/3} < 0.007$ so excluding conditions when W and H are not expected to have much influence gives

$$L \sim Q'^{0.94} \, W^{-0.50} \, H^{-0.09} \tag{3}$$

We ask if this corresponds to a simple dimensionless correlation of

$$\frac{L}{Q'^{2/3}} = C \left[\frac{W}{Q'^{2/3}}\right]^n \left[\frac{H}{Q'^{2/3}}\right]^m \tag{4}$$

One would expect there to be a constraint on three regression coefficients representing two independant dimensionless variables. This constraint is

$$0.94 = \frac{2}{3}\,[1 + n + m]$$

The right handside is in fact $2/3 \cdot 1.59$ i.e. 1.06 which appears not to be significantly different from 0.94 given the indices have standard errors of 0.034, 0.025 and 0.018 respectively for 0.94, -0.50 and -0.09. We therefore seek to rearrange equation (3) and analyse equation (4) directly.

The results are $C = 0.00242$
$n = -\ 0.496$
$m = -\ 0.070$

with a coefficient of variation $r^2 = 0.90$.

Figure 3 shows the results.

There is some evidence that the correlation breaks down at high $W/Q'^{2/3}$, the four extreme right hand points being for small W and high Q′.

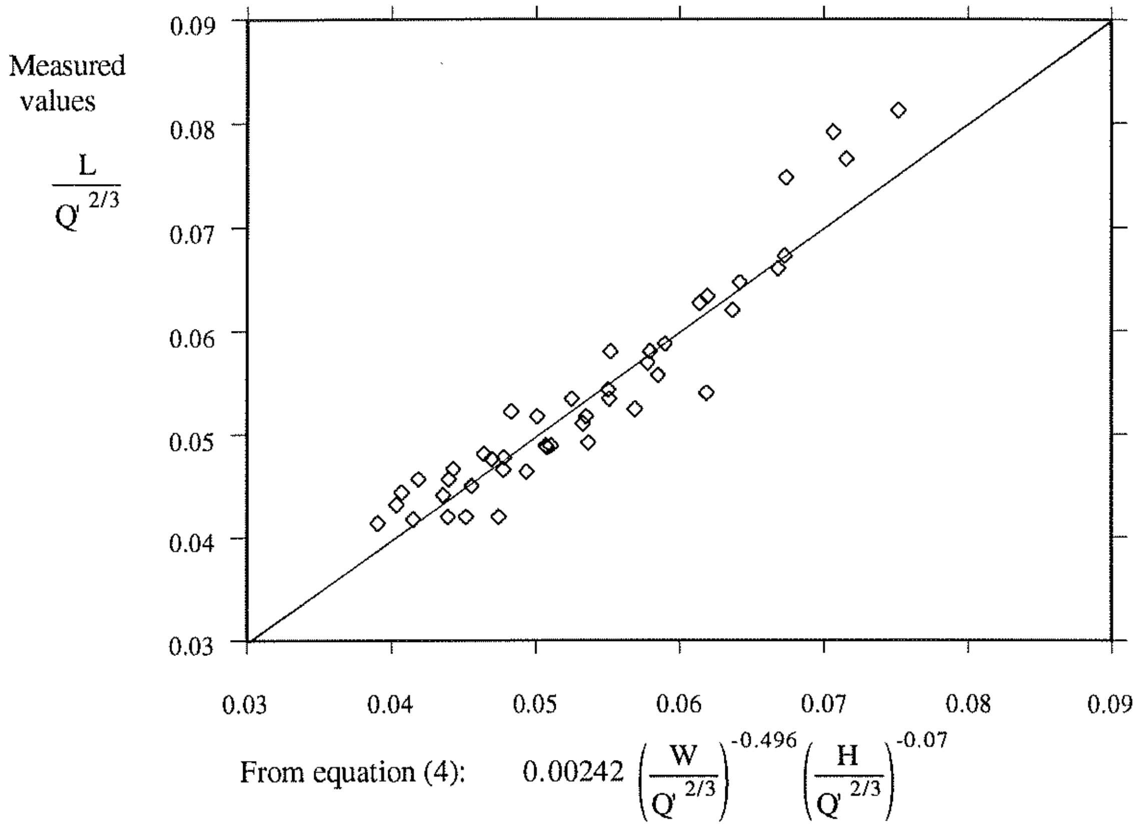

Fig. 3 Power law regression according to equation (4) (for $W/Q'^{2/3} < 0.007$).

4 Experiments carried out in Borås

Experiments of a somewhat similar nature as described above were carried out at SP. The difference in experimental set-up were mainly the following:

1 Two sets of experiments were carried out; where all sides of the stack were open (here referred to as Borås 3D) and; where only two sides were open, the front and back were closed (here referred to as Borås 2D). In the Lund experiments two sides and the front were open, the back was closed (see Figure 1).

2. Only the heat release rate (Q) and the width of the flue (W) were altered, the height of the gaps (H) was fixed at 0.05 m. The burner length was 0.6 m in the Borås experiments but 0.4 m in the Lund experiments.

3. Only two stacks of inert material were used, while in the Lund experiments, 4 stacks were used (see Figure 1).

4. Different measuring apparatus were used so measurements of flame heights and heat release rates may differ in the two experimental series.

The Borås experiments are described in detail in a seperate publication by Ingason [4]. Here we shall plot the Borås data with the Lund data for comparison. The results are given in Figure 4.

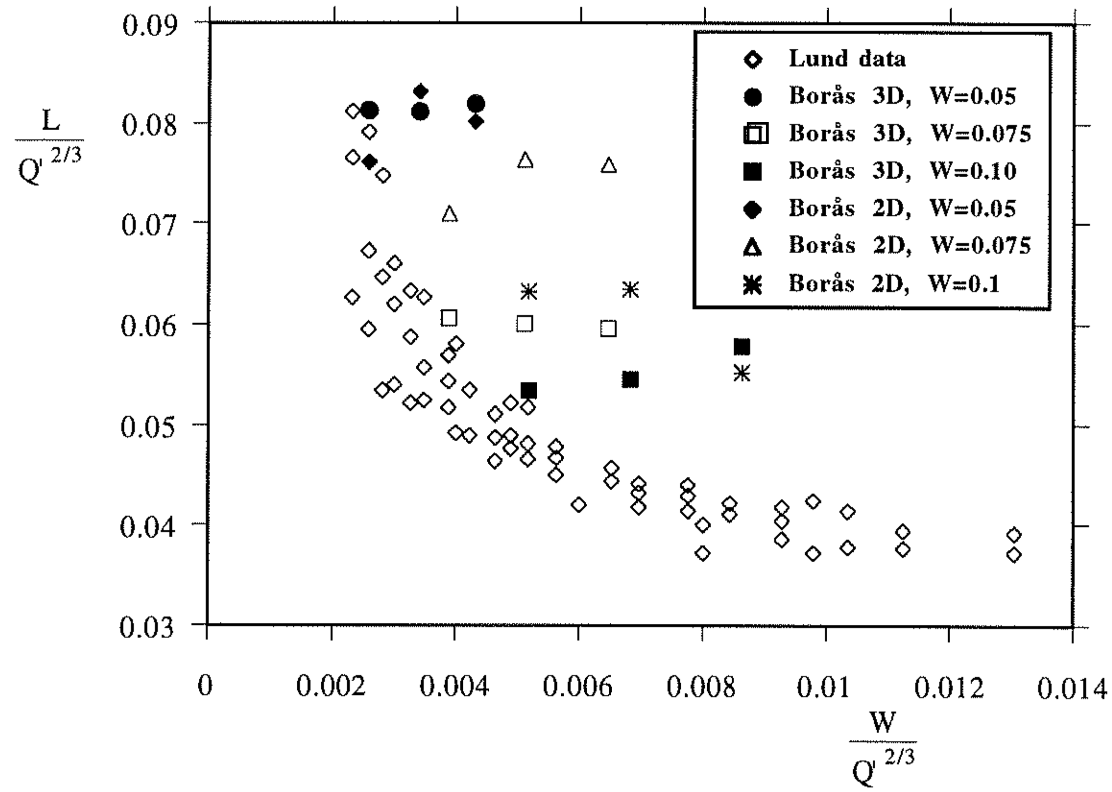

Figure 4. Borås data plotted onto the Lund data (Lund data separately shown in Figure 2).

Figure 4 is shown here only to draw attention to the differances in the results from the two experiments. No attempt will be made here to fully analyse the inconsistency between the two experimental series because of the many differances in the experimental set-up enumerated above. Attention should, however, be drawn to the fact that for most of the Borås 3D data $L/Q^{'2/3}$ is constant for a fixed W, indicating that L is proportional to $Q^{'2/3}$ in the 3D experiments where a 2/5 exponent on Q would be expected.

The SP experiments, with W = 0.05 m and 0.10 m appear not to differ much between 2D and 3D interpretation as much as do those for the intermediate condition of W = 0.075 m.

It should be noted, though, that the highest data points on flame height may not be valid in the above context since these flames reach out of the stack.

5 Conclusion

This pilot study must be seen as being incomplete and preliminary. Clearly, more detailed and varied experiments must be carried out in order to draw any definite conclusions on the geometric effects on flame heights in rack storages. The following preliminary findings may, however, be noted:

1. The Lund results are better interpreted as two dimensional than three dimensional.

2. The analysis shows that, for the Lund experiments, varying the height of the vertical gaps has less influence on flame length than does varying the width of the horizontal gaps.

3. For a geometry similar to the set-up in the Lund experiments, approximate flame height in a stack can be calculated using equation (4). The regression equation gives surprisingly good results (see Fig 3) considering the relatively complex geometry involved.

4. No conclusions are given here for geometries significantly different from the Lund experimental set-up. More detailed and varied experimental work is clearly needed and some such work is presently being carried out at the Swedish National Testing and Research Institute [4].

References

[1] Thomas, P.H., Some Comments on Fire Spread in High Racked Storage of Goods, Department of Fire Safety Engineering, Lund University, 1993.

[2] Thomas, P.H., Ninth Symposium (International) on Combustion, Academic Press Inc, p.844, 1989.

[3] Hasemi, Y., Proceedings of Second International Symposium on Fire Safety Science, p.275, 1989.

[4] Ingason, H., Fire Experiments in a Two Dimensional Rack Storage, SP REPORT 1993:56, Borås 1993.

Table 1

Q (kW)	L (m)	W (m)	H (m)
24	0,90	0,050	0,10
30	1,15	0,050	0,10
34	1,30	0,050	0,10
40	1,65	0,050	0,10
24	0,80	0,075	0,10
30	0,95	0,075	0,10
34	1,05	0,075	0,10
40	1,20	0,075	0,10
50	1,55	0,075	0,10
24	0,70	0,100	0,10
30	0,80	0,100	0,10
34	0,90	0,100	0,10
40	1,05	0,100	0,10
50	1,45	0,100	0,10
24	0,57	0,150	0,10
30	0,73	0,150	0,10
34	0,80	0,150	0,10
40	0,90	0,150	0,10
50	1,05	0,150	0,10
24	0,57	0,200	0,10
30	0,67	0,200	0,10
34	0,73	0,200	0,10
40	0,83	0,200	0,10
50	0,93	0,200	0,10
24	0,97	0,050	0,05
30	1,33	0,050	0,05
34	1,53	0,050	0,05
40	1,75	0,050	0,05
24	0,75	0,075	0,05
30	0,95	0,075	0,05
34	1,10	0,075	0,05
40	1,35	0,075	0,05
50	1,65	0,075	0,05
24	0,70	0,100	0,05
30	0,85	0,100	0,05
34	1,00	0,100	0,05

Q (kW)	L (m)	W (m)	H (m)
40	1,10	0,100	0,05
50	1,45	0,100	0,05
24	0,65	0,150	0,05
30	0,75	0,150	0,05
34	0,85	0,150	0,05
40	0,95	0,150	0,05
50	1,05	0,150	0,05
24	0,60	0,200	0,05
30	0,70	0,200	0,05
34	0,80	0,200	0,05
40	0,90	0,200	0,05
50	1,00	0,200	0,05
24	0,60	0,200	0,15
30	0,70	0,200	0,15
34	0,80	0,200	0,15
40	0,87	0,200	0,15
50	1,00	0,200	0,15
24	0,65	0,150	0,15
30	0,75	0,150	0,15
34	0,83	0,150	0,15
40	0,93	0,150	0,15
50	1,05	0,150	0,15
24	0,68	0,100	0,15
30	0,83	0,100	0,15
34	0,93	0,100	0,15
40	1,00	0,100	0,15
50	1,23	0,100	0,15
24	0,73	0,075	0,15
30	0,87	0,075	0,15
34	1,00	0,075	0,15
40	1,13	0,075	0,15
50	1,35	0,075	0,15
24	0,80	0,050	0,15
30	0,95	0,050	0,15
34	1,15	0,050	0,15
40	1,35	0,050	0,15