AN EXPERIMENTAL AND MODELING STUDY ON THE EFFECT OF OPENING LOCATION IN THE UNDER-VENTILATED COMPARTMENT FIRE

By

LUJIA WANG

Bachelor of Science in Mechanical Engineering

Oklahoma State University

Stillwater, OK

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AN EXPERIMENTAL AND MODELING STUDY ON

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UNDER-VENTILATED COMPARTMENT FIRE

Thesis Approved:

Dr. Haejun Park

Thesis Adviser

Dr. Robert Agnew

Dr. Virginia Charter

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Title of Study: AN EXPERIMENTAL AND MODELING STUDY ON THE EFFECT OF OPENING LOCATION IN THE UNDER-VENTILATED COMPARTMENT FIRE

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Abstract: For compartment fires, a series of reduced-scale experiments and modeling were carried out in order to investigate how and why various opening location affects the compartment fire behaviors included: the temperature inside of the compartment (T_{in}), the external flame height (h_f), the heat release rate inside of the compartment ($\dot{Q}_{in}$) and the heat release rate outside of the compartment ($\dot{Q}_{ex}$). The existing equation showed fire behavior only depends on the opening area and height. The results were analyzed and compared to the current air mass inflow equation, and the results showed that various opening locations could influence the compartment fire behaviors. Two factors K and O were introduced to show that various opening locations can lead to different amounts of airflow into the compartment, and the different ratios of oxygen were consumed within total oxygen inflowed. This thesis contributed to the current knowledge of compartment fire's ventilation factor and can be applied to architecture design from a fire safety perspective.

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CHAPTER I

INTRODUCTION

On 14 June 2017 in London, UK, a fire broke out in Grenfell Tower. The fire started by a fridge-freezer on the 4th floor and broke out of the kitchen window. The building's combustible cladding allowed the fire to spread to the upper floors externally. The whole upper building was involved with fire, and a total of 72 people died [1]. Nowadays, with an increase in urban city building density, compartment fire with external flame is a significant hazard to both upper floors and nearby buildings. This is due to the external flame, which can quickly spread by intense radiant or combustible cladding. Compartment fire is combustion in an enclosure like a fire burning in a room, car, train, airplane, etc. Unlike free burn, compartment fire has different phenomena due to limited oxygen in the compartment. The fuel will react with the oxygen contained in the room, but it will reach a point where that oxygen is not enough for combustion, which will lead to unburned fuel accumulate in the compartment. This situation is called an under-ventilation condition. When the under-ventilation condition occurs, if there is an opening like a door left open or window break during the fire, the unburnt fuel will leave the compartment through the opening and react with outside oxygen, which creates the external flame [2], [3]. Since the fire source is outside of the room, the sprinkler system may not have any meaningful effect, and fire can spread to the upper floor like ignite the upper floor's curtains. When the upper floor gets involved with fire, fire from both floors might merge and can lead to a more significant fire [4]. To prevent and/or decrease the risk of the external flame from the compartment fire, many compartment fire researches had been done in the past 60 years. However, the number of firefighter and civilian fatalities in residential fires have not been reduced. Also, the modern building structure and materials have been developed and changed over time, but we are still using old correlations developed in the 1960s and 1970s. More phenomenon and correlations need to be explored about compartment fire.

CHAPTER II

LITERATURE REVIEW

Researchers typically built a scaled-down box to simulate the compartment fire and cut out an opening at the front side wall as an opening window. A vertical cement board is attached to the front wall as the upper floor. Selected fuel will be ignited inside of the box [5]. Parameters including maximum heat release rate inside the compartment, compartment temperature, external flame height, and neutral plane height are essential and need to be analyzed. Whit an opening, due to buoyancy effect, hot gases tend to leave the compartment through the upper part of the opening, and fresh air tends to flow into the compartment through the lower part of the opening as Figure 1 showed.

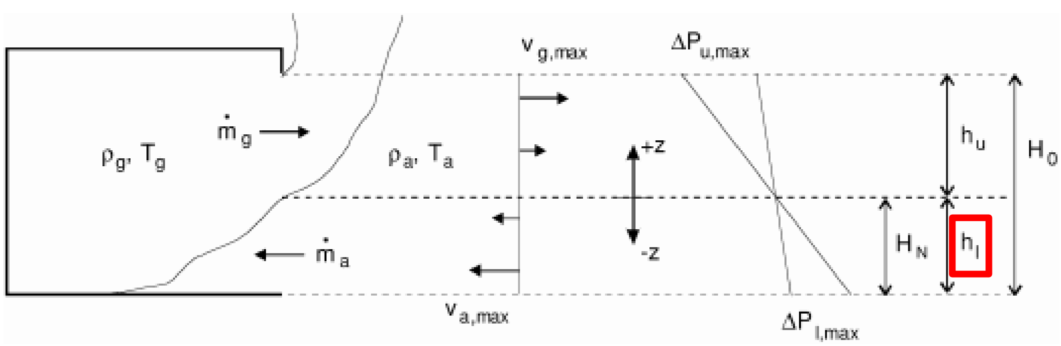

Figure 1. under-ventilated compartment flow diagram

The interface height is the neutral plane height (h_1). Karlsson and Quintiere [6] developed an equation for neutral plane height as Eq. (1)

$$h_1 = \frac{H_O}{1+(\frac{\rho_a}{\rho_g})^{1/3}}$$ *Equation 1*

Where:

h_1: neutral plane height (m)

Ho: Height of opening (m)

ρ_a: air density (kg/m^3)

ρg: gas density (kg/m^3)

The mass inflow rate into the compartment is expressed as Eq.(2)

$$\dot{m}_a = \frac{2}{3} C_d W \rho_a \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_a}} {h_1}^{3/2} \qquad \textit{Equation 2}$$

Where:

$\dot{m}_a$: air mass flow rate (kg/s)

C_d: drag coefficient

W: width of the opening (m)

g: gravitational acceleration (m/s^2)

By substitute Eq. (1) into Eq. (2), the equation for $\dot{m}_a$ can be rearranged as Eq. (3)

$$\dot{m}_a = \frac{2}{3} C_d A \sqrt{H_O} \sqrt{2g} \rho_a \sqrt{\frac{(\rho_a - \rho_g)\rho_a}{[1+\left(\frac{\rho_a}{\rho_g}\right)^{\frac{1}{3}}]^3}} \qquad \textit{Equation 3}$$

Where:

A: Opening area (m^2)

Karlsson and Quintiere (2000) defined $\sqrt{\frac{(\rho_a - \rho_g)\rho_a}{[1+\left(\frac{\rho_a}{\rho_g}\right)^{\frac{1}{3}}]^3}}$ as density factor and its value became relatively close to a constant equal to 0.214 when the ratio of gas and ambient temperature larger than 2 as shown in Figure 2.

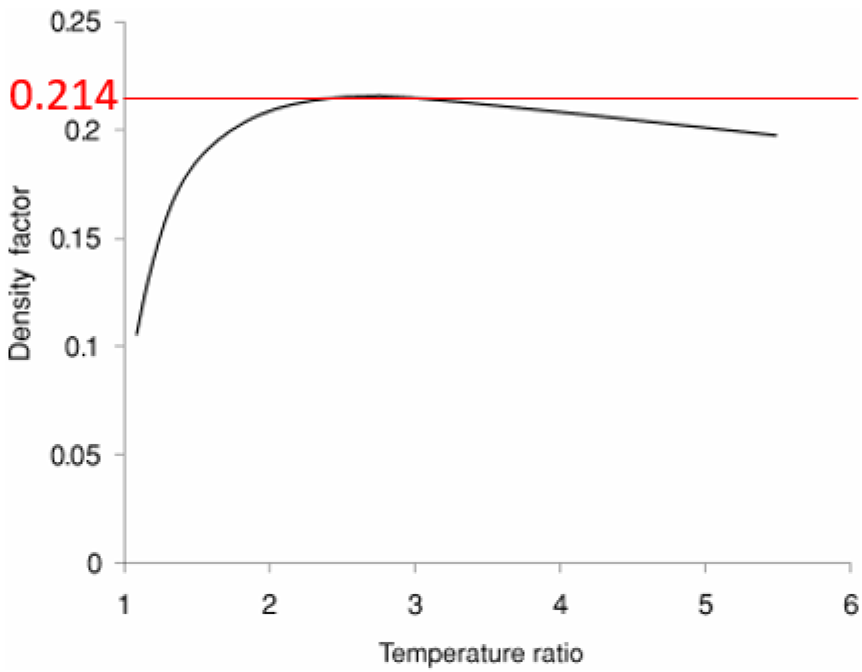

Figure 2. Density factor in Eq. (3) as a function of temperature ratio, T_g / T_a

By assuming density factor =0.214, $C_d = 0.7$, g=9.81m/s^2, $\rho_a = 1.2$kg/m^3, Eq. (3) turned into the well-known Eq. (4)

$$\dot{m}_a = 0.5 \cdot A\sqrt{H_o} \qquad \text{Equation 4}$$

The inflow was assumed to be air, and all the air entered the compartment burned. Since the heat of combustion of air is 3000 kJ/kg, the heat of the heat release rate inside the compartment can be shown as Eq. (5)

$$\dot{Q}_c = 3000 \times \dot{m}_a = 1500A\sqrt{H_o} \qquad \text{Equation 5}$$

Where:

$\dot{Q}_c$: The critical heat release rate inside of the compartment (kW)

Eq. (4) & (5) are well known and used in compartment fire researches. Those two equations can be read as the air mass flow rate into the compartment, and the maximum heat release rate inside the compartment only affected by the area and height of the opening. However, those two well-known equations developed with an opening located in the middle of the façade wall. Lu did experimental studies on flame behavior with an opening at various elevations. The results have shown that compartment temperature and external flame height increase as the opening moves from the bottom to the middle and decrease when the opening moves from the middle to the top. Also, the compartment's heat release rate decreases as the opening moves from the bottom to the top [7]. A significant number of researches have been done with an opening located at the middle of the façade. More studies need to be done with various opening locations because different airflow paths might lead to significantly different compartment fire phenomenon than the current knowledge. The objectives of this research are to investigate how and why various opening location affects the compartment fire behaviors included: the temperature inside of the compartment (T_{in}), the external flame height (h_f), the heat release rate inside of the compartment ($\dot{Q}_{in}$) and the heat release rate outside of the compartment ($\dot{Q}_{ex}$). Air inflow rate and percentage of oxygen burned in the compartment with different opening locations were analyzed and two new factors K and O were introduced to present and explain the influences of various opening locations on compartment fire behaviors. This research can contribute to the current understanding of compartment fire behaviors and apply to architecture design from a fire safety perspective. The rest of the paper will present the experiment and modeling setup, results, and data analysis will be conducted.

CHAPTER III

METHOD

3.1 General setups

The compartment fire tests have been conducted through both experiment and computer modeling with designed fire size. The experimental and modeling results were compared and analyzed. Both experiments and modeling simulated the compartment fire with a scaled box 0.8 (W) x 0.8 (H) x 1.2 (L) m as Figure 3 shown.

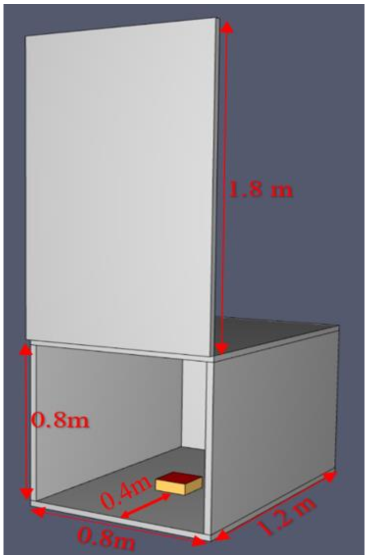

Figure 3. Compartment box configuration

The box was built with 1in calcium silicate boards and 0.5in ceramic fiberboards. A 0.8 (W) x 1.8 (H) m cement board was used to simulate the upper floor. A propane gas burner with a controllable flowrate was installed 0.4m away from the façade wall.

Façade walls with bottom, middle, and top opening 0.3x 0.3m are shown in Figure 4. Base on Eq. (5), the target fire sizes to generate external flame need to be larger than 75kW. 90, 110, 130, and 150 kW were selected for fire sizes. The fire size can be controlled by changing the propane gas flowrate, and a cone-calorimeter was used in experiments to measure and validate the fire size.

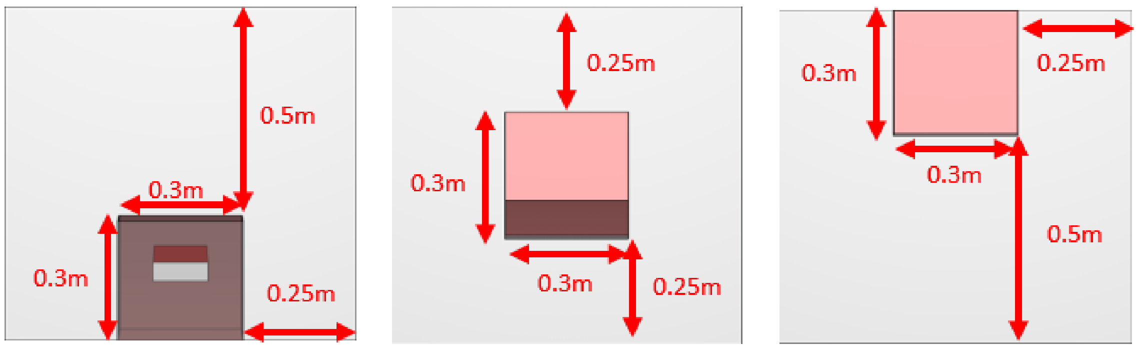

Figure 4. Bot, mid, top opening configuration

3.2 Experiment setups

To investigate how and why various opening location affects the compartment fire behaviors included: the gas temperature inside of the compartment (T_{in}), the external flame height (h_f), the heat release rate inside of the compartment ($\dot{Q}_{in}$) and the heat release rate outside of the compartment ($\dot{Q}_{ex}$). The experiment setups are shown in **Error! Reference source not found.**. Fourteen K-type thermocouples were installed to measure the gas temperature within the compartment. Fifteen K-type thermocouples were installed to measure the outflow gas temperature profile at the opening, which can be used to calculate the neutral plane height by applying the integral ratio method and least-squares method [8]. LabVIEW program was used to collect the thermocouple data. A CCD camera was used to record the flame shape and height. From the recording, flame height and neutral plane height data were extracted by MATLAB code.

Figure 5. Experiment measurement devices setup

3.3 Modeling setups

FDS modeling has the same setup as the experimental setup but has a more substantial capability to directly measure critical parameters that are hard to be measured in the experiments. For example, other than thermocouples, heat release rate measurement devices were installed to directly measure the heat release rate inside ($\dot{Q}_{in}$) and outside ($\dot{Q}_{ex}$) of the compartment. Flow measurement devices were installed to measure both mass inflow and outflow rate of the following particles: total mass flow, air, oxygen, fuel, product, CO_2, CO, N_2, water vapor, unburn fuel gas (propane), and soot. Besides, the heat release rate per unit length (HRRPUL) was measured to calculate the external flame height (h_f) by integrating the HRRPUL value until it reaches 99% of the total heat release rate [9]. In order to have a relatively realistic condition, FDS wall materials were defined as shown in Table 1 to account for the heat loss through the walls. Autoignition temperature (AIT) was set at 450 C because FDS default settings only consider required chemicals includes fuel and oxygen for ignition. Spurious fire may occur even when the temperature did not reach the ignition point. Defining AIT can prevent spurious fire occurs [10].

Table 1. FDS wall materials setup

	Calcium silicate	**Ceramic fiber**	**Cement**
Density [kg/m^2]	250	18	1400
Specific heat [kJ/(kg·K)]	1.03	1.13	1.05
Conductivity [W/(m·K)]	0.05	0.8-0.22 (260 - 1093 C)	0.36
Emissivity	0.9	0.9	0.9
Absorption Coefficient (1/m)	5.0E4	5.0E4	5.0E4

Other than defining AIT, simulation mesh size is another significant parameter that can influence the accuracy. Sensitivity analysis was conducted on three different mesh sizes, including 5cm, 2.5cm, and 1.25cm as the table shown. With the 5cm mesh size, the results show significant differences. 1.25 and 2.5 cm mesh sizes have relatively similar results. Smaller mesh size can improve the accuracy, but with a 1.25 cm mesh size, each simulation took 8 to 11 days with the Pete Supercomputer provided by Oklahoma State University. Consider limited computer capability, project time management, and acceptable tolerance. The 1.25 cm mesh size was selected for this research.

Table 2. Sensitivity analysis on FDS mesh sizes

Fire case	**Parameters**	**1.25cm cell (Pete super Computer,16core)**	**2.5 cm cell (4 core)**	**5cm cell (4 core)**	**%difference 1.25 vs 2.5**	**%difference 2.5 vs 5**
90kW with mid opening	$\dot{Q}_{total}$ (kW)	87.6	86.6	79.9	**1.11%**	**7.75%**
	$\dot{Q}_{in}$(kW)	54.5	54.3	30.1	**0.47%**	**44.61%**
	T_{in}(C)	974.7	967.7	652.3	**0.72%**	**32.59%**
	Flame height h_f(m)	0.8	0.9	0.9	**12.5%**	**0%**
	Simulation time(hr)	207	40.2	3.2		
150kW with mid opening	$\dot{Q}_{total}$ (kW)	148.7	147.5	139.5	**0.87%**	**5.41%**
	$\dot{Q}_{in}$(kW)	49.3	45.2	30.3	**8.33%**	**33.02%**
	T_{in}(C)	946.6	895.6	676.4	**5.38%**	**24.47%**
	Flame height h_f(m)	1.2	1.35	1.3	**12.5%**	**3.85%**
	Simulation time(hr)	260	49.3	3.8		

3.4 Test matrix

The test matrixes were designed to show the influence of opening locations with different fire sizes as Table 3 shown.

Table 3. Test matrix

Experiment Test #	**Heat release rate (kW)**	**Opening location**	**FDS simulation Test #**	**Heat release rate (kW)**	**Opening location**
E1	90	Bot	F1	90	Bot
E2	90	Mid	F2	90	Mid
E3	90	Top	F3	90	Top
E4	110	Bot	F4	110	Bot
E5	110	Mid	F5	110	Mid
E6	110	Top	F6	110	Top
E7	130	Bot	F7	130	Bot
E8	130	Mid	F8	130	Mid
E9	130	Top	F9	130	Top
E10	150	Bot	F10	150	Bot
E11	150	Mid	F11	150	Mid
E12	150	Top	F12	150	Top

CHAPTER IV

RESULT

To investigate how various opening location affects the compartment fire behaviors, the gas temperature inside of the compartment (T_{in}), the external flame height (h_f), the heat release rate inside of the compartment ($\dot{Q}_{in}$), and the heat release rate outside of the compartment ($\dot{Q}_{ex}$) were measured through experiments and FDS modeling.

4.1 Steady-state data trimming

Each experiment took about 1500 to 1800 sec depending on the time it took the compartment to reach to steady-state. In order to get to steady-state, the compartment box needed to be preheated before steady external flames occur at the target fire sizes (90, 110, 130, 150kW). The experiments were conducted during the winter season, and ambient temperatures were about 5 to 10 degrees Celsius. Without preheating, the fires were extinguished because the temperature inside of the compartment was not high enough to maintain the fire. The fire sizes were increased from 30kW to the target fire rates slowly for all experiment tests. Total heat release rate data measured by the cone calorimeter and temperature data within the compartment were used to determine the period of steady-state. Only 600-sec steady-state data were trimmed out and used for analysis as Figure 6 showed. Each FDS simulation was run for 1000 sec, and 400 to 1000 sec data were trimmed out and used for analysis.

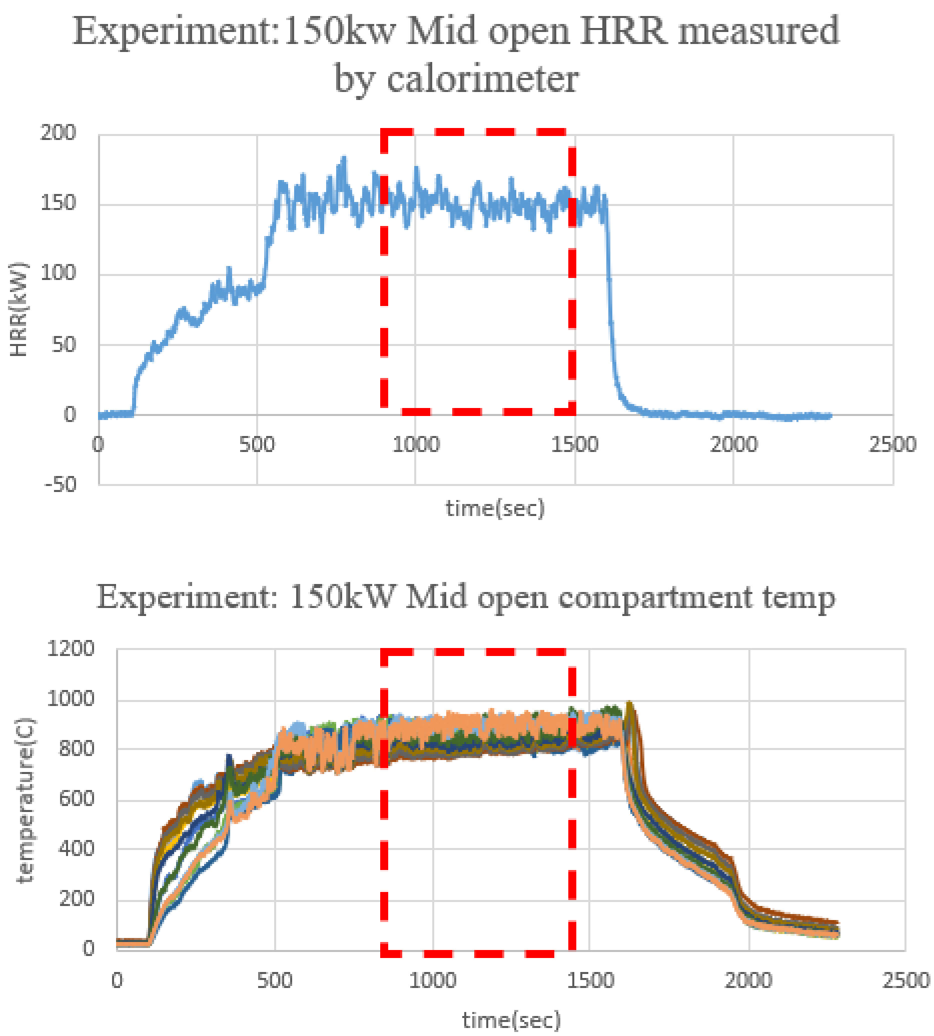

Figure 6. Steady-state data trim example

4.2 Gas temperature within the compartment (T_{in})

The experiment and modeling results of temperature measured by thermocouples are shown in Figure 7 and Figure 8. Modeling results are about 150 degrees Celsius higher than the experiment results, and this might due to the default ambient temperature setting in FDS is 20 C, but the ambient experiment temperature is 5 to 10 C. Experiments had small winds lead to more heat loss through the compartment wall which is another potential reason for the difference. Even though there is a 150C difference, both results show a similar pattern between three different opening locations. The average gas temperature with the middle opening is the highest. The compartment with a top opening has the lowest average gas temperature in side of the compartment.

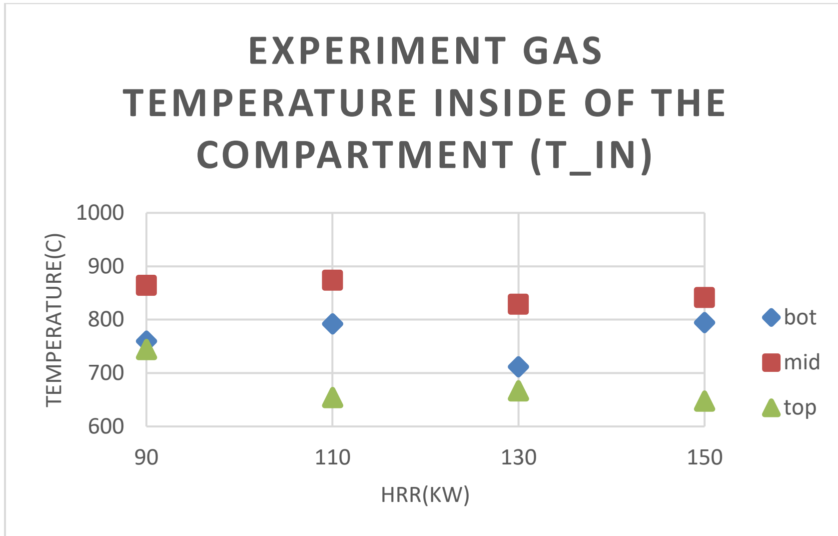

Figure 7. Experiment results: The average gas temperature within the compartment

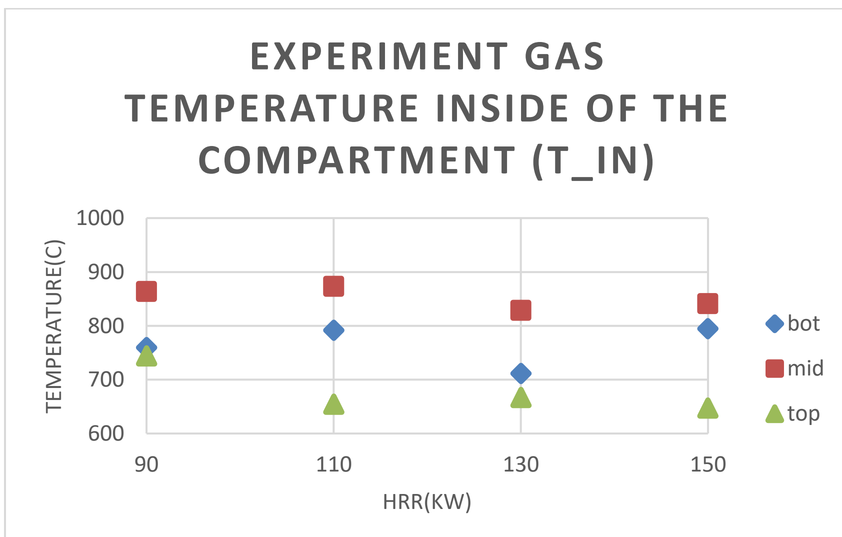

Figure 8. FDS results: The average gas temperature within the compartment

4.3 Heat release rate inside of the compartment ($\dot{Q}_{in}$)

The gas temperature within the compartment is corresponding to the heat release rate within the compartment. Higher gas temperature means more fuel burned inside the compartment, leading to a higher heat release rate inside the compartment. Based on the gas temperature results, the compartment with a middle opening should have the highest HRR inside the compartment. The compartment with a top opening should have the lowest HRR inside the compartment. In experiments, there was no proper method to measure the HRR inside the compartment, but it was measured in FDS with a heat release rate measurement device. The results are shown in Figure 9, and it shows the same trends as the prediction based on gas temperature results.

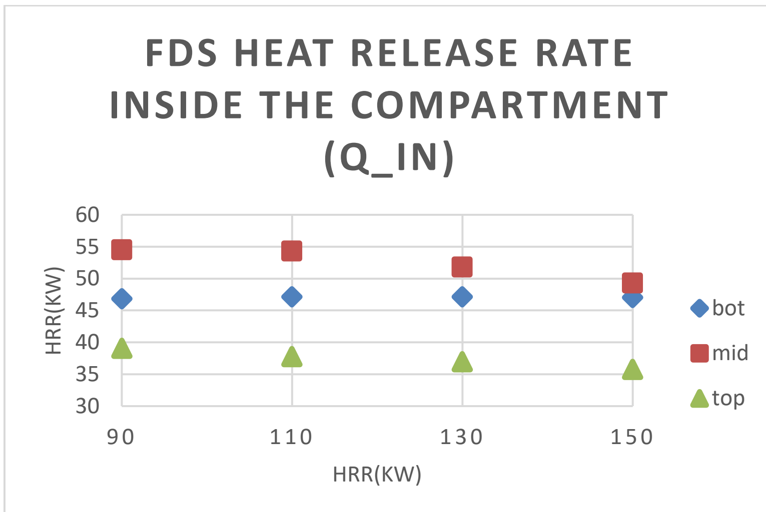

Figure 9. FDS result: Heat releases rate inside of the compartment

4.4 External flame height (h_f)

The experimental external flame height results were extracted from the videos with a MATLAB code as shown in Figure 10. The modeling external flame height results were measured by the HRRPUL devices as shown in **Error! Reference source not found.**. The results are relatively similar between experiment and modeling. With 90 kW and 110 kW fire cases, the FDS modeling results had a slight difference value than the experiment value. One potential reason might be the external flame with a lower heat release rate might not as stable as high heat release rates like 130kw and 150kw. The flames had more fluctuation. The probability of the camera caught the flame height is lower at lower heat release rates [11] which can lead the MATLAB flame extraction code to have acceptable inaccuracy. Even with some data differences between experiments and modeling, both results show the same trends. The compartment with a top opening has the tallest external flame height. The compartments with a bottom opening and a middle opening have relatively similar external flame heights.

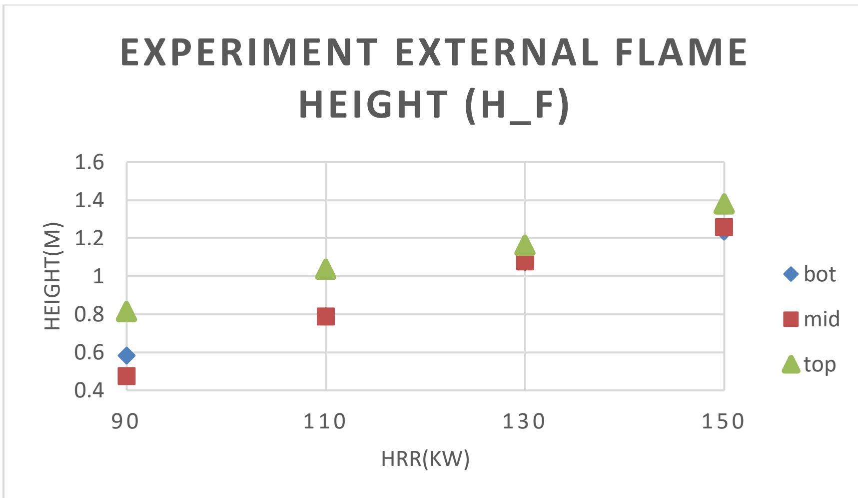

Figure 10. Experiment result: External flame height

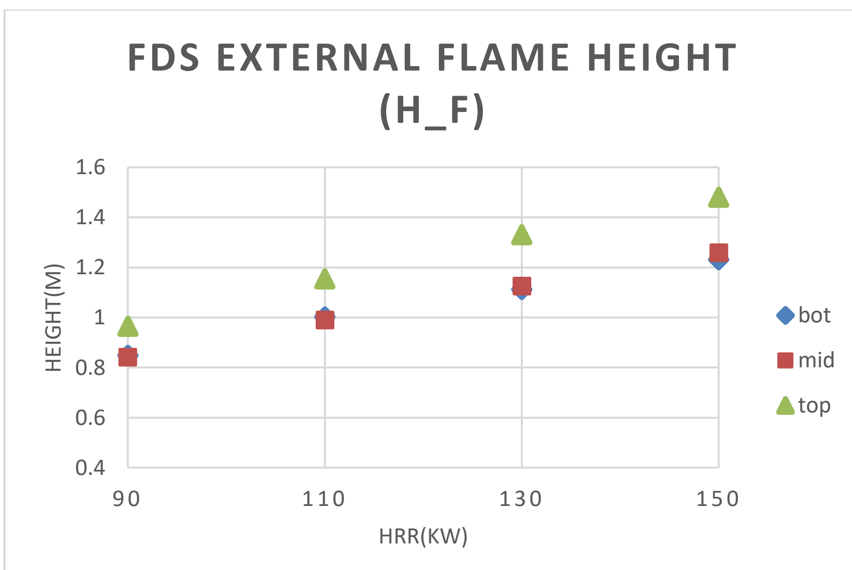

Figure 11. FDS results: External flame height

4.5 Heat release rate outside of the compartment ($\dot{Q}_{ex}$)

The external flame height is corresponding to the heat release rate outside of the compartment. A taller flame height means more fuel is burned outside, which leads to a higher HRR outside of the compartment. Based on the external flame height results, the compartment with a top opening should have the highest HRR outside of the compartment, and the compartment with a bottom and a middle opening should have similar HRR outside of the compartment. In experiments, there were no proper methods to measure the HRR outside of the compartment, but it was measured in FDS with the HRRPUL devices. The results are shown in Figure 12, and it shows the compartment with a top opening has the highest HRR outside, which corresponding to the prediction base on the external flame height results. The heat release rates outside of the compartment with a middle opening are slightly lower than the compartment with a bottom opening.

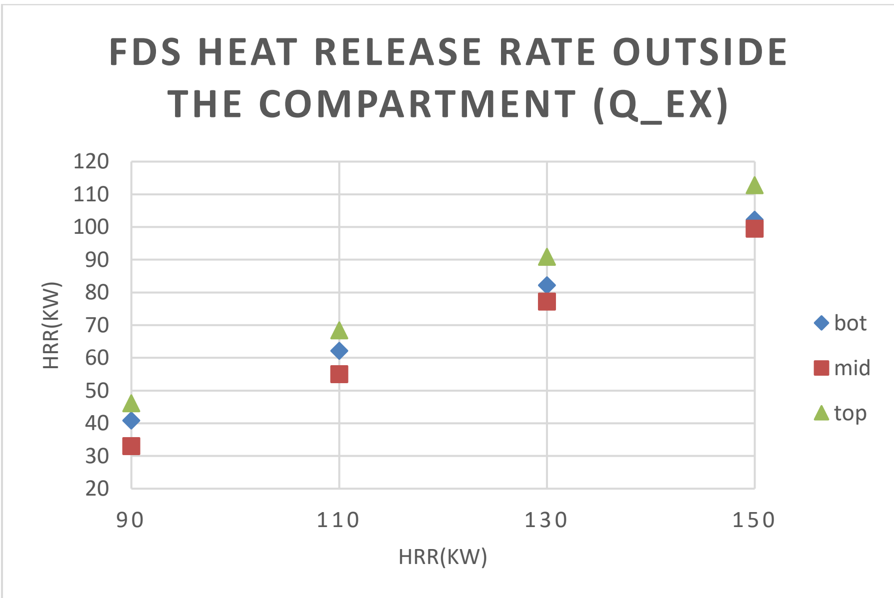

Figure 12. FDS result: Heat release rate outside of the compartment

CHAPTER V

DISCUSSION

Opening locations can influence the compartment fire behavior. With bottom, middle and top opening, the results showed the following trends: $T_{in\_mid} > T_{in\_bot} > T_{in-top}$; $Q_{in\_mid} > Q_{in\_bot} > Q_{in\_top}$; $h_{f\_mid} \approx h_{f\_bot} < h_{f\_top}$; $Q_{ex\_mid} < Q_{ex\_bot} < Q_{ex\_top}$. Those trends agree with the energy balanced rule as Eq. (6) shown [12].

$$\dot{Q}_{ex} = \dot{Q} - \dot{Q}_{in} \qquad \text{Equation 6}$$

Where

$\dot{Q}$: total heat release rate (kW)

As the compartment with a middle opening had the highest heat release rate inside, it had the lowest heat release rate outside since the total heat release rate remain relatively constant. With different opening locations, the airflow path should be different, which can lead to different air mass inflow rates. According to Eq. (3), with the same opening area and height, the air mass inflow should be relatively similar to Eq. (4), which is a constant number. The air mass inflow rate and heat release rate within the compartment should be the same for the compartments with three different opening locations.

However, the air mass inflow rates measured with FDS mass flow rate measurement devices show different results than Eq. (3) and Eq. (4) as Figure 13 shown. The existing equations overestimated the air mass inflow rate.

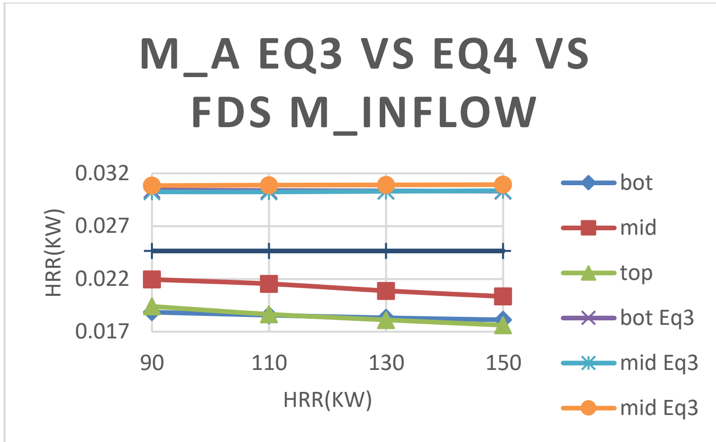

Figure 13. FDS air mass_inflow compare to Eq.3&4

5.1 Factor K

To quantify the differences with three different opening locations, factor K as shown in Eq. (7) was introduced to show: with various opening locations, the ratio of air that enters the compartment in FDS modeling to the value based on the existing Eq. (3) or Eq. (4).

$$K = \frac{\dot{m}_{air\_FDS}}{\dot{m}_{a\_Eq.3} \ \ or \ \dot{m}_{a\_Eq.4}} \qquad \text{Equation 7}$$

Results of K are shown in Figure 14 and Figure 15.

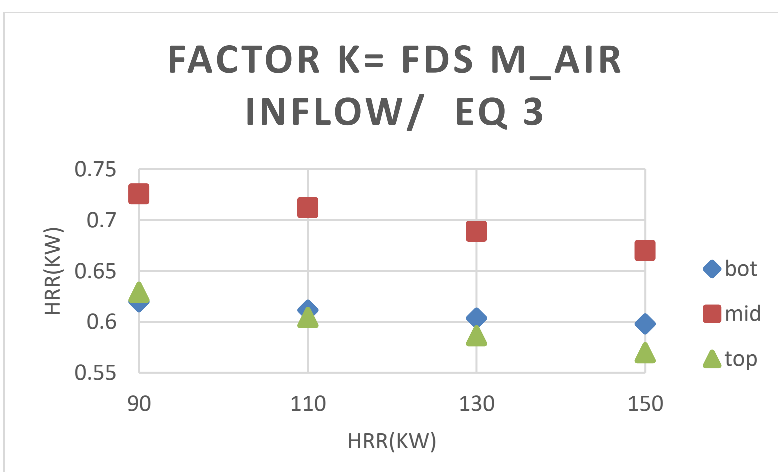

Figure 14. Factor K based on Eq.3

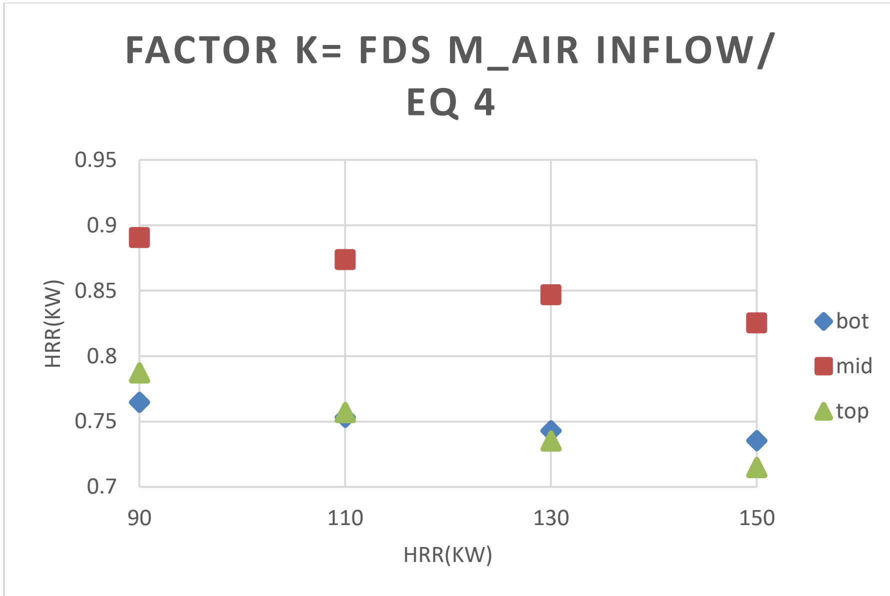

Figure 15. Factor K based on Eq.4

Factor K shows that with various opening locations, the amount of air that enters the compartment and available to burn is different, leading to different gas temperatures and heat release rates within the compartment. The compartment with a middle opening allows about 10% more airflow into the compartment than the compartments with a bottom and a top opening. More air was available to burn inside of the compartment, which leads to higher gas temperature and heat release rate inside of the compartment. Also, the existing equations assumed all the inflow is air, but FDS mass flow measurement devices showed a small amount of outflow gas was entrained back to the compartment. The inflow contains air, entrained unburned fuel, and entrained product as shown in Figure 16.

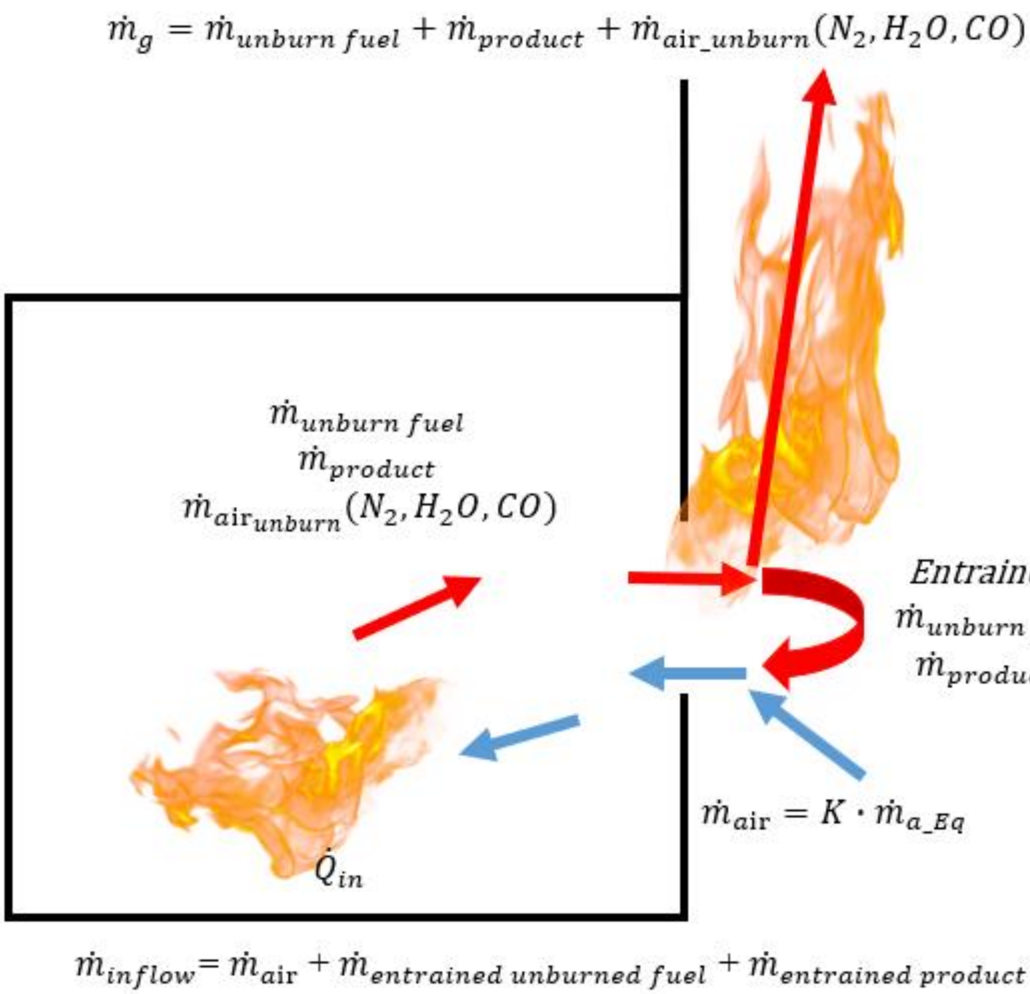

Figure 16. Compartment fire flow diagram

5.2 Factor O

Besides the air inflow rate, the percent of oxygen burned inside the compartment can be another potential reason for different fire behaviors. Eq. (3) and Eq, (4) assumed all the air that enters the compartment is consumed, but based on the FDS results, not all oxygen in the compartment is consumed. The FDS heat release rate measurement device measured the heat release rate inside the compartment, and FDS sets 1kg oxygen consumed can generate 13100 KJ. So, the oxygen consumed rate can be calculated as Eq. (8)

$$\dot{m}_{O_2\ consumed} = \frac{Q_{in}}{13100\ kJ/kg} \qquad \text{Equation 8}$$

Where:

$\dot{m}_{oxygen\ consumed}$: oxygen consumed rate (kg/s)

Factor O as shown in Eq. (9), was introduced to show that: with various opening locations, the ratio of oxygen that actually consumed in the compartment to the amount of oxygen that enters the compartment measured by FDS.

$$O = \frac{\dot{m}_{O_2\ consumed}}{\dot{m}_{O_2\ inflow}} \qquad \text{Equation 9}$$

Where:

$\dot{m}_{O_2\ inflow}$: Oxygen mass flow rate into the compartment directly measure by FDS mass flow measurement device (kg/s)

Factor O showed within all the oxygen inflow how much oxygen was actually consumed inside the compartment for various opening locations, as Figure 17 shows. The compartment with a bottom and middle opening burned about 79% to 89% of income oxygen. The compartment with a top opening has a significantly lower factor O which means only about 67% of income oxygen was consumed inside the compartment.

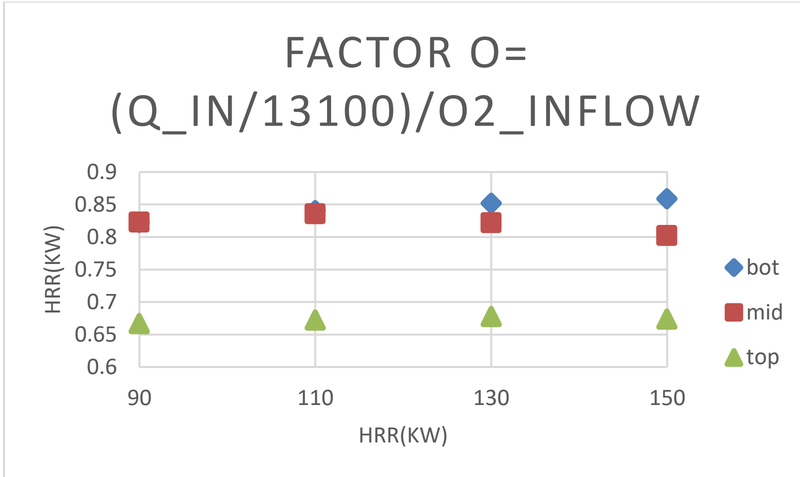

Figure 17. Factor O

5.3 Updated $\dot{Q}_{in}$ and compartment fire flow diagram

Since oxygen mass fraction within the air was defined in FDS output files as $y_{O_2} = 0.230997$, the rate of oxygen entered the compartment can be calculated as $y_{O_2} \cdot \boldsymbol{K} \cdot \dot{m}_{a\_Eq}$. Combined with factor O, the rate of oxygen burned in the compartment can be expressed as $\boldsymbol{O} \cdot y_{O_2} \cdot \boldsymbol{K} \cdot \dot{m}_{a\_Eq}$. As a final result, the heat release rate inside of the compartment showed in Eq. (5) can be updated to Eq. (10), and the compartment fire flow diagram can be updated as Figure 18.

$$\dot{Q}_{in} = 13100 \cdot \boldsymbol{O} \cdot y_{O_2} \cdot \boldsymbol{K} \cdot \dot{m}_{a\_Eq} \qquad \text{Equation 10}$$

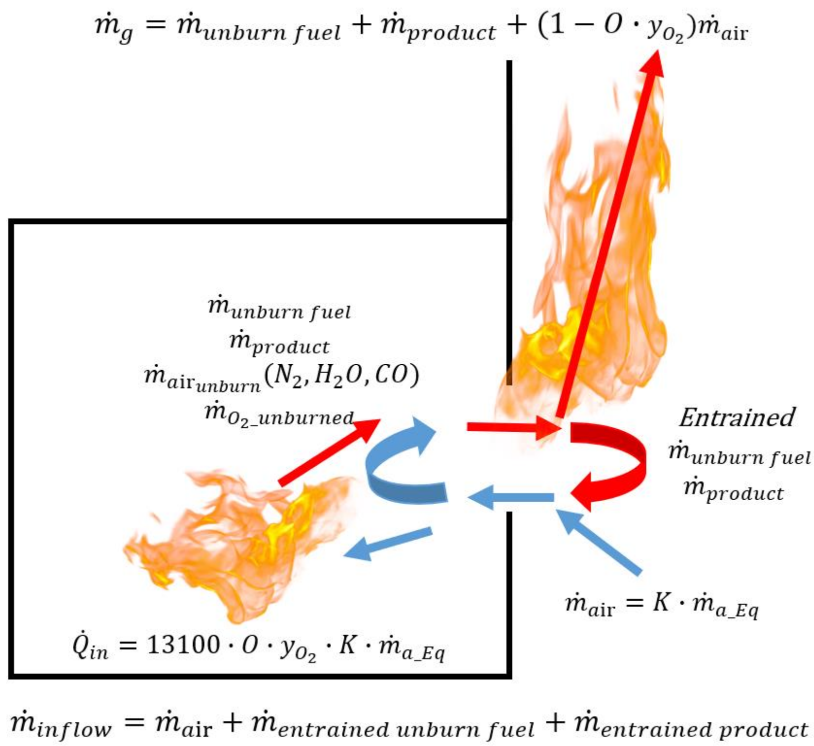

Figure 18

Figure 18. Final updated compartment flow diagram

Eq. (10) showed not only the area and height of the openings can determine the compartment fire behavior, but O and K are also the critical parameters that can influence the compartment fire behavior. And both factors O and K various depending on the opening location.

CHAPTER VI

CONCLUSION

This thesis investigated how and why various opening location affects the compartment fire behaviors included: the temperature inside of the compartment (T_{in}), the external flame height (h_f), the heat release rate inside of the compartment ($\dot{Q}_{in}$), and the heat release rate outside of the compartment ($\dot{Q}_{ex}$). Both experiment and modeling results showed the following trends:

$T_{in\_mid} > T_{in\_bot} > T_{in-top}$;

$Q_{in\_mid} > Q_{in\_bot} > Q_{in\_top}$;

$h_{f\_mid} \approx h_{f\_bot} < h_{f\_top}$;

$Q_{ex\_mid} < Q_{ex\_bot} < Q_{ex\_top}$.

Based on existing Eq. (3) and Eq. (4), only opening area and height are the critical factor for compartment fire behaviors. However, the results showed opening location could affect the compartment fire behavior. To investigate the reasons, factors O and K were introduced to show that with various opening locations, the rate of oxygen enters the compartment and the ratio of oxygen consumed in the compartment can be different, which leads to different compartment fire behaviors. The compartment with a middle opening has the best ventilation flow. More oxygen can be combust inside, leading to the highest gas temperature within the compartment, the highest heat release rate inside the compartment, the lowest external flame height, and the lowest heat release rate outside.

The compartment with a top opening has the worst ventilation flow and the lowest ratio of oxygen consumed inside. It leads to the lowest gas temperature inside the compartment, the lowest heat release rate inside of the compartment, the tallest external flame, and the highest heat release rate outside. The top opening is the most hazardous to the upper floor because the distance is short. With the tallest external flame and highest heat release rate outside, the opening at the top is even more hazardous to the upper floors.

This research showed a general compartment fire behavior with various opening locations, more research can be done to collect factors K and O with different sizes of the compartment, opening size, fire size, and opening shape in the future.

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VITA

Lujia Wang

Candidate for the Degree of

Master of Science

Thesis: AN EXPERIMENTAL AND MODELING STUDY ON THE EFFECT OF OPENING LOCATION IN THE UNDER-VENTILATED COMPARTMENT FIRE

Major Field: Engineering Technology

Biographical:

Education:

Completed the requirements for the Master of Science in Engineering Technology at Oklahoma State University, Stillwater, Oklahoma in May, 2021.

Completed the requirements for the Bachelor of Science in Mechanical Engineering at Oklahoma State University, Stillwater, Oklahoma in 2019.

Experience:

Graduate Teaching Assistant at Engineering Technology, Oklahoma State University, Stillwater, Oklahoma (August, 2019- May, 2021).