Fires in Enclosures with Single Ventilation Openings - Comparison of Long and Wide Enclosures

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ABSTRACT

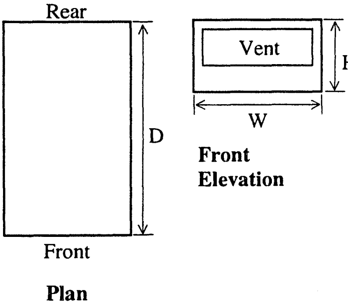
The rate of burning of fires in enclosures is usually assumed to be proportional to the ventilation factor $A\sqrt{h}$. This paper reports an experimental program designed to investigate the influence of opening width and enclosure shape on the burning rate by comparing the burning rate and behaviour of fires in long enclosures and wide enclosures with similar openings. Fire tests were conducted in enclosures 1500 mm by 600 mm by 300 mm high with ventilation openings of several widths. It was found that the burning behaviour and fuel mass loss rates of fires in long and wide enclosures differ markedly when the width of the ventilation opening is less than the full width of the enclosure. When the ventilation opening width is equal to that of the enclosure, the flows within the enclosure are essentially two dimensional, but when the opening width is less than that of the enclosure the flows within the enclosure are more complex and three dimensional. The mass loss rates for the same opening sizes in wide enclosures were found to be substantially greater than those in long enclosures for both full width (in the long enclosure) and partial width openings.

Key words: Burning rate, mass loss rate, enclosure fires, ventilation factor, enclosure shape

INTRODUCTION

The rate of burning (as measured by heat release rate or mass loss rate) in enclosure fires is usually assumed to be proportional to the ventilation factor $A\sqrt{h}$ where A is the area of the ventilation opening and h is its height [1]. It is also usually assumed that, following flashover, the gases in the enclosure are well stirred and that there is no net flow created by buoyancy within the enclosure [1].

The form of enclosure considered and nomenclature used in this paper are shown in Figure 1.



Notes:

Ventilation opening in front wall only.

W = enclosure width
D = enclosure depth
H = enclosure height
w = vent width
h = vent height

FIGURE 1. Enclosure Details

Examination of the results of fire tests using uniformly distributed wood cribs within large enclosures of this form [2,3] indicates that these assumptions may be invalid in some circumstances. In these tests (which are discussed in more detail in [4]) ignition in several of the tests took place at the rear of the enclosure (that is, as far from the single vent as possible)

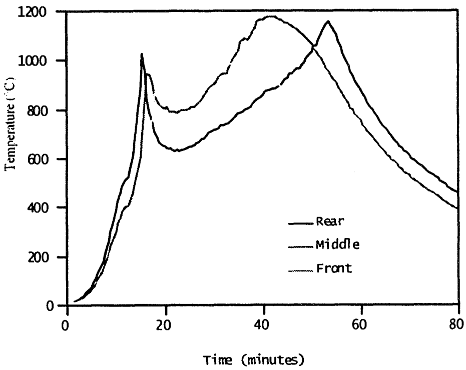


FIGURE 2. Temperature - Time Relationships for Long Enclosure with Wood Cribs as Fuel (W = 5.6 m, D = 22.9 m, H = 2.8 m, ignition at rear)

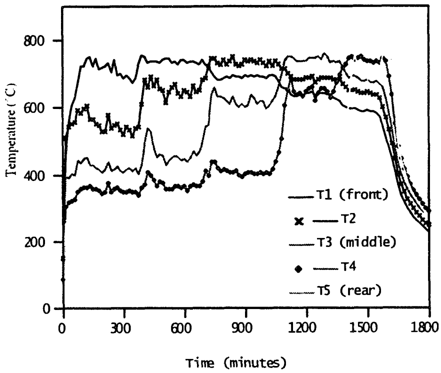


FIGURE 3. Temperature - Time Relationships for Long Enclosure with Trays of Liquid Fuel (W = 0.3 m, D = 1.5 m, H = 0.3 m)

and, following a short period of growth in that region, the fire progressed towards the front of the enclosure without burning all of the fuel. Once burning was established at the front of the enclosure it ceased at the rear of the enclosure as noted by observers [3] and indicated by the temperatures at various locations within the enclosure (Figure 2). The fire then proceeded to burn back through the enclosure as the more forward fuel was consumed. Comparison of the results of these tests with those for shorter enclosures also indicated that the relationship of the burning rate to the ventilation factor ($A\sqrt{h}$) may also be significantly affected by the enclosure shape.

Programs of tests in small enclosures using wood cribs (with and without accelerant consisting of 96% ethanol and 4% methanol) and trays of liquid fuel (96% ethanol and 4% methanol) have demonstrated the same behaviour [4,5]. In these tests, fires ignited at the rear of the enclosure always progressed towards the front of the enclosure without consuming much of the fuel available at the rear. Once the fire was established at the front of the enclosure flaming ceased further back in the enclosure, and the remaining fuel was consumed from the front of the enclosure to the rear as indicated by the temperature-time curves for a typical test (Figure 3) [4].

Detailed examination of summarised results of tests conducted as a CIB international cooperative program [6] also indicates that the enclosure dimensions might influence the rate of burning as much or more than the ventilation factor. Table 1 presents a summary of the CIB results for each size of ventilation opening tested. It can be seen that there is very wide variation in the mass loss rates obtained for each vent size. Detailed examination of the results and regression analysis indicates that, even after the effects of the spacing of the sticks used in the cribs is accounted for, there remains wide variation in the mass loss rate for each opening size. The strongest remaining influences in the correlation are the opening height (which in these tests was always equal to the enclosure height, that is $h = H$) and the **width of the enclosure**, rather than the width of the vent [4]. If the burning rate was indeed proportional to the ventilation factor $A\sqrt{h}$ (that is, proportional w and to $h^{1.5}$) the opening width would be expected to have the stronger influence.

TABLE 1 Range of Mass Loss Rates for Vent Sizes in CIB Tests

Vent Size w x h (mm)	Number of Tests	Range of R_{8030} (g/s)
125 x 500	5	3.5 to 4.7
250 x 500	15	2.8 to 12.2
250 x 1000	15	13.5 to 25
500 x 500	17	0.5 to 27.8
500 x 1000	29	30.5 to 72.8
750 x 1500	15	48 to 168
1000 x 500	12	11.2 to 36.8
1000 x 1000	22	5.7 to 93.8
1500 x 1000	1	119
1500 x 1500	3	240 to 283
2000 x 500	2	47.3 to 48
2000 x 1000	29	28.2 to 139
3000 x 1500	18	32 to 425
4500 x 1500	1	370
6000 x 1500	3	355 to 479

Note: R_{8030} is the rate of burning during the period in which the fuel mass fell from 80% to 30% of its initial value [6]

This paper reports an experimental program designed to investigate the influence on the burning rate of opening width and enclosure shape by comparing the burning rate and behaviour of fires in long enclosures and wide enclosures with similar openings. The influence of the opening height h is not addressed as the opening height was varied only slightly.

EXPERIMENTAL PROGRAM

The enclosures used were all 1500 mm by 600 mm by 300 mm high (interior dimensions), with the roof, floor and walls of 3 mm steel sheet except as noted below.

In each test five litres of liquid fuel (96% ethanol and 4% methanol) in ten trays each 250 mm square and 25 mm high (each containing 500 ml of fuel) was burned with the tray furthest from the vent ignited first when the ambient temperature made this possible. If the ambient temperature was sufficiently high the flames flashed briefly throughout the enclosure before stable burning commenced in the front of the enclosure adjacent to the vent. When burned in the open, trays containing the same quantity of fuel burned in an average of 418 seconds.

Temperatures were recorded using ten thermocouples each 25 mm from the roof and placed centrally over a tray of fuel (Figure 4). The fuel mass loss was recorded by weighing the entire enclosure.

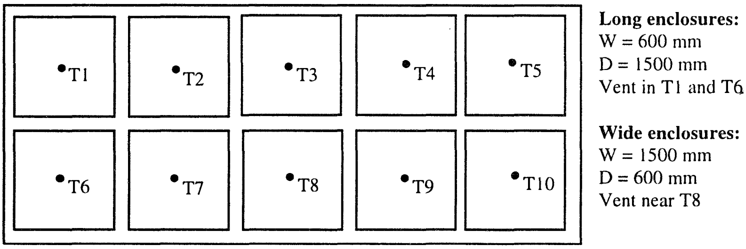


FIGURE 4. Tray and Thermocouple Positions and Numbers

In all tests one long wall of the enclosure was glass so that the behaviour of the fire inside the enclosure could be observed and recorded. In the long enclosure tests the short wall incorporating the vent was also made of glass. The vent and enclosure shapes tested are shown in Table 2.

OBSERVATIONS

The burning behaviour in the long and wide enclosures was significantly different except when the vent width was equal to the width of the enclosure (w = W).

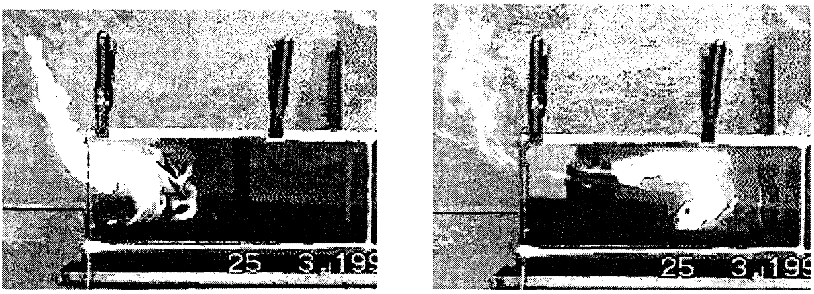
In the case of full width vents (w = W) the behaviour was as indicated in Figures 5, 6, 7 and 9. Figure 5 shows that when burning was at the front of the enclosure a flame front established itself at the front of the front trays (rather than over the whole tray as happened when burned in the open). When the fuel in those trays was exhausted the flame front jumped to the front of the next row of trays where it proceeded to burn until the fuel in each tray was exhausted. It then jumped to the next rearward tray and so on until finally the fuel in the rear most row of trays was exhausted. The flame front extended over the full width of each tray and close to the lip of the tray was quite thin, except as noted below. Burning took place in three phases or stages but the mass loss rate was essentially constant throughout each test (Figure 9).

TABLE 2 Summary of Tests

Test	Vent Size w x h (mm)	Enclosure Shape W x D (mm)	Mass Loss Rate at Various Phases of Burning (g/s)			Duration of Burning (s)	Maximum Temperature (°C)
			I	II	III & IV		
137	1500 x 275	1500 x 600	-11.2			475	909
132	600 x 275	1500 x 600	-7.8	-5.2		707	939
93	600 x 300	600 x 1500	-2.7			1669	822
94	600 x 300	600 x 1500	-2.8			1592	776
95	600 x 300	600 x 1500	-2.9			1515	823
119	600 x 300	600 x 1500	-3.0	-2.1		1605	809
126	300 x 275	1500 x 600	-3.6	-5.0	-2.7	1212	802
133	300 x 275	1500 x 600	-3.4	-4.9	-2.5	1125	813
141	300 x 275	600 x 1500	-3.5	-2.1	-1.6	2200	853
142	300 x 275	600 x 1500	-3.2	-2.1	-1.5	2208	814
145	200 x 275	1500 x 600	-3.1	-3.6	-2.0	1615	768
146	200 x 275	1500 x 600	-2.7	-3.9	-1.9	1595	787
143	200 x 275	600 x 1500	-2.9	-1.8	-1.1	2688	740
144	200 x 275	600 x 1500	-2.9	-1.8	-1.1	2684	744

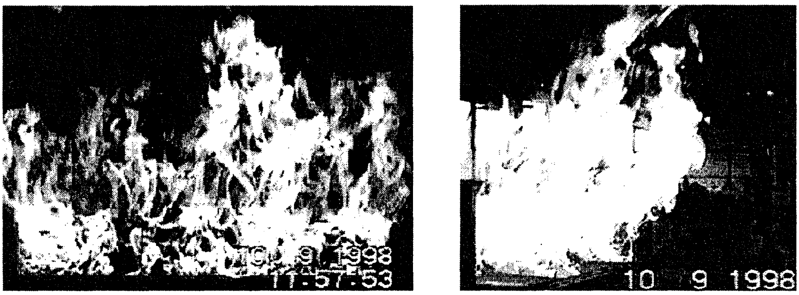
In the initial phase, with burning in the front row of trays, the flow through the vent was somewhat less stable than in the second stage. However the flow was essentially the same, with ambient air entering the enclosure at the bottom of the vent and moving along the bottom of the enclosure until the fuel was reached. At this point flames curved backward and upward. When the flames collided with the roof they split, the majority moving forwards towards the vent, with a smaller component moving towards the rear of the enclosure (Figure 5).

The second phase was when burning was in the second and subsequent rows of trays with the flow mentioned previously more strongly formed and well defined. The exiting flames and hot gases occupied approximately the top third of the enclosure between the burning trays and vent. The third phase occurred when the fuel in the rear most tray was burning with the flame front generally becoming somewhat thicker, apparently due to the influence of the back wall. In all of these phases, the behaviour was essentially two dimensional, that is, looking from one side of the enclosure to the other there was no significant change across the width. Thus a narrow full height slice along the length of the enclosure would adequately represent the entire enclosure. The temperatures in the enclosures reflected the observations above (Figures 6 and 7). Initially, after stable burning commenced, high temperatures initially occurred only at the front of the enclosure, with higher temperatures gradually occurring towards the rear of the enclosure as the flame front moved to the rear. Thus the front of the enclosure experienced high temperatures for longer than the rear of the enclosure.



(a) After moving forward burning takes place at front of trays closest to vent

(b) After fuel in front trays is exhausted burning takes place at front of rear trays



(c) From front, appearance is of enclosure fully involved

(d) Diagonal view, some front trays empty, others still burning

FIGURE 5. Burning in Wide Enclosures Full Open at Front (Ignition at rear)

In the long enclosures when the vent was not the full width of the enclosure ($w < W$, $D > W$) there were four phases of burning (Figure 10). The third and fourth phases were essentially the same as the second and third phases mentioned above for the full width vent case. That is, once the burning was well back from the vent, the behaviour appeared essentially the same as in the full width vent case - essentially two dimensional away from the vent. However this was not so when the burning was at or near the front of the enclosure (phases I and II burning). It was apparent that when the burning was close to the vent the flame front essentially extended across only the width of the trays directly exposed to the vent. As the flames travelled back across the trays they spread laterally and continued to do so as they rose towards the roof and then (mostly) travelled forward towards the vent, with a small proportion of the gases moving towards the rear of the enclosure. The sides of the forward moving flow collided with the front wall on each side of the vent and were deflected sideways and backwards into the adjacent regions of the enclosure. Thus, during this period, there was much stronger circulation of hot gases within the enclosure which picked up and transported fuel towards the vent.

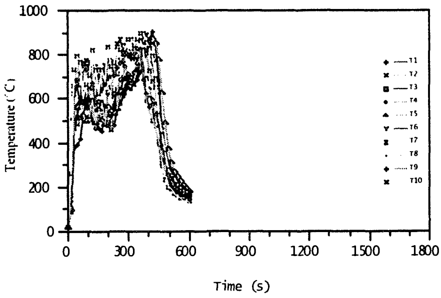


FIGURE 6 Temperature-Time Relationships for Wide Enclosure with Opening 1500 x 275 mm (w = W)

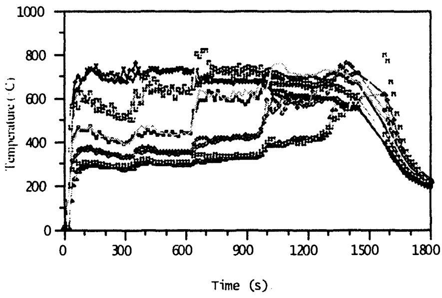


FIGURE 7 Temperature-Time Relationships for Long Enclosure with Opening 600 x 300 mm (w = W)

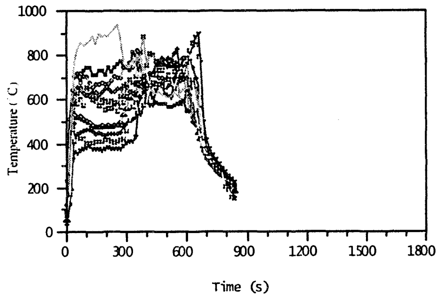


FIGURE 8. Temperature-Time Relationships for Wide Enclosure with Opening 600 x 275 mm (w < W)

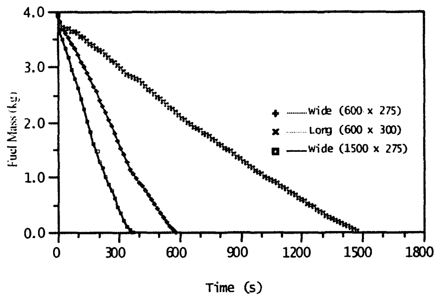
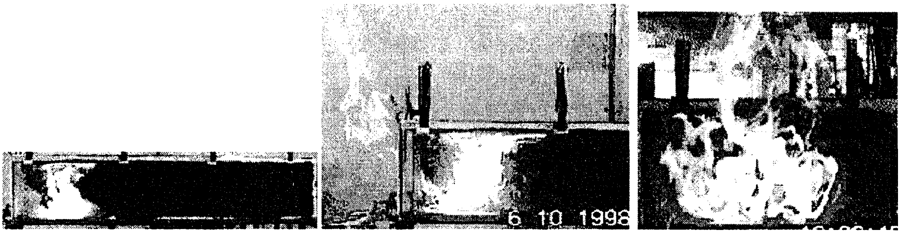


FIGURE 9. Comparison of Mass - Time Relationships for Wide and Long Enclosures

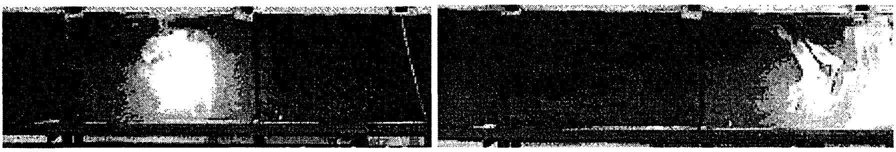
The flow through the vent was clearly rich in unburnt fuel during phases I and II and a large flame extended from the vent, larger than generally occurred in the long enclosure cases. Comparison of the temperature-time and mass-time plots for this case (Figure 13 with Figure 16 and Figure 15 with Figure 17) indicates that although the mass loss was high during phases I and II the temperatures in the enclosure were generally less than during the later phases, even though the mass loss rates at that stage were lower. This is similar to the behaviour observed in a recent test with wood cribs in a long enclosure (4,5). It was apparent that the behaviour during the first phase of burning in these tests was essentially three dimensional, with the flows in the enclosure having a component both along the enclosure and across the enclosure.



(a) After ignition at rear, burning progresses rapidly to front

(b) When burning of front tray is well established the flames emanate from the front of the tray and rise rapidly towards the roof

(c) From the front and side, some front trays empty others still burning



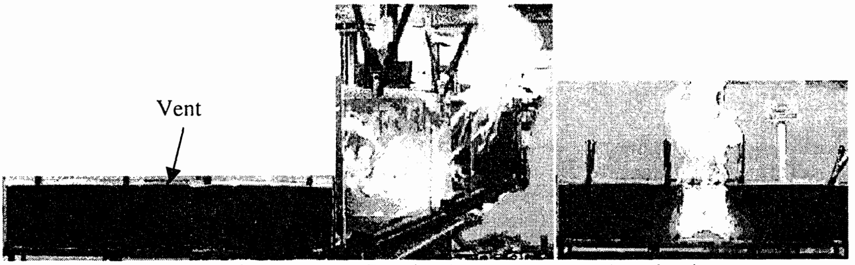
(d) Burning in third row of trays

(e) Burning in the rear tray with the fuel nearly exhausted

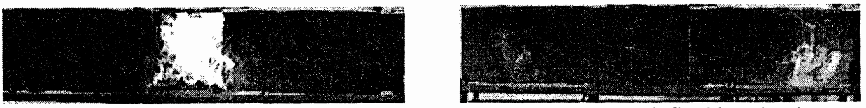
FIGURE 10. Burning in Long Enclosure with Partial Width Vent (Ignition at Rear)

The second phase of burning in these enclosures was essentially a transition between the first phase and the later phases, but was still clearly three dimensional. Combustion took place further back from (but still close to) the vent. As the fuel towards the front of the enclosure was used up the appearance gradually changed to the two dimensional flows described above for the full width vent cases, except in the region close to the vent.

The burning in the wide enclosures with a partial width vent ($w < W$, $D < W$) was clearly three dimensional throughout, but there were three phases of burning still apparent (Figures 11). In this case, phase I consisted of burning across the front of the most forward trays, with the width of the flame front at the front of the tray equal to the width of the vent. As the flames travelled across the tray(s) they spread laterally and continued to do so when they swung upwards and when deflected by the roof, mostly forward towards the vent with a smaller proportion towards the rear of the enclosure. A substantial proportion of the forward moving flow was deflected by the front wall of the enclosure into the adjacent areas of the enclosure. They then travelled laterally, looping back lower in the enclosure where they collided in the middle and joined the flow out of the enclosure, underneath the hotter gases exiting the enclosure without recirculation.



(a) Before Ignition, glass front with 300 mm wide opening (b) Burning in tray near vent (tray T8) (c) Burning in rear tray (tray T3)



(d) Burning fuel primarily from trays T3, T7 and T9 (e) Fuel nearly exhausted, final burning in trays T6 and T10

FIGURE 11. Burning in Wide Enclosure with Partial Width Vent (Ignition at Rear)

It was apparent during this and the subsequent phase that the flow of flames and hot gases exiting the enclosure occupied a substantially greater depth than in the full width vent case, generally over half the depth of the vent and often two-thirds or more of the depth.

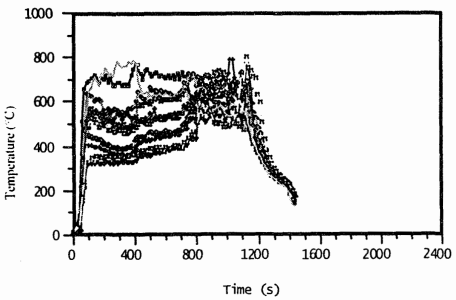


FIGURE 12 Temperature-Time Relationships for Wide Enclosure with Opening 300 x 275 mm

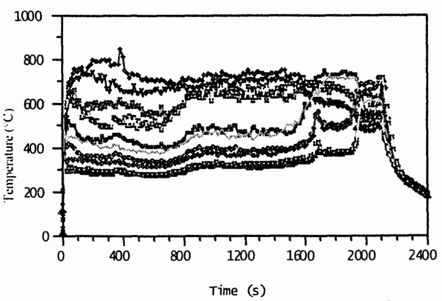


FIGURE 13 Temperature-Time Relationships for Long Enclosure with Opening 300 x 275 mm

Once the fuel directly adjacent to the vent was burnt, the flame front moved back to some extent from the vent, but the same general flows were apparent. There was an area clear of flames (but largely surrounded by flames) that was the path for in-flowing air moving towards the rear tray(s) in the region directly behind the vent. The flames were confined to the region of the enclosure behind the vent with some broadening of the flames towards the rear at mid-height and towards the front at the top (Figure 11(c)).

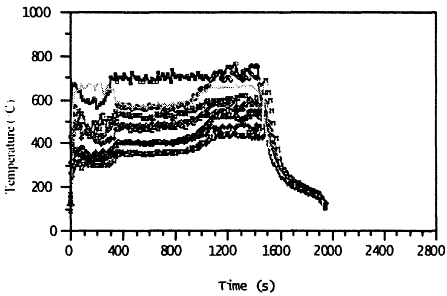


FIGURE 14. Temperature-Time Relationships for Wide Enclosure with Opening 200 x 275 mm

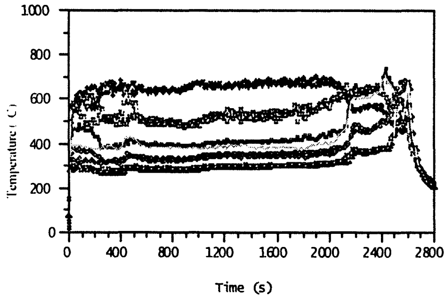


FIGURE 15. Temperature-Time Relationships for Long Enclosure with Opening 200 x 275 mm

Once the fuel directly adjacent to the vent was burnt, the flame front moved back to some extent from the vent, but the same general flows were apparent. There was an area clear of flames (but largely surrounded by flames) that was the path for in-flowing air moving towards the rear tray(s) in the region directly behind the vent. The flames were confined to the region of the enclosure behind the vent with some broadening of the flames towards the rear at mid-height and towards the front at the top (Figure 11(c)).

When the fuel from the trays in line with the vent was consumed, burning transferred to the trays on each side of them, in effect creating two separate fires. The flames and out-going flows from these fires collided behind the vent and created the flow that came out of the vent, generally filling half to two-thirds of the vent. (Unfortunately, due to soot build-up on the glass, these flows are not entirely apparent in Figure 11 but are able to be seen in the video record from which the images in Figure 11 were taken.)

The order of burning in these tests (once burning near the vent was established) was tray 3, tray 8, then trays 7 and 9, then trays 2 and 4, then trays 6 and 10 and finally trays 1 and 5. However, in some tests burning in some trays was never apparent, because much of the fuel in trays away from the opening was evaporated and transported towards the opening. This is similar to the behaviour observed in other tests with both liquid and solid fuels [4,5] .

DISCUSSION

Comparison of the fuel mass loss rates in each phase of burning (Table 2 and Figures 9, 16 and 17) reveals that:

1. for the enclosures with the vent across the full width of the enclosure (w = W, Tests 93, 94, 95, 119 and 137, Figure 9) the mass loss rates are essentially constant through the test with the rate for the 1500 mm wide vent (in the 600 mm deep enclosure) being 3.7 to 4.1

times those for the 600 mm wide vent (in the 1500 mm deep enclosure) compared to a 2.5 times increase in width and slight decrease in opening height

2. for the enclosures with 600 mm wide openings (Tests 93, 94, 95, 119 and 132, Figure 9) the mass loss rate for the wide enclosure (w < W) case (Test 132) is on average 2.7 times the mass loss rates for the long enclosure (w = W) cases even though there is a slight decrease in opening height

3. for the other enclosures with partial width vents (w < W, Figures 16 and 17) the mass - time curves for the long and wide enclosures are virtually identical during phase I burning but differ considerably in phases II, III and IV with the mass loss rates for the wide enclosures being about 2.4 and 2.1 times those for the long enclosures for the 300 mm and 200 mm wide vents respectively during phase II and about 1.8 for both vent sizes during phases III and IV

4. the maximum temperatures in the tests were generally (but not always) higher for the tests with shorter durations of burning and lower for those with longer durations

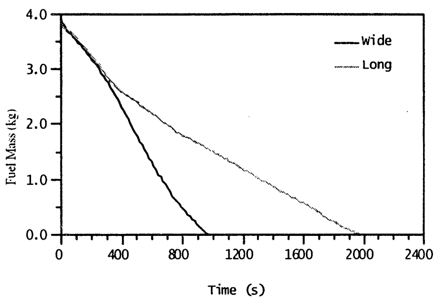


FIGURE 16. Comparison of Mass-Time Relationships for Wide and Long Enclosures with Vents 300 x 275 mm

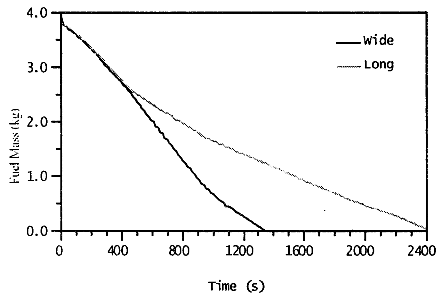


FIGURE 17. Comparison of Mass-Time Relationships for Wide and Long Enclosures with Vents 300 x 275 mm

Thus, in summary, the burning rates for a given vent size in wide enclosures were substantially higher than those for long enclosures - the ratios in the enclosures tested varying from 1.8 to 2.7.

These differences in mass loss rates are reflected in slightly smaller relative changes in the duration of burning - the ratios in the enclosures tested varied from 1.7 to 2.3.

Examination of Figures 6 to 8 and 12 to 15 reveals that the regions of the enclosures closest to the vents experienced higher temperatures for longer than those regions remote from the vents. In addition, comparison of the mass loss curves with the temperature curves reveals that the temperatures in the enclosures were higher in the latter phases of the tests even though the mass loss rate was lower than earlier in the tests. Based on the observed behaviour this was due to the withdrawal of the burning from the region of the vent (in addition to a substantial flame outside the enclosure) into the regions of the enclosure remote from the vent. Thus, more of the heat was released within the enclosure than earlier in the test where a substantial proportion of the mass loss was associated with heat released outside the enclosure.

CONCLUSION

Based on the limited range of enclosures covered in the experimental program the behaviour of a fire in an enclosure with a full width opening is substantially different from that in an enclosure with a partial width opening. In addition, the behaviour of a fire in a long enclosure with partial width opening ($w < W$, $D > W$) is different from that in a wide enclosure with a partial width opening ($w < W$, $D < W$) once the burning moves from the region of the vent.

This results in average mass loss rates in long enclosures being substantially less than those that occur in wide enclosures with the same size vent - in the enclosures covered in this experimental program the average mass loss rates in the long enclosures were from 0.35 to 0.56 those in the wide enclosures with the same size vent.

These differences significantly effect the durations of fires in such enclosures and thus the length of time that the boundaries and exposed structure in the enclosure are subjected to high temperatures - in the enclosures covered in this experimental program the fire durations in the long enclosures were from 0.43 to 0.59 those in the wide enclosures with the same vents.

It is also apparent that the assumptions mentioned in the introduction are invalid for the enclosures tested.

ACKNOWLEDGMENTS

The authors are grateful to Rob Ralph, Michael Culton and Paul Tisch for carrying out the experimental program and to BHP for funding the research

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