On fire flames out of vertical openings

Thomas, Philip H

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

LUND INSTITUTE OF TECHNOLOGY · LUND · SWEDEN
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P H THOMAS

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Division of Building Fire Safety
and Technology
Lund Institute of Technology
Box 118
S-221 00 LUND, Sweden
Tel +46-46-10 73 60

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SUMMARY

Some recent Swedish data on compartment fires are reviewed. Measured burning rates were as high as 7.7 $A\sqrt{H}$ kg/min where A is the opening area in m^2 and H is its height in m.

A conventional power law is shown to relate the burning rate and the measured external flame length as well as does an empirical proportionality. The corrections to be allowed in both methods for the burning within the compartment and for the effective origin of the flames are both somewhat uncertain.

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Fire Research Station
Building Research Establishment
Borehamwood
Herts WD6 2BL

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ON FIRE FLAMES OUT OF VERTICAL OPENINGS

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INTRODUCTION

Law[1] has reviewed the early work on correlating flame length data including the early works of Yokoi[2], Thomas[3], Webster and Raftery[4] and Seigal[5].

Following the studies of Yokoi[2] and Thomas[3] she has shown that one is justified in correlating flame data by means of dimensionless parameters derived from considerations of buoyancy in plumes and she has discussed correlations of the type

$$\frac{Z_f}{H} = f\left\{\frac{R'}{\rho_o\sqrt{g}\;H^{3/2}}\,,\ \frac{W}{H}\right\} \tag{1}$$

where Z_f is flame length
H is opening height
W is opening breadth
ρ_o is air density
g is acceleration due to gravity
and R' is the rate of mass loss of fuel per unit window breadth (kg/m.s).

Thomas originally developed for wood a correlation of the form

$$Z_f + H = 18.6\ R'^{2/3} \tag{2}$$

on the grounds that the origin of the effect of buoyancy was at the base of the window opening. This is likely to be valid only for some situations, not universally. Compare Fig 1 and Fig 2, where some factors influencing the type of flow are suggested. For some fully developed fires a datum at the neutral pressure axis may be most suitable; for others the base of the emerging hot gas layer would be the better choice if there is a well defined layer.

The 2/3 power law is analogous to that for a plume from a line heat source. If a flame were represented by a zone of uniform temperature the characteristic vertical and entrainment velocities would increase as $\sqrt{Z}$ and the total air flow into the flame would increase as $Z^{3/2}$. For a flame to be as long as is determined by the air

$$Z^{3/2} \propto R'$$

All correlations raise the problem of correcting a total measured mass loss rate for the combustion occurring within the compartment and of defining the air requirements of the unburnt fuels that leave it. One might be tempted to allow for 5.5 $A\sqrt{H}$ kg/min to be allocated for the burning inside a compartment having a window area A m^2 and window height H m in which the fire is fully developed. This would be in accordance with the well known view that ventilation controlled fires burn, on average at a nearly stoichiometric rate

$$R = 5.5\ A\sqrt{H} \qquad (3)$$

although there are data with larger values[6 7] of the ratio $R/A\sqrt{H}$ as well as some of the present data quoted here. What however is germane to this discussion is that it is the air flow and hence the energy liberated inside which is limited to a value 30 $A\sqrt{H}$ kg/min. The works of Gross and Robertson[6], the report of the *international cooperative research programme* by CIB[7], Thomas and Nilsson[8], and Saito[9] have shown that $\frac{R}{A\sqrt{H}}$ is not constant. Another empirical relationship better than equation (1) for cellulosic fuels in non-combustible compartments[9] is

$$R = 3.0\ (A\sqrt{H})^{0.8}\ (A_T)^{0.2} \qquad (4)$$

where A_T is the total internal surface area in m^2 of the compartment. The reason for the wide acceptance of 5.5 $A\sqrt{H}$ as a design base for a total burning rate may be less to do with physics than with the statistical *distribution of window size, fuels etc.*

Recent experiments

Jansson and Onnermark[10] have recently presented data for 7 wood crib fires in a room 4.2 m x 2.8 m x 2.6 m high with one window 1.3 m high and breadth between 1 m and 2.8 m. The cribs were weighed and the data are given in Table 1. Ondrus et al[11] have conducted similar experiments but the fuel was not weighed whilst burning and measurements of flame height comparable to those of Jansson and Onnermark were not made but temperature profiles are available (see Table 2).

By and large the steady burning of cribs is not normally much affected by their being inside a well ventilated compartment and we shall use a formula[12] to estimate the burning rates of cribs in the fuel controlled fires. Flame lengths for those fires where lengths are unreported are taken from the position where the temperature rise is 500°C.

Jansson and Onnermark introduce three new features into their discussion.

I. They produce a linear correlation between flame length and the external burning rate (see II).

II. They allow for combustion within the compartment by deducting an amount appropriate to the onset of flashover.

III. They use $A\sqrt{H}$ to normalise R in accordance with dimensional analysis requirements but do not normalise Z at all. However H was constant in their experiments.

Applying the same correction (II) to equation (2) also gives an adequate correlation of Jansson and Onnermark data (see Fig (3)). However, once flashover has occurred air flow into a compartment (and hence the rate of energy release in what can become a ventilation controlled fire) is determined by hydrostatic forces not by entrainment and one wonders how sensitive the correlations are to the "correction".
Fig 4 shows a correlation using $R' - 4A\sqrt{H}/W$ instead of R' in equation(2) and Z_f instead of $Z_f + H$. This in effect assumes the exit gases are leaving the upper part of the opening horizontally and the effective origin of the buoyancy is the neutral axis*.

A value for the correction of less than 5.5 is in principle consistent with the fact that excess fuel will depress the neutral axis and reduce the air inflow but the effect is not large. We see this from the conventional hydraulic equation that describes fully developed fires. Thus, equation (5)

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*This is approximate. The base of the layer is probably a better choice but the difference is least for large flames.

$$M = \frac{\frac{2}{3} \times 0.7 . \rho_a . A . H^{3/2} \sqrt{2g \frac{\theta}{T_o + \theta}}}{\left[1 + \left(\frac{T_o + \theta}{T_o}\right)^{1/3} \left(1 + \frac{R}{M_1}\right)^{2/3}\right]^{3/2}} \quad (5)$$

gives for $\theta = 900°C$, $T_o = 290°K$, $\rho_a = 1.3$ kg/m³, even for $\frac{R}{A\sqrt{H}}$ three times the conventional 5.5 and higher than any of the tests reported reported here, the value of $\frac{M}{A\sqrt{H}}$ as much as about 75% of its conventional value.

This would make the energy correction 5.5 x 0.75 $A\sqrt{H} = 4.A\sqrt{H}$ but it is a maximum figure for these tests - not a mean as our use of it implies. The effect on the neutral axis is not large enough to be the whole explanation of the difference between 4 and 5.5 kg/m$^{5/2}$. One of the tests, giving Z_f 0.5 m has a negative value of $R - 4A\sqrt{H}$ and clearly for such fires the correlation is inappropriate. One could fit the data by an equation with, say, a coefficient less than 4 but then the correlation would not lie so close to the line based on equation (2).

Linear correlations

It is idle to pursue the discussion of such few data in too much detail but we can speculate on the generality of the linear equation demonstrated by Jansson and Onnermark. The free plume does appear to give rise to a 2/3 power. Indeed Law's statistical analysis suggests a lower not a higher fraction. But a wall plume suffers frictional drag and one can expect a lessening dependence of entrainment on height. If there were no dependence at all of the mean entrainment velocity on flame height than for an effective air fuel ratio of 'r' we have

$$\rho_a . \frac{\overline{V}_e Z_f W}{r} = R'_{net} . W \quad (6)$$

where R' is the rate of supply of fuel externally per unit breadth of opening.

$$\therefore Z_f = \frac{r}{\rho_a \overline{V}_e} R' \quad (7)$$

For wood fires with flames in the open effective values of r may reach 20. (400% excess air to the top of the flame).

For ρ_a = 1.2 kg/m³ the coefficient of $\frac{0.7}{H^{3/2}}$ *ie 0.47 in kg min units obtained* in the best straight line corresponds to a velocity of entrainment $\overline{V}_e$ of 0.6 m/sec. An assumption of less excess air gives a lower estimate. Such a figure is plausible if perhaps high. The best straight line in Fig 4 gives $\frac{V}{\rho_a \overline{V}_e} \approx 0.7$ giving an estimate for V_e of 0.4 m/s.

We have presented above a linear relationship between Z_f and R' (equation (7)). However this is not quite the form proposed by Jansson and Onnermark whose correlations are in the form

$$Z_f = \alpha \frac{R}{A\sqrt{H}}$$

$$\text{ie} \quad Z_f = \alpha \left(\frac{R'}{H^{3/2}}\right) \tag{8}$$

Since H was constant in all their experiments it is not possible to distinguish between one and the other forms. If one returns to dimensional analysis the results of Yokoi and Thomas et al are a particular form of a general relationship

$$\frac{Z}{H} = f\left[\frac{(R')^2}{\rho^2 g\, H^3} \cdot \frac{W}{H}\right]$$

If Z_f does not depend on W for a given R' then if $Z_f \propto R'$ dimensional arguments require

$$\frac{Z_f}{H} \propto \frac{R'}{H^{3/2}}$$

$$\text{ie} \quad Z_f \propto \frac{R'}{H^{1/2}}$$

It is therefore possible to extrapolate Jansson and Onnermark's data to other building conditions only if these involve small changes in H.

Burning inside and outside the compartment

We have, above, made assumptions regarding the extent to which the combustion is partitioned between inside and outside the compartment. One can take Jansson and Onnermark's flashover line to indiqate a minimum release of energy causing flashover but this is not the maximum rate of energy release inside a compartment. Flashover leads to ventilation control and changes in the flow of air into the compartment so that the system moves to the conventional fully developed fire,where air flow is determined by hydrostatic forces not by entrainment.

The Jansson and Onnermark concept seems to imply that although extra air enters the compartment after flashover it leads only to external flaming. Calculations of the energy balance of fully developed fires, however, suggest that higher rates of energy release are involved internally.

A different view is stated by Harmathy[13] in many publications. Here a fraction 'δ' is broadly defined for ventilation controlled fires as the fraction of energy released internally (if δ is less than unity). δ exceeding unity implies all energy is released internally.

δ is related to the compartment geometry by Harmathy by

$$\delta = 0.79 \sqrt{h_c^3/\emptyset} \qquad (9)$$

where $\emptyset$ is a ventilation parameter proportional to $A\sqrt{H}$. No experiments have yet been reported in which h_c has been varied in a way to test this relation. On the other hand the experiments reported by Jansson and Onnermark (see Table I) included 4 experiments in which A, H and hc were kept constant. h_c equalled 2.6 m and $A\sqrt{H}$ equalled 2.67 $m^{5/2}$. Harmathy's $\emptyset$ is $1.3 \sqrt{9.81} \times 2.67 = 10.75$ kg/s for these experiments. Hence

$\delta = 0.79 \sqrt{\dfrac{2.6^3}{10.75}}$ which is barely larger than unity.

For two other experiments A was smaller, making δ even larger so that no external combustion need be considered, yet for these fires flames 3.5 m and

3.7 m long were recorded.

δ was derived from

$$\delta = (h_c/l)^{3/2} \quad (l > h_c) \tag{10}$$

where l is a hypothetical flame length[13].

As will be seen from the arguments discussed above a flame length is expected, for wide windows, to be independant of window width if the burning rate is expressed as per unit window width. On the other hand Harmathy gives, in deriving equation (8)

$$l = 1.17\ \theta^{1/3} \tag{11}$$

for the ventilation controlled regime, which implies a dependance on width of window. Equation (2), with $l = Z + H$ and $R' = \frac{R}{A\sqrt{H}} . H^{3/2}$ and a conversion from second to minutes gives

$$l = 18.6 \times \left(\frac{R/A\sqrt{H}}{60}\right)^{2/3} \times H = 3.8\ H \left(\frac{R}{5.5\ A\sqrt{H}}\right)^{2/3}$$

Hence equation (10) may be rewritten as

$$\delta = \left(\frac{h_c}{3.8\ H}\right)^{3/2} \times \left(\frac{5.5\ A\sqrt{H}}{R}\right)$$

$$= \left(\frac{2.6}{3.8 \times 1.3}\right)^{3/2} \times \left(\frac{5.5\ A\sqrt{H}}{R}\right) = 0.38 \left(\frac{5.5\ A\sqrt{H}}{R}\right) \tag{12}$$

This suggests that flames should come out of the opening in all the experiments of Jansson and Onnermark but whether it is a realistic description of the partition between inside and outside burning awaits further study. For example, the coefficient 3.8 seems to be too large since l/H is usually observed to be somewhat less than this.

Equation (12) tells us nothing about δ unless we know R or, as in Harmathy's equations, make assumptions about it. One can refine these by using equation (4) instead of equation (3) but even equation (4) must be applied with caution, being based on wood fuel and cribs. It does however predict values of $^{R}/A\sqrt{H}$ in the Jansson Onnermark tests somewhat larger than 5.5 but not as large as their largest recorded results of over 7 kg/min $m^{5/2}$.

The experiments by Ondrus et al[11]

The experiments by Ondrus et al on the behaviour of external insulation on facades are of interest here, because two employed non-combustible facades.

The compartment dimensions were very close to those in the Jansson and Onnermark experiments, A_T was 50 m² and $A\sqrt{H}$ 3 $m^{5/2}$ (W = 2.8 m).

Some of the fuel (184 kg) was in the form of cribs (see Table I). If we adopt the same value* of $^{R}/A\sqrt{H}$ (ie 7.1) as the average of the ventilation controlled fires in Table I then the limit for fuel controlled fires is 3 x 7.1 ~ 21.3 kg/min. The cribs had a value of $h.A_v/A_s$ of 0.014 m and A_s = 58m² where A_v is the horizontal open area of the crib, A_s the wood surface and h_c the crib height. The estimated rate of mass loss[12] for free burning is $0.07 \sqrt{h_c A_v A_s}$ = 28.5 kg/m² so both fires would appear to be ventilation controlled, yet they are different in the lengths of the flame. The 23 kg of polyurethane foam pyrolyses faster than the same amount of wood and would be expected to produce longer flames outside the compartment.
Based on the relative heats of vaporisation and the calorific contents of polyurethane and wood, estimates of the effects of a given thermal environment in a fully developed room fire suggest that about 1½ times as much fuel is produced. This requires about 2 to 2½ as much air for burning. Hence we shall treat the 8 m² of polyurethane fuel as equivalent to 20 m² of wood.

*No doubt an underestimate in view of the presence of a wall lined with wood as well as the cribs.

The result for this fire as a whole is not very dependant on the details of the modification. Available theory is hardly sufficient to estimate the burning rate which for ventilation controlled fires can be above 5.5 $A\sqrt{H}$ and can be influenced by the exposed fuel area and the type of fuel. Estimates of the mean rates of burning are therefore rather crude.

The data are shown plotted in Figs 3 and 4 according to these estimates but the plausibility of the correlation is not sufficient argument to support the assumptions.

CONCLUSION

Linear and non linear correlations can be fitted to the data discussed here. Doubts about the effective origin of the plume and of what allowance is to be made for combustion within the compartment remain unresolved. One difficulty to be dealt with is the inadequacy of methods for dealing with the secondary effects of fuel and compartment details on burning rates in ventilation controlled fires.

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REFERENCES

1. Law M. Engineering Journal. Am Inst. of Steel Construction. Second Quarter 1978, 59.

2. Yokoi S. Study of the prevention of fire spread caused by upward hot current. Building Research Institute of Japan. Report No.34 1960.

3. Thomas P H. 9th Symposium (International) on Combustion. Academic Press. 1963 p.844.

4. Webster C T and Raftery M. The burning of fires in rooms. Part II. DSIR & FOC JFRO Borehamwood. FR Note 411 1959.

5. Seigal L G. Fire Technology. 1969 5 1.43.

6. Gross D and Robertson A. 10th Symposium (International) on Combustion Institute. Pittsburgh (1965) p.931.

7. Thomas P H and Heselden A J M. CIB Report 20 DSIR & FOC JFRO FR Note 923/1972.

8. Thomas P H & Nilsson L. Fully developed compartment fires: New correlation of burning rates DSIR & FOC JFRO FR Note 979/1973.

9. Saito F. Experimental study of compartment fires using model boxes. Building Research Institute of Japan Research Paper 81, 1979.

10. Jansson R and Onnermark B. Flame heights outside windows. FOA Report C20445-A3 1982 Stockholm.

11. Ondrus J et al. Unpublished report. Dept of Building Fire Safety and Technology, Lund.

12. Smith PG and Thomas P H. Fire Technology 1976 6 1.29.

13. Harmathy T Z. Fire Severity. Basis for Fire Safety Design. Am Conc. Inst. SP-80 (1983 115).

TABLE 1 - Jansson and Onnermark's data

W	$A\sqrt{H}$ $m^{5/2}$	M_o	R kg/min	$\Delta R/W$	$R/A\sqrt{H}$	Z	$(R-4\ A\sqrt{H})/W$
1.2	1.78	520	13	6.5	7.3	3.7	4.9
1.2	1.78	500	13.8	7.2	7.7	3.5	5.6
1.8	2.67	500	19.3	7.2	7.25	2.6	4.8
2.3	3.41	500	20.3	5.7	6.0	2.3	2.9
1.8	2.67	126	9.5	1.8	3.55*	0.5	-0.72
1.8	2.67	160	12.0	3.1	4.5*	1.4	0.72
1.8	2.67	198	14.3	4.4	5.4*	1.9	2.0

*These tests would appear to have "flashed over" in the sense that temperatures exceeding 600°C were obtained but were not fully developed. One assumes that the compartment was not "filled with flame".

TABLE 2 - Data for two tests by Ondrus et al at Lund

		Test 1	Test 2
Fuel			
Crib		184 kg 58 m^2	184 kg 58 m^2
Wall of wood Exposed area		188 kg 11 m^2	126 m^2 5 m^2
Polyurethane Exposed area		23 kg 8 m^2	
Estimated burning rate (crib)		28.5 kg/min	28.5 kg/min
Additional burning rate (A) Pro rata basis (B) With polyurethane area x 2½		$\frac{19}{58}$ x 28.5 = 10 kg/min = 15.2 kg/min	$\frac{5}{58}$ x 28.5 = 2.5 kg/min
Total rate of burning R	(A) (B)	38.5 kg/min 43.7 kg/min	31 kg/min
Estimate of R_1 (to reach 600°C in compartment (see Jansson and Onnermark)		$\frac{\Delta R}{W} = \frac{R - R_1}{2.8}$	
= 5.3 kg/min	(A) (B)	11.85 13.70	9.15
		$(R - 4A\sqrt{H})/W$	
	(A) (B)	9.46 11.3	6.8
Flame height above top of window			
To 500°C isotherm		5.2 m	2.8 m
To 425°C isotherm		6.0 m	3.4 m

Estimates of R for both tests are in excess of the conventional limit for ventilation controlled fires. We have probably overestimated what is allowable for the crib and underestimated the contribution of the wall and the polyurethane.

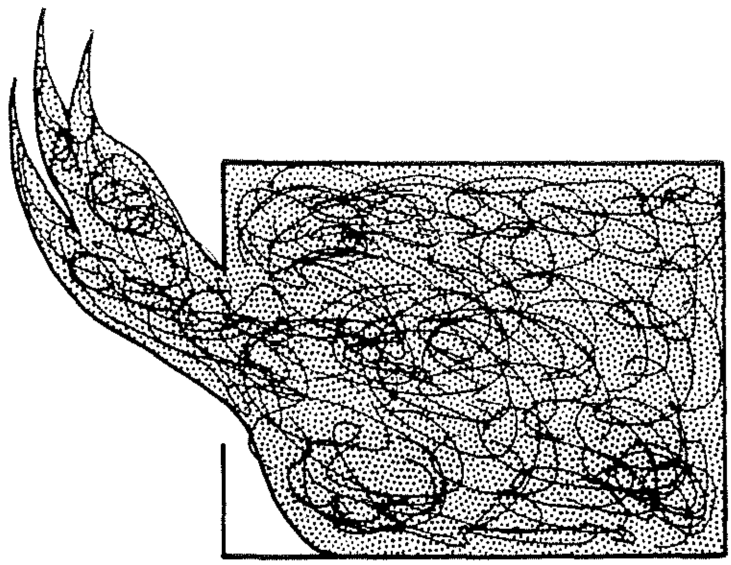


Figure 1 'Fully developed' fire - Air inlet determined by hydrostatic fires Short, shallow compartment fuel near opening

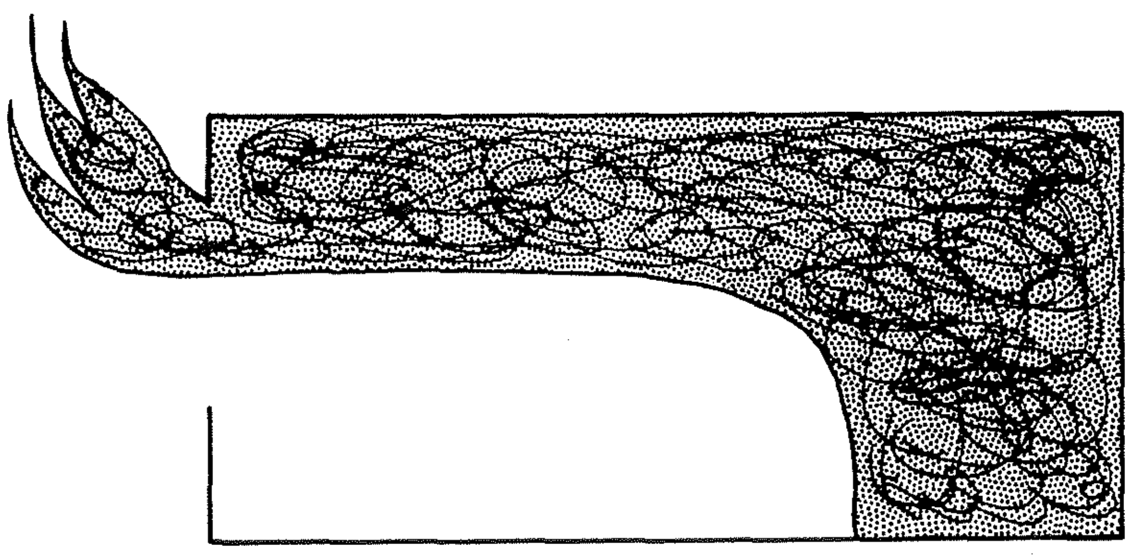


Figure 2 Inlet flow not limited by window but by entrainment into flames Long deep compartment, fuel only at rear

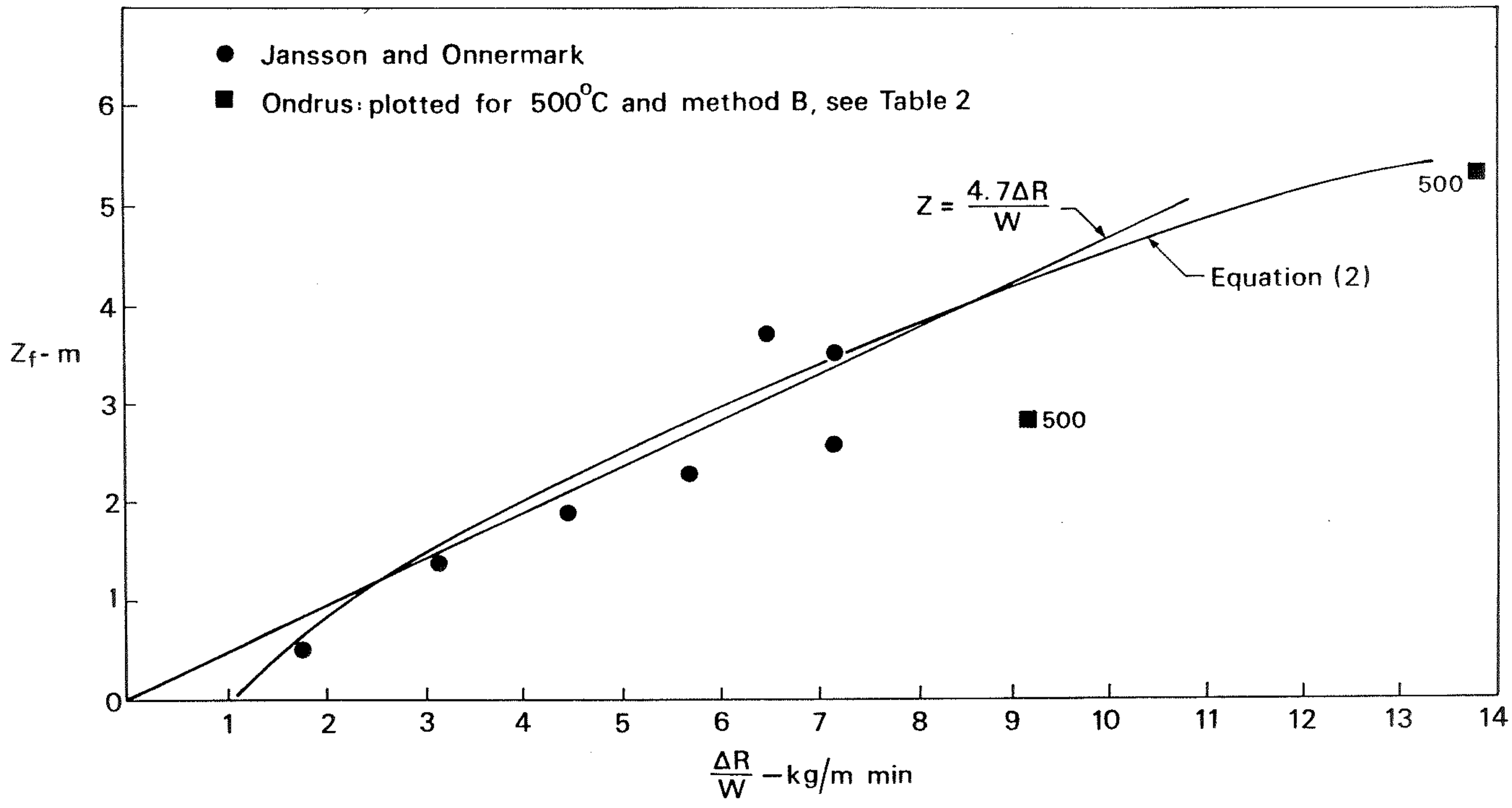
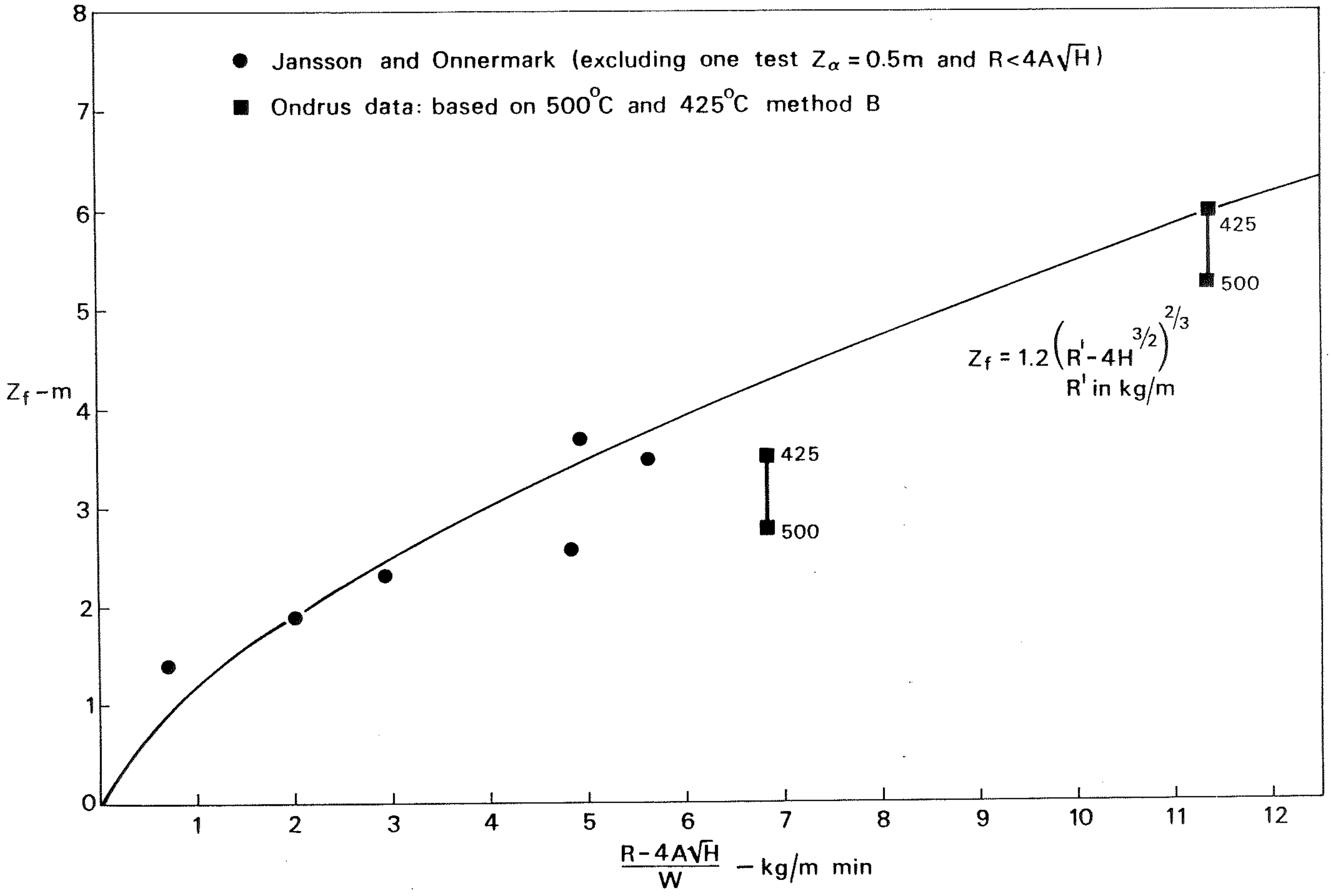
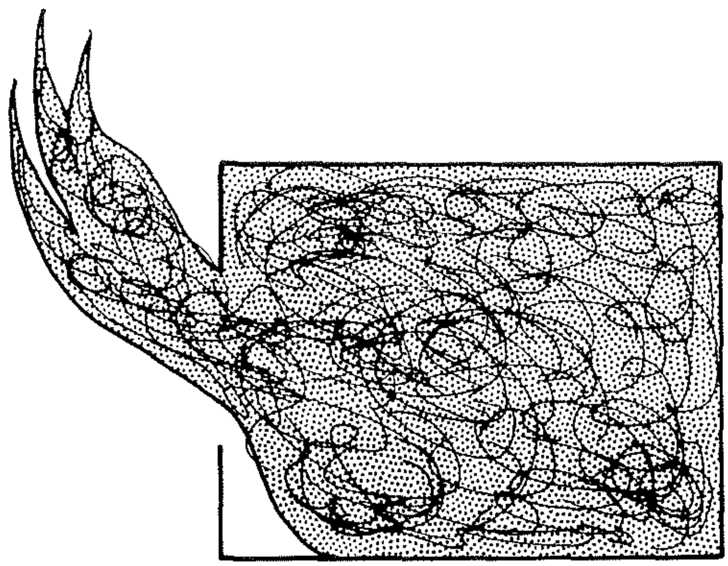


Figure 3 Correlations of flame length based on onset of flashover



Jansson and Onnermark (excluding one test $Z_\alpha = 0.5$m and $R < 4A\sqrt{H}$)
Ondrus data: based on 500°C and 425°C method B
$Z_f = 1.2\left(R' - 4H^{3/2}\right)^{2/3}$
R' in kg/m
425
500
425
500
Z_f – m
$\frac{R - 4A\sqrt{H}}{W}$ – kg/m min
0
1
2
3
4
5
6
7
8
9
10
11
12



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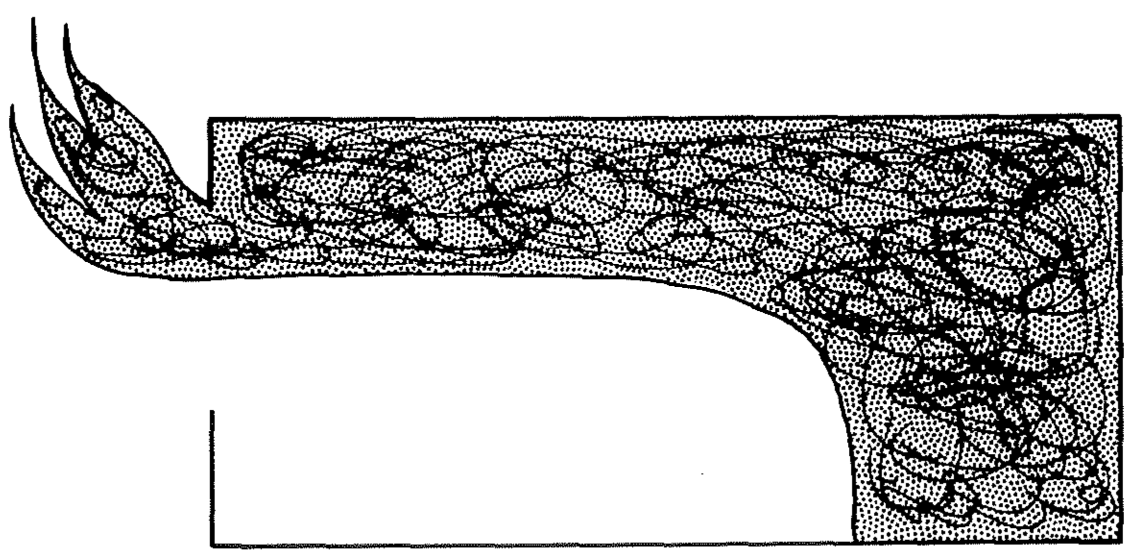

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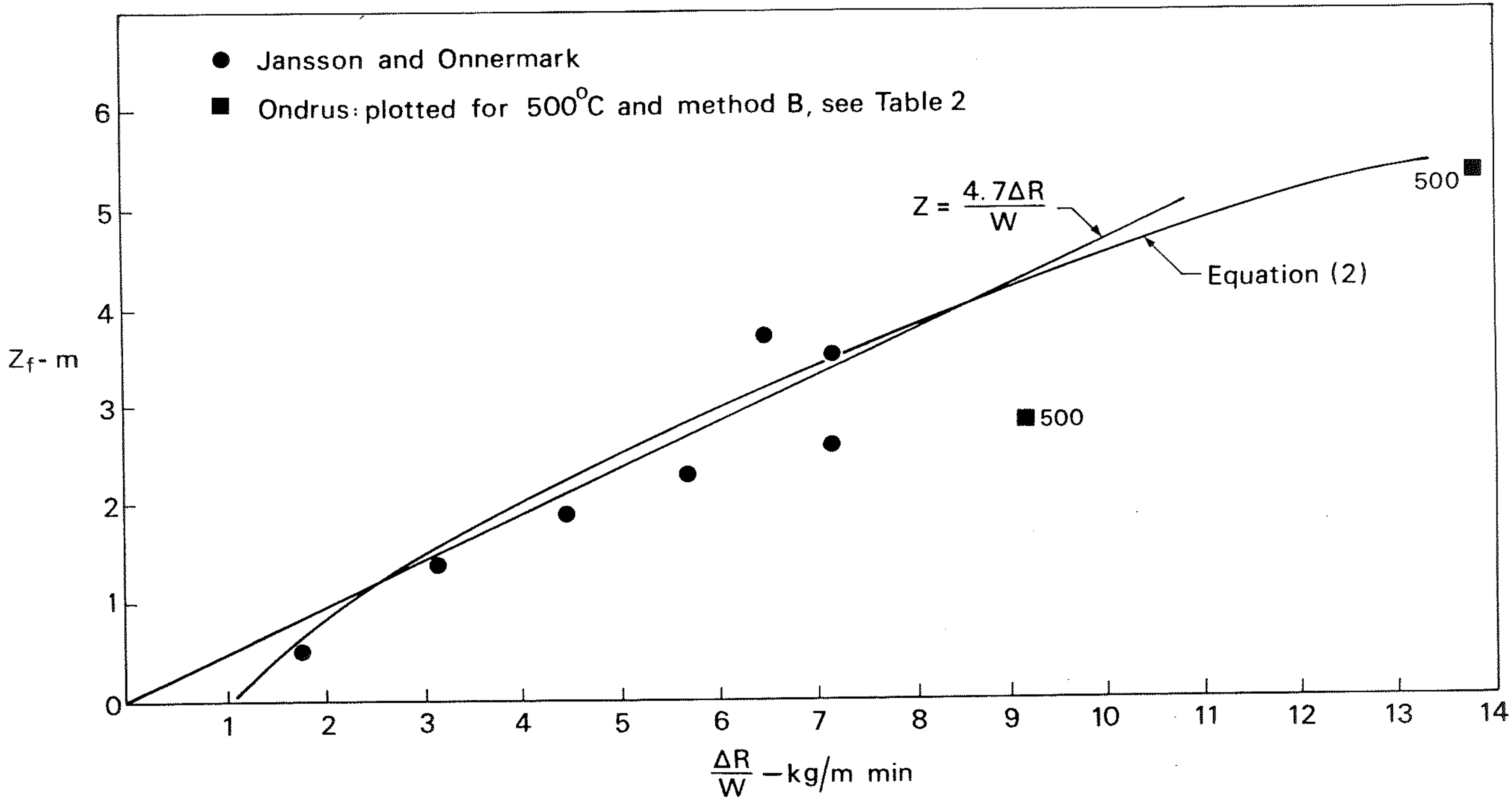

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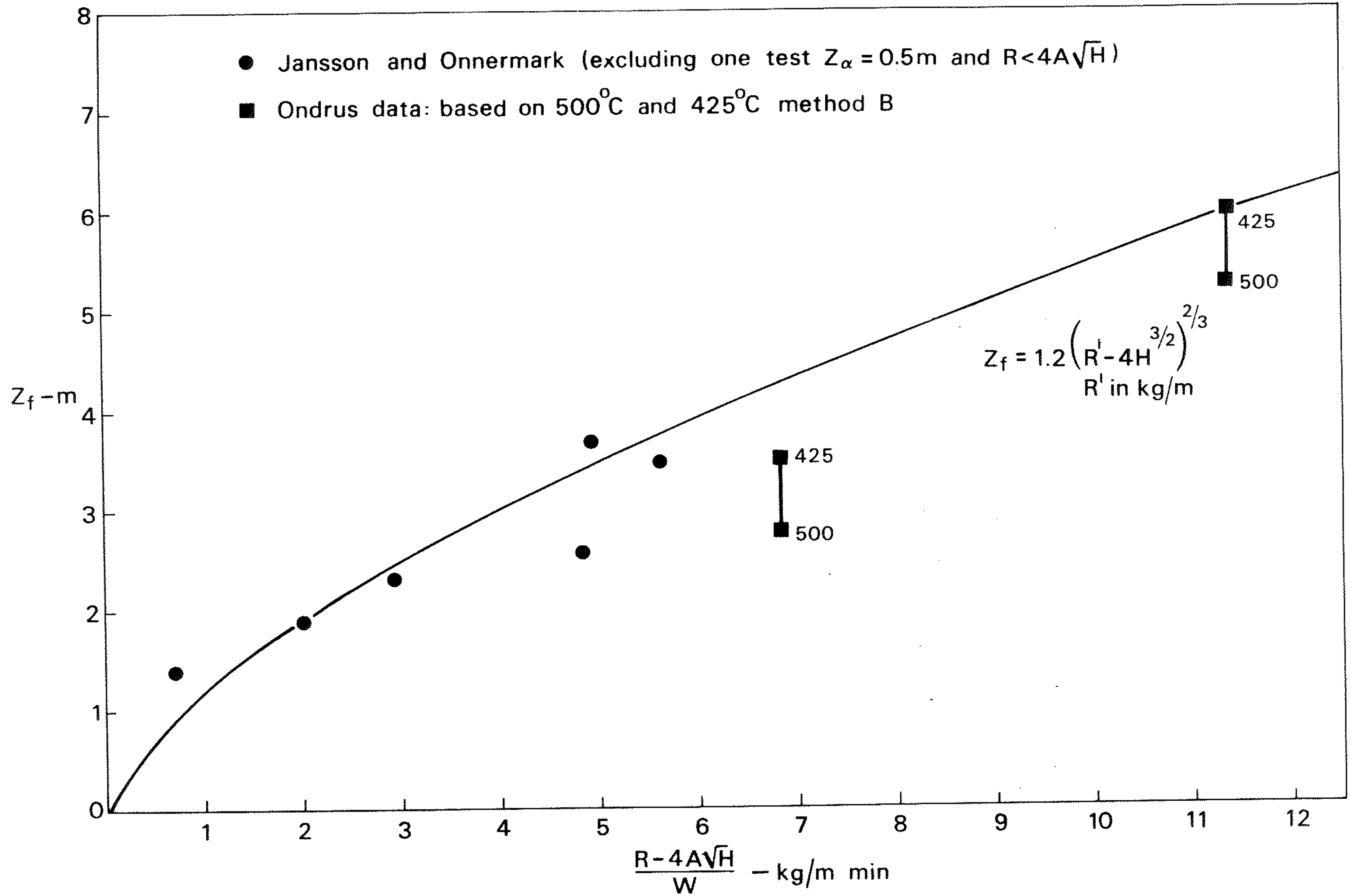

Figure 4 Correlation of flame length based on $4A\sqrt{H}$