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AIR STARVED COMPARTMENT FIRE ANALYSIS ON DIFFERENT WOOD CRIB SIZES

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Abstract

Pine wood cribs of fixed spacing and height with varying stick length and number of sticks were burnt in a 1.57m^3 fire enclosure to study compartment fires at a low ventilation rate of 10 air changes per hour, the effect of increasing the fire load by increasing the length of the stick shows that increasing the mass of the wood crib and increasing the length of the sticks affects the manner in which the cribs burn. A two phase combustion occurred with the larger wood cribs, with auto-ignition giving rise to the two phase combustion. All heat release rates were similar expect for the second smallest crib which gave a higher value of 14kW. It was however, observed that the heat release rate by mass loss rate over predicts the one by oxygen consumption by a factor of 6. The second smallest wood crib behaved differently giving rise to high values in all the results.

Keywords: Wood crib, Ventilation, Combustion, Compartment fires, Heat release rate.

1.0 Introduction

Compartment fire is used to describe a fire which is confined within a room or similar enclosure within a building (1). The presence of walls and ceilings in compartment fires makes them quite different from those fires burning in the open air (2). In free space or open air fires, most of the heat and smoke generated would be lost to the ambient rapidly whereas in compartment fires, the heat and smoke generated would be confined in the upper part of the compartment and then lost to the environment through exits from the room. Compartment fire can be divided into three stages (1) namely: growth or pre-flashover stage, fully developed or post-flashover fire and decay period.

An air starved fire has low air inlet and low fire gases outlet as in the fire rig test facility used by Andrews et al. (3, 4, 5, and 6). The air inlet and the exit of the gases all occur within the same opening but in the case of the fire rig used by Andrews et al., which is air starved fires, the air comes in through the bottom of the rig while the gases escape through the exhaust at the top of the compartment at a controlled ventilation rate.

Fire in an enclosure is well ventilated at its initial stage because enough oxygen is available. The oxidation process dominates and the fire is easy to control and extinguish, but if the fire is allowed to grow, especially with limited ventilation and large surface area of the burning material, less O_2 is available, the reduction process dominates and increasing amounts of the products of incomplete combustion are generated, creating dangerous conditions (7). Polymers containing only carbon, hydrogen and oxygen will give carbon dioxide (CO_2) and water when they undergo complete combustion, but less complete combustion will also give a mixture of pyrolysis products e.g. Carbon monoxide (CO), hydrocarbons (HCs), oxidative pyrolysis products, such as organo-aldehydes, and particulates (8).

This work compares the temperature obtained during the experiment with the temperatures measured during the full-scale experimental air starved compartment fires.

2.0 Basic Calculations

Mass loss rate (g/min) = $\dfrac{\Delta mass}{\Delta Time}$

The heat release rate by O_2 consumption was calculated using the equation:

$$HRR\ (O_2) = 0.232\left(1-\frac{O_2}{20.9}\left(1+{F}/{A}\right)\right)\times\left(ventilation_{rate}\left({kg}/{s}\right)\right)\times 13.1\,{MJ}/{kg}\ ({MJ}/{s})$$

Where:

HRR = Heat release rate (MJ/s)

O_2 = is the concentration of oxygen (%)

The heat release rate by mass loss rate was calculated using the formula below:

HRR= Mass loss rate x Calorific value

Equivalence Ratio $\phi = \dfrac{AFR_{stoichiometric}}{AFR}$

The mass of air to fuel ratio is obtained by dividing the measured entrainment of air into the fire chamber by the mass loss rate as shown below;

$$Mass\ AFR = \left(\frac{Air\ \ flow(kg/s)/3.6}{Fuel\ \ mass\ loss\ rate\ (g/s)} \right)$$

The air to fuel ratio using this method is not very accurate and sort of misleading because it assumes that all the air entrained is used up by the fire. As such, the Chan's method was preferred which is more accurate. The generation of fire products in compartment fires can be quantified in terms of species yields, defined as the mass of species produced per mass of fuel burned (g/g).

3.0 Experimental Procedure and Equipment

3.1 The Fire Rig Test Facility

The 1.57m^3 fire rig test facility used by Andrews et al. (4, 5, 6, and 9), with dimensions 1.4m x 0.92m x 1.22m was used to carry out the experiments. The pine wood cribs were burnt in it using ethanol as accelerant.

Figure 1: Photograph showing the fire rig enclosure with wood crib inside

The fuel load (the pine wood crib) was burnt on a platform that was placed centrally in the test facility, this was supported on three legs that went through to three load cells in the air plenum below the fire test chamber. This cooled the load cells and allowed the fire mass burn rate to be determined. The load cells have a resolution of 1 gram and can accommodate a maximum load of 10kg. The early stages of the fire were observed through a high temperature air sealed glass door of the enclosure, this air sealed door was fitted with an outer door of 25mm thick insulation so that when the fire was fully developed there was no radiative heat loss through the glass door. The rig was set to use a forced ventilation rate from a compressor system through a thermal mass flow meter to maintain the air flow rate. A fixed ventilation rate of 20kg/hr which translates to about 10.68 air changes/hour was used for all the five experiments done. A computer was used for data log, i.e. for collecting the temperatures from the thermocouples. There is an arrangement of thermocouples of Type K in the rig that were used to determine the mean temperature of the fire. These thermocouples are 70mm from the ceiling and had an insulated outer diameter of about 3mm. After the fire developed, the fire product gases flowed across the ceiling and were exhausted from the fire through four slots around the edge. The products flowed along the backside of the ceiling and out through a 152mm short flue into a cowl and then with air entrainment into a discharge chimney with extraction fan where they are finally discharged to the atmosphere.

3.2 Fuel

The fuel used in this experiment is the pine wood cribs. The wood cribs were constructed by interlaying slots of wood to create a 3-dimensional lattice. Evo-stick wood glue was used to glue the struts together to prevent the wood from collapsing during the experiment. All the sticks had a cross-sectional dimension of 19 x 19mmsq. The wood cribs were untreated and the experiment was first tried with the wood cribs having large spacing between the sticks, for the larger wood crib, when a larger spacing was used, the wood just burnt in the middle and self extinguished. For this reason, the spacing was reduced so that there won't be enough air between the sticks to extinguish it.

Table 1: The Description of the pine wood cribs used

Stick Length (cm)	Weight (kg)	Air Changes/hour	Height (cm)	Spacing (cm)	Number of Layers	Total Number of sticks	Number of sticks per layer	Air Flow rate (kg/hr)
20	1.4	10.68	26.6	7.5cm	14	38	3	20
30*	3.1	10.68	26.6	7.5cm	14	50	4	20
40	4.6	10.68	26.6	7.5cm	14	62	5	20
50	7.1	10.68	26.6	7.5cm	14	74	6	20
60	9.6	10.68	26.6	7.5cm	14	88	7	20

The number of layers and spacing were kept constant so that only the number of sticks per layer varied. Ethanol was used as the accelerant to initiate the fire. The calorific value of the pine wood was considered to be 19MJ/kg (11). The elemental analyzer was used to determine the composition of the pine wood.

Table 2: Composition of the wood crib used

Element	MW (Molecular Weight)	% Mass	Volume for unitmass-mol	Mol. Ratio
C	12	47.25	0.4725/12 =0.0394	1
O	16	47.07	0.4707/16 = 0.0294	0.746
H	1	5.68	0.0568/1 = 0.0568	1.442

4.0 Results and Discussion

The 5.86kg/m^3 wood crib fire had its highest temperature of 532^{o}C at 89min, 537^{o}C for the 4.52kg/m^3 at 44min, 436^{o}C for the 2.93kg/m^3 at 31min, 434^{o}C for the 1.97kg/m^3 and 349^{o}C for the 0.89kg/m^3. From figure 16, the temperature curves shows that the temperature increase initially irrespective of the size of the wood crib. The three large wood cribs show an unsteady growth indicating two phase combustion but the smaller cribs showed a quite steady state growth. When compared with the temperatures obtained in the freely ventilated temperatures measured during full scale experimental compartment fires, the lightly loaded fire of 15kg/m^2 recorded a temperature of about 500^{o}C and the largest wood crib recorded around the same temperature. This shows that a realistic temperature has been obtained though if the experiment was carried out with free ventilation, the temperature would be much higher.

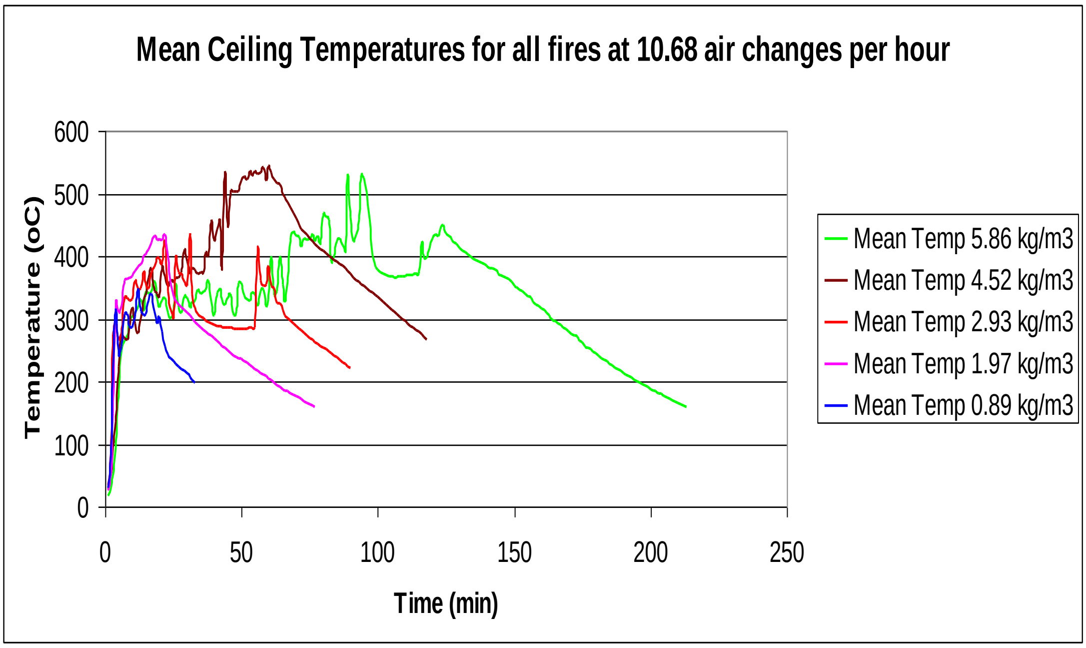


Figure 2: Mean ceiling temperatures over time

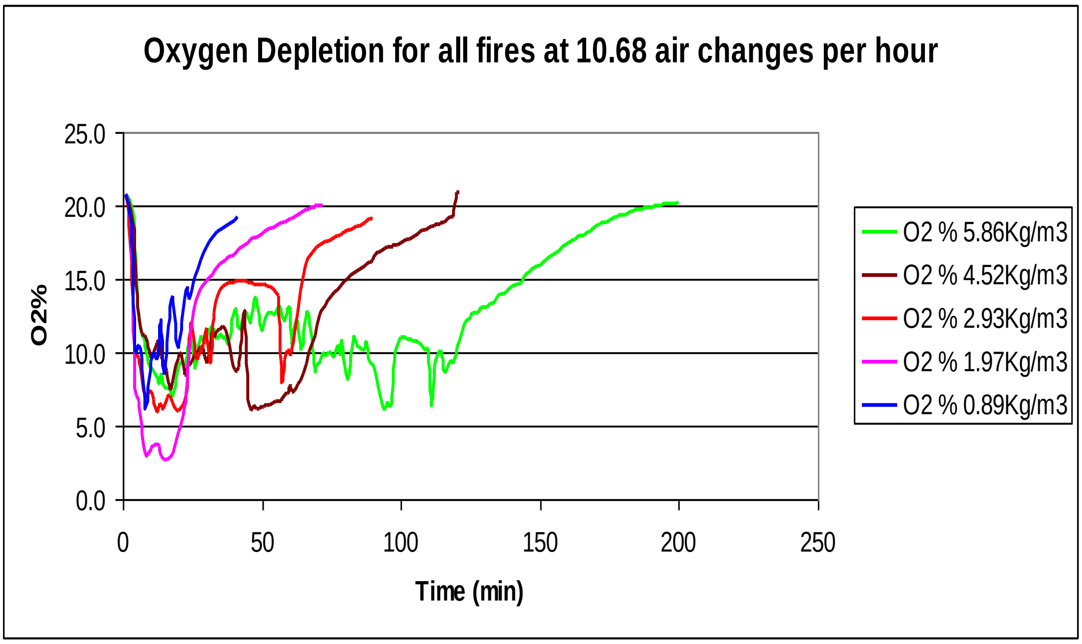


Figure 3: Oxygen Depletion over time for all fires

The 1.97kg/m^3 fire showed the lowest oxygen depletion which is quite strange, there was oxygen consumption to about 7% and then an increase at stages when the burning was slow and then a decrease again at stages where the auto-ignition was suspected to have occurred for the bigger cribs.

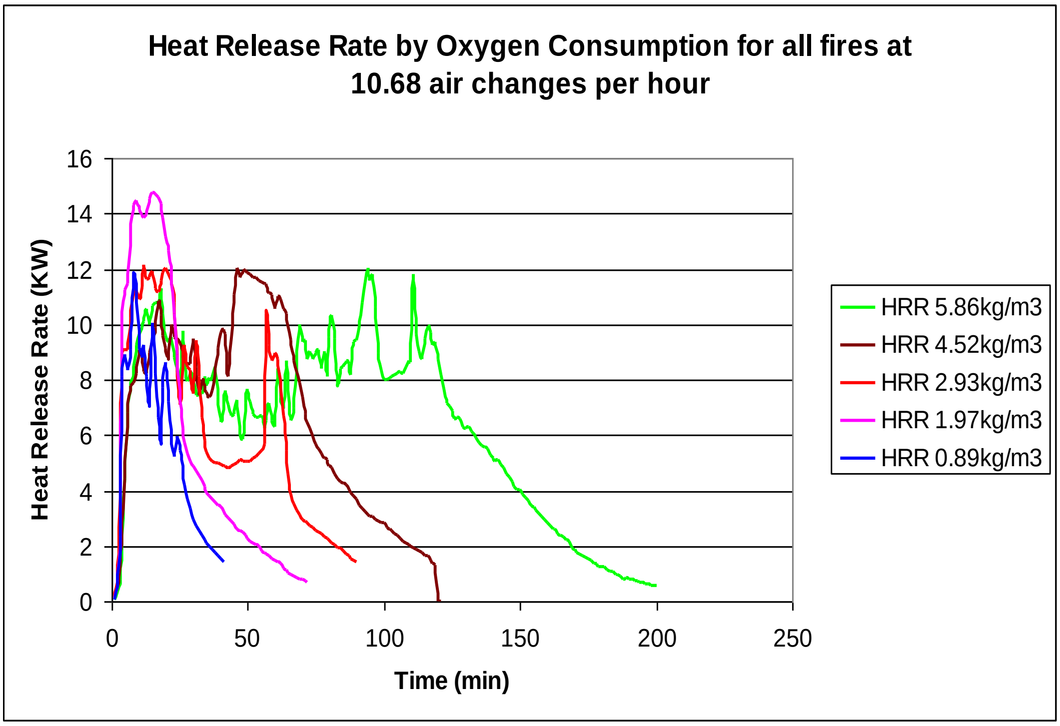


Figure 4: Heat Release rate by oxygen consumption over time

The heat release rate increase steadily at the early stages of the fire for all the fires. The 0.89kg/m^3 fire has a peak heat release rate of about 12kW in 8mins before decreasing steadily. The 1.97kg/m^3 fire followed the steady state curve pattern, getting to its peak heat release rate in about 16mins before starting to decay. The peak heat release of all the fires never went beyond 12kW, with the exception of 1.97kg/m^3 fire that was up to 14kW. It was however observed during the experiment that there was a loud sound when the larger wood cribs were burning. It is however assumed that it was auto-ignition, or cracking of the wood that occurred at that period leading to a sudden rise in the heat release rate as well as the temperature. Figure 4 shows that the larger wood cribs deviate from the t-squared fire which compartment fires are believed to exhibit where the initial growth period is nearly always accelerating with the assumption that the energy release rate increases as the square of the time but surprisingly the smaller cribs behaved conventionally. The larger the load, the longer the fire lasts.

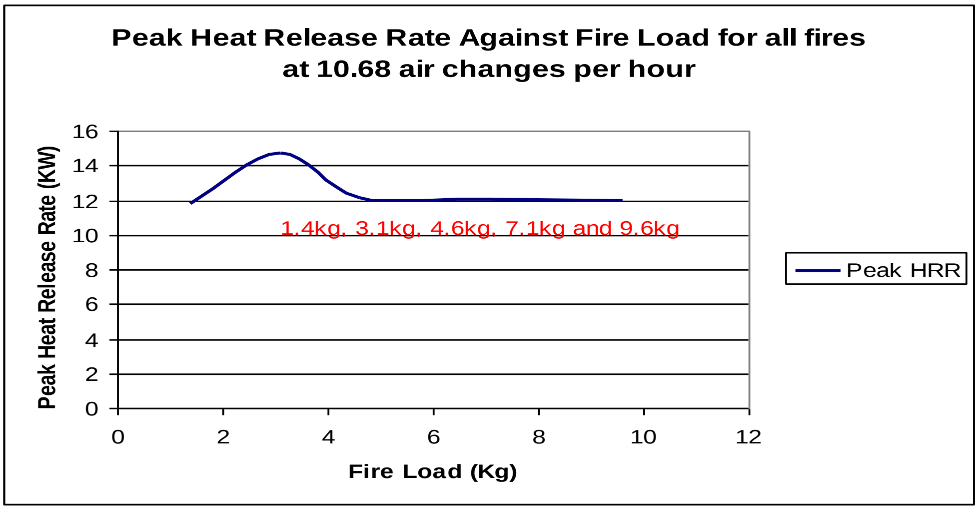


Figure 5: Peak Heat release rate against fire load over time

The mass loss rate for the three fires are shows that 5.86kg/m^3 fuel load was too large and it's weight could not be measured using the load cell, while that of 1.97kg /m^3 was giving errors so its values were ignored. Greater mass was lost at the stages where the burning was intense, that is having high heat release.

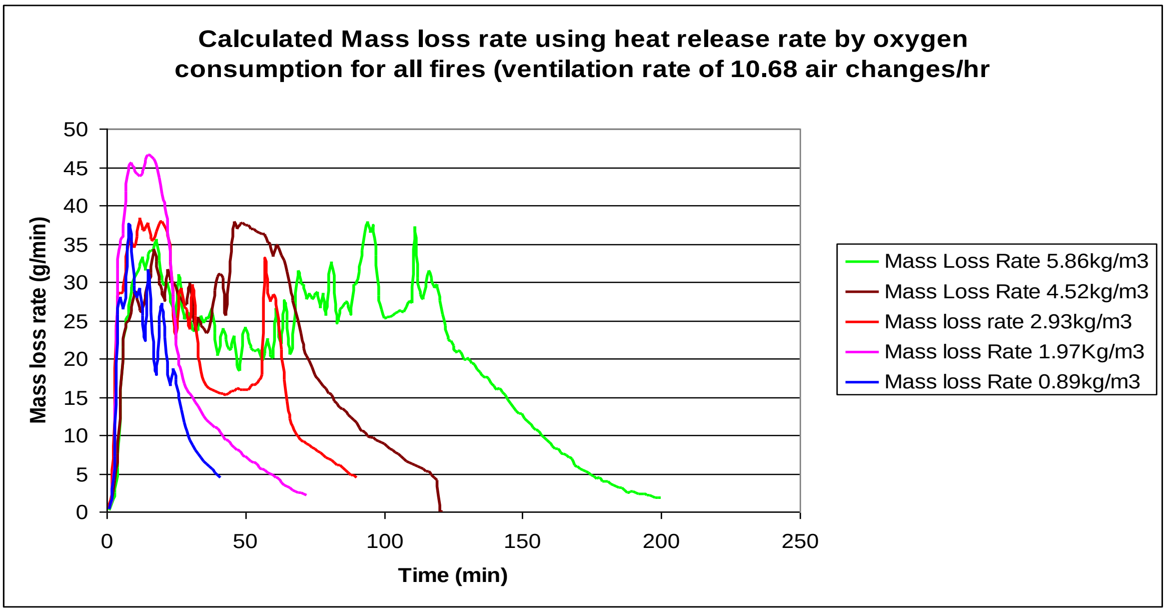


Figure 6: Calculated mass loss rate using heat release rate by oxygen consumption over time

The calculated mass loss rate using the heat release rate by oxygen consumption clearly shows a major disagreement with the measured mass loss rate. The measured mass loss rate is higher by a factor of almost 4.

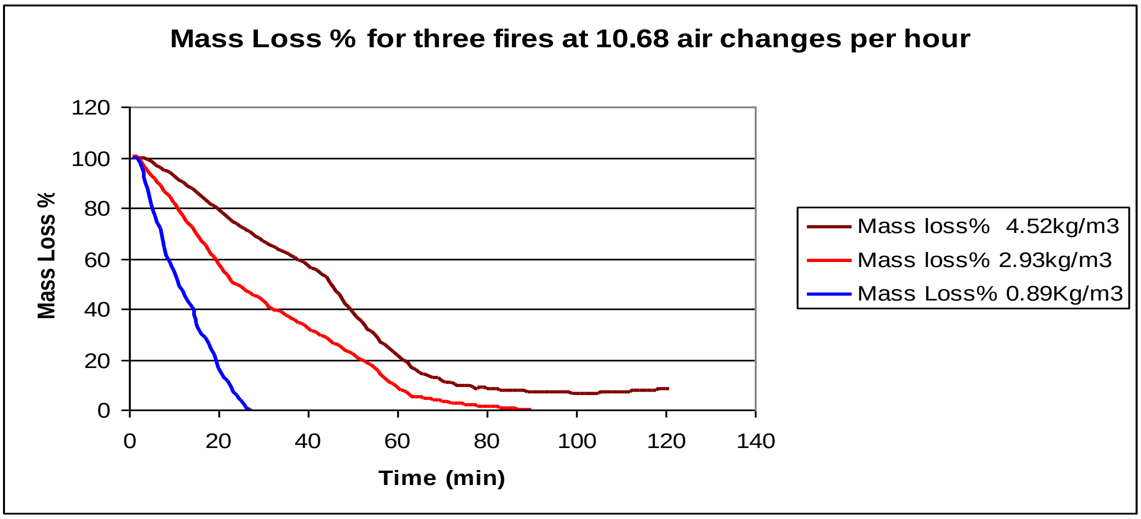


Figure 7: Mass loss % over time for three fires

The fire mass loss as a percentage of the initial mass is shown as a function of time as in figure 8 for the three fires. The three fires had a very similar initial fire development with the smallest wood crib burning faster. As expected the 4.52kg/m^3 fire burnt more slowly than the rest of the two wood cribs. The greater mass loss occurred after 20mins for the 2.93kg/m^3 fire, while a greater mass loss occurred at about 50mins for the 4.52kg/m^3 fire.

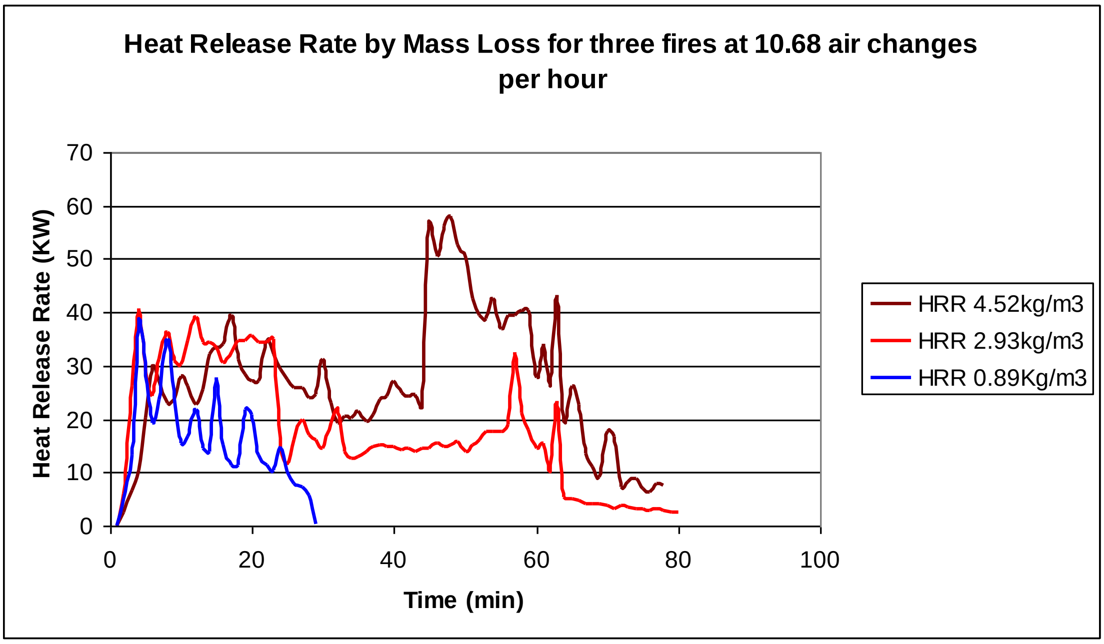


Figure 8: Heat release rate by mass loss over time

The heat release rate by mass loss rate over time estimates the heat release rate. For example the peak heat release rate for the smallest wood crib was 12kW using the oxygen consumption method while that of the mass loss rate was found to be 38kW, that of the 2.93kg/m^3 wood was 12KW using oxygen consumption method and 40kW using the mass loss rate method, the 4.52kg/m^3 was 12kW using the oxygen consumption method and 58kW using the mass loss rate method. This is more than a factor of 4 higher than that obtained by the oxygen consumption method, the oxygen method does not agree with that of mass loss rate method for wood cribs. Therefore, the heat release rate for mass loss needs to be corrected for combustion inefficiency due to CO effect. The fact that the two graphs take the same pattern suggests that there must be a factor missing out, which could be the oxygen in the wood. Previous work carried out by Andrews et al. on pool fires and other fire load showed that the two methods agree to some extent. Other researchers in the literature showed that the two methods agree, but their experiments were carried out with excess oxygen so the oxygen in the wood is not needed. But with limited ventilation, this is not the case.

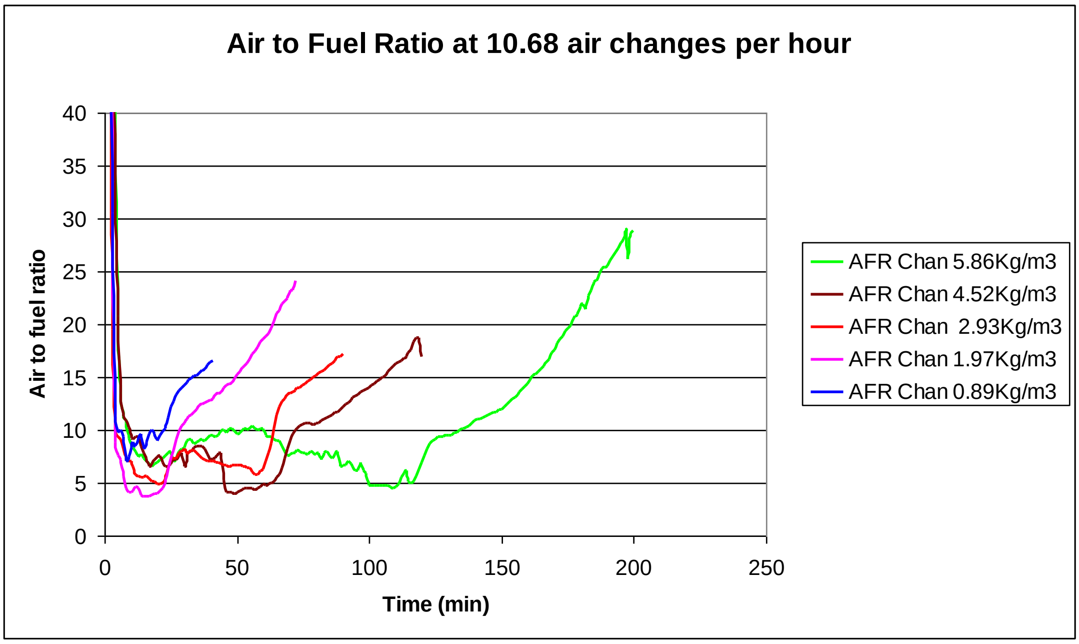
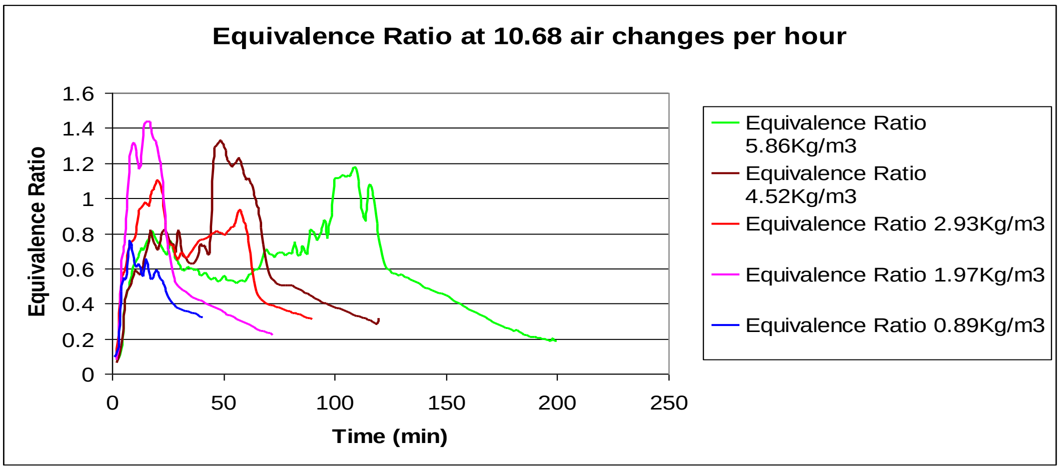


Figure 9: Air to fuel ratio over time



`Figure 10: Equivalence ratio over time

The air to fuel ratio was obtained by Chan's equation which was based on carbon balance of the main gases released by the fire. This showed the air consumption by the fire. The equivalence ratio shows that the smallest wood was over-ventilated or fuel lean with an equivalence ratio of less than unity, but all other fires indicated limited ventilation or fuel rich at some stage with equivalence ratio greater than unity. The stage where the heat release rate was highest indicated that the fire was burning rich and the air to fuel ratio was lowest at that stage. For the 2.93kg/m^3 fire, the fire burnt rich after 16mins of ignition before starting to burn lean. Although there was a sudden rise in temperature the fire was still lean.

Figure 12 and 11 show the main fire parameters i.e. mean temperature, oxygen depletion, heat release rate and equivalence ratio, the largest wood crib was chosen for the illustration.The oxygen depletion is the O_2% from the exhaust which shows how much oxygen is left after combustion, the heat release rate was obtained using the oxygen consumption method.

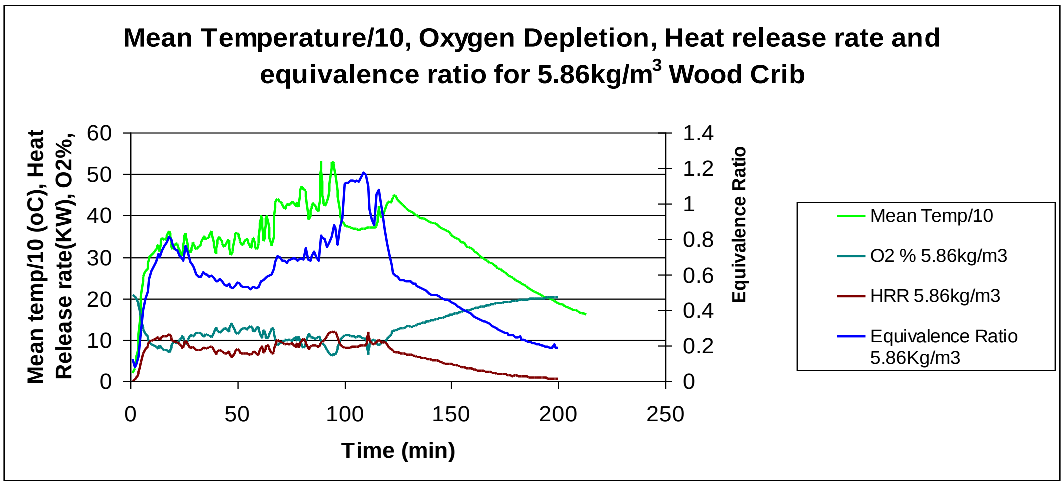


Figure 11: Mean temperature/10, oxygen depletion, heat release rate and equivalence ratio for the 5.86kg/m^3 fire

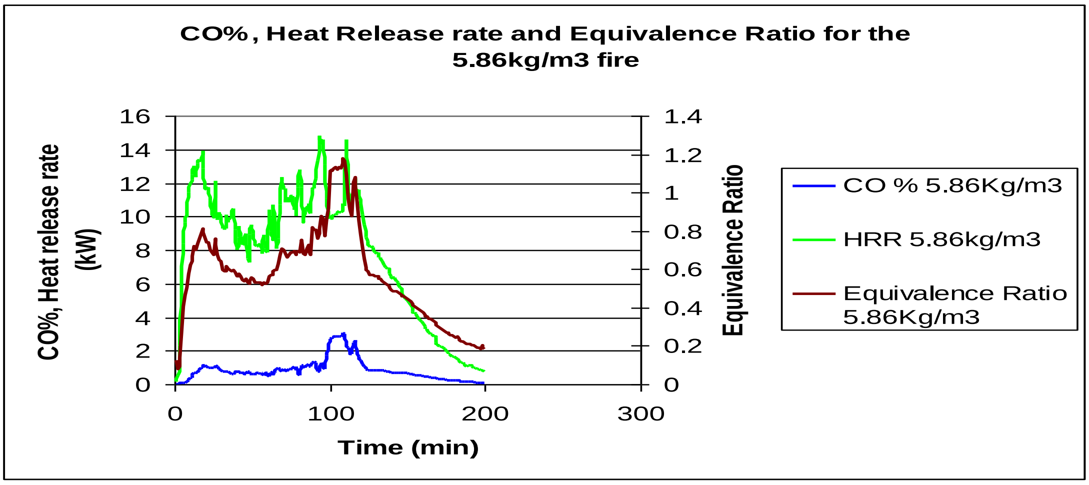


Figure 12: CO, heat release rate and equivalence ratio over time for the 5.86kg/m^3 fire

The largest wood with 5.86 kg/m^3 fire was off-scale and its weight could not be measured. The temperature increases as the heat released increases and the oxygen concentration decreases as the heat release rate increases, indicating that as heat is being released by the fire, oxygen is being consumed while it increased when the heat release rate was low. The equivalence ratio shows the type of burning taking place as the fire is burning. The equivalence ratio showed that the fire was burning lean at the early stage of the fire but burnt rich at the stage where the heat release rate was at its peak. This also corresponded to the stage where auto- ignition was suspected to have occurred. The temperature reached its peak of 532^{o}C in 89mins.

The heat release rate curve for 0.89 kg/m^3 wood does not follow the steady state curve for compartment fires when the bigger cribs were burnt, but surprisingly the smaller cribs behaved conventionally. The temperatures of the two smaller cribs were not significantly different but the heat release rate of the second smallest (1.97kg/m^3fire) was highest among all the fires, which is not what was expected. It was expected that the heat release rate increases as the load increased because it takes longer to burn. The 1.97kg/m^3 fire was taking heat from the initial source i.e. the hot wood; it had undergone a heat sink.

The oxygen consumption was highest at the peak heat release phase indicating that as the combustion is taking place and heat is being released, oxygen is being consumed because definitely the fire needs oxygen to burn. What is exciting though the 1.97kg/m^3 fire had the highest oxygen consumption which is okay as it has the highest heat release rate of about 14kW. The smallest crib (0.89kg/m^3 fire) didn't consume as much oxygen as the 1.97kg/m^3 fire which might be that it simply burned out fast or something to do with the access of oxygen into the compartment.

5.0 Conclusion

The effect of increasing the fire load by increasing the lengths of the stick has been observed. An additional heat release rate was experienced at the end of the bigger wood cribs indicating that auto-ignition took place and a two phase combustion occurred. The burning becomes slower as the load increases. Therefore, the orientation and arrangement of the wood cribs play an important role in the way the wood crib burns. There was a major disagreement between the heat release rate by oxygen consumption and heat release rate by mass loss, the heat release rate by mass loss was a factor of 5 higher than that obtained by oxygen consumption.

6.0 References

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