Development of Smoke Management Demonstration Apparatus

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Abstract: *Fire safety is a critical design factor in tall buildings. Smoke is recognized as the major killer in fire situations. Building fires produce both smoke and heat. The amount of smoke produced and their physical and chemical properties are greatly affected by the interior building materials which is in today's buildings are mostly made of cellulose and plastics. Stairwell and passage pressurisation systems are an important component of the means of egress system in many buildings. Besides early warning system using smoke detectorts, smoke management, mitigation and containment should be an essential part of any HVAC design. This paper presents the outcome of developing a smoke management demonstration apparatus for education proposes. This apparatus can help the student undertaking fire safety engineering course and HVAC related courses to have hands on experience at laboratory scale. In the future, the student will also be able to compare their Computational Fluid Dynamics (CFD) results with experimental works. A real world experience is an important component in an engineering education curriculum.*
***Keywords** : Smoke, venting, demonstration apparatus.*

1. Introduction

In recent years, there is an increasing number of high-rise building development in big cities of the developed countries but also in developing countries like Indonesia. Construction of high-rise building is not only to meet the housing needs, but also to represent economic development. No wonder many countries build high-rise buildings as an icon of the country's achievement. Construction of tall buildings or commonly referred to as high rise building face many challenges, one of which is fire safety technology.

The field of fire safety engineering is in growing stages, since fires caused by the absence or weakness of application of fire safety has an enormous impact on the loss of life caused by the smoke which is a cause of death in the event of fire.

Planning and management of fire safety is a major challenge for a multi-storey building as the building type is very susceptible to smoke during a fire event. Smoke produced during fire can spread into other parts of the building and potentially life-threatening and damaging property. Thus, a high-rise building should have and maximizing the smoke control system since the design stage to emergency operation. Smoke control system can effectively to limit the spread of smoke to various rooms in the building [ASHRAE (2007), Wild, J.A. (1998)].

Furthermore, smoke control systems in buildings are aiming to secure occupants of a building in fire to evacuate safely to the assembly point. However, the flow of smoke during the fire spreads tend to move into a room in the vicinity of fire through various openings, such as cracks in construction, effluent piping, ducting, and the doors open. Factors causing smoke to spread to areas outside the compartment is the chimney effect, the effect of fire temperature, weather conditions, especially wind, mechanical and air treatment systems [ASHRAE (2007)].

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High-rise building fire stairs deservedly have a pressurization system as it has a very important part for evacuation in the event of a fire. Fire stairs are planned specifically for rescue in the event of a fire. In principle, pressurization system of fire stairs provide a difference in air pressure from the stairwell to another room in the building. The method is designed to control smoke movement. In the process of evacuation of fire stairs door opens, the air supply should be provided with sufficient velocity to prevent smoke entering the stairwell.

This study presents the outcomes of experimental works using the mock-up of the smoke management demonstration apparatus. The smoke management demonstration apparatus are design for educational proposes. This apparatus will help the student undertaking any HVAC related courses to have hands on experience at laboratory scale. In the future, students will also be able to compare their Computational Fluid Dynamics (CFD) results with experimental works.

2. Theory

2.1. Compartment Fire

Fire room or compartment is an event where there are flames confined in a room. Factors that limit the spread and growth indoors is the firing rate and duration of combustion. Fire compartment can be divided into several phases, ignition, growth, flashover, fully developed fire and decay.

The factors that influence the development of a fire in an enclosure can be divided into two main categories: those that have to do with the enclosure itself, and those that have to do with the fuel. These factors are :

- the size and location of the ignition source
- the type, amount, position, spacing, orientation, and surface area of the fuel packages
- the geometry of the enclosure
- the size and location of the compartment openings
- the material properties of the enclosure boundaries

With very few exceptions, particulate smoke is produced in all fires. The effect of reduced visibility is to delay escape and increase the duration of exposure of the occupants of a building to the products of combustion. These will contain a highly complex mixture of partially burned species, some of which are capable of causing individuals to be overcome. The length of exposure will be increased if the visibility is poor.

The yield of particulate smoke from a burning material may be assessed by one of the following methods:

- Filtering the smoke and determine the weight of the material, this method is only suitable for small-scale testing.
- Collecting smoke on the known volume and determining the optical density of the smoke, this method can be done for small to medium skale.
- Flowing smoke a pipe, and then to measure the optical density where the obstruction flow has been established and integrated in a single device for measuring the total particulate smoke.

Optical density measurements done by measuring the intensity of a beam of light caused by smoke particles passing through the beam.

The sensor beam of light to work with the fire intensity light through the light source and then received by the receiver (photo cell) which read as Io. By the time the smoke from passing

ISBN 978 979 8510 61 8

through the light beam sensor, the measured intensity values are identified as Ix, the intensity of which was reduced from the initial intensity. The relationship between the value of the intensity Io and Ix can be explained through Bouger's Law, as follows [Mulholland, G.W. (2002)]:

$$I_x = I_0 \exp\left(-KL\right) \qquad [1]$$

where K is the value of the absorption coefficient with units of m-1 and L is the distance of the light source and photo cell. For optical density value has units of (1/m), which can use the equation [Mulholland, G.W. (2002)]:

$$OD = \log_{10}\left(\frac{I_o}{I_x}\right) = KL \qquad [2]$$

The amount of light transmission values obtained from the comparison of the measured intensity of the smoke and the initial intensity may be expressed using the equation:

$$T = \frac{I_x}{I_0} = 1 - \frac{N}{100} \qquad [3]$$

where T is the value of the transmission of light received by the photo cell in units of percentage (%) and N is the percentage of opacity measured at the photo cell (%). Thus, from the relationship equations [2] and [3] obtained a new equation, namely:

$$T = \exp(-OD) \qquad [4]$$

Thus, the value of the optical density is linearly related to the value of the transmission through the equation:

$$OD = \log_{10}\left(\frac{1}{T}\right) \qquad [5]$$

By getting the value of the absorption coefficient of the equation (2.6) and (2.7), the concentration of smoke measured period can be determined by using the equation [Mulholland, G.W. (2002)]:

$$m = \frac{K}{K_m} \qquad [6]$$

where Km is the specific extinction coefecient with units m2g-1. Thus, time in units of grams of smoke can be determined through the relationship of concentration during smoke through the equation:

$$M_s = V_r \times m \qquad [7]$$

Vr is the volume of the room where the smoke was accommodated on a space with units of m^3. By getting the value of the property, it can be determined the value of soot yield (g / g) by the equation [Mulholland, G.W. (2002)]:

$$Y_s = M_s / M_b \qquad [8]$$

where M is the mass of fuel burned with units of grams.

Past catastrophes involving fire have shown that it is the smoke and fumes given off by the fire that are the greatest danger to people trapped in buildings. The precise concept of the total fire protection and smoke management system to be incorporated into a building is a very important subject during the planning phase of any construction project.

The objectives of smoke management systems are to minimise smoke migration through a building due to a fire occuring within that building. The ASHRAE text Principles of Smoke Management (Klote and Milke 2002) states that "smoke movement can be managed by use of one or more of the following mechanisms: compartementation, dilution, air-flow, pressurization, or bouyancy". The pressurization approach for controlling smoke can be carried out using mechanical fans and applied in stairway pressurization, elevator pressurization, and any other smoke control systems.

Pressurised stairwell are designed and constructed aiming to provide a smoke-free exit a building during a fire. In addition, pressurized stairway also provides access to the firefighters in performing their duties. In a floor fires, pressurized stairs should be able to maintain a positive pressure differential at the stairwell door closed to prevent smoke entering the stairwell.

The smoke venting demonstration apparatus developed in this program was built to scale 1:20, which means that the size of the compartment is scaled geometrically according to this ratio. A Froude scaling technique was considered here [Quintiere, J.G. (2006), Ingason, H. (2007)]. The influence of the material thermal inertia and radiation effects on fire spread were not considered.

It is necessary to perform dimensional analysis in order to generate comparative data comparison is quite ideal. Dimensional analysis calculated in this study is the HRR and time, as follows [Ingason, H. (2007)]:

$$\dot{Q}_F = \dot{Q}_M \left(\frac{L_F}{L_M}\right)^{\frac{5}{2}} \qquad [9]$$

where L is the length scale and the index M refers to the model scale, while F is the actual scale. Next is a dimensional analysis to be used in experiments and simulations, as follows:

$$t_F = t_M \left(\frac{L_F}{L_M}\right)^{\frac{1}{2}} \qquad [10]$$

where t represents the time of data collection were carried out both in the experiment and the simulation.

3. Experimental Model Development

3.1. Design Mock-up

A small scale model of high rise building (a mock-up) has been designed and constructed with a scale of 1: 20 of the actual building size. Thus, the model has the sizes of 65 cm width, 86 cm length, and 200 cm tall. This model is equipped with enclosed stairwell pressurised with a adjustable-speed fan to represent stairwell pressurization system of a high-rise buildings.

The design specifications for the manufacturing the mock-up are as follows:

1. The mock-up design has the size of 70 cm x 65 cm x 200 cm or 1:20 scale use than the actual 10 stories building.
2. Each story is connected with scaled stairs.
3. The interior of the model was made of transparent acrylic material of 3 mm thick, while the outer frame and the lid using transparent acrylic of 5 mm thick.
4. The mock-up was placed on the moveble base for easy access and storage.
5. The doors are equipped with hinges, so that they can be opened or closed as needed.

6. The area close to the exit stair was protected with drop walls to represent passive protection means of smoke spread.
7. A rectangular duct shaft for supplying air during fire mode (when the stairwell pressurization fan is activated), was installed with openings in every floor.

The final mock-up is also equipped with smoke extraction system.

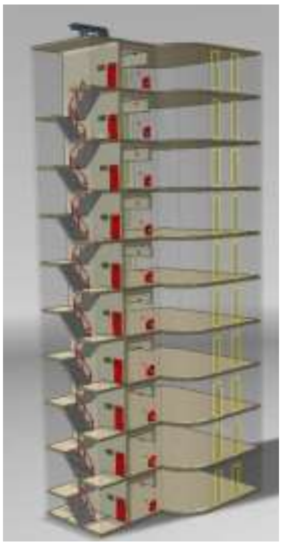

Figure 1. The design mock-up

After the mock-up design was completed, the construction of the mock-up was carried out by professional maker using laser cutting technique to ensure the accuracy and finest. The mock-up was mainly made of acrylic material. Although the cost is relatively expensive, but it has the advantage of safer and lighter than glass, with almost the same level of clarity for smoke opacity measurement and visual observations. Nevertheless, good care of sample burning process should be placed to ensure that only the smoke was realease during the smoldering heating of the sample.

Figure 2. The stairwell pressurization system and the dropwall.

Measuring devices and data acquisition system

a. Temperature measurement

Type K Thermocouples were used during the experimental for measuring air and smoke temperature in various places. The data was recorded using National Instrument cDAQ-9174, CompactDAQ chassis (4 slot USB), and NI 9211 4-Ch ±80 mV, 14 S/ s, 24-Bit Thermocouple Differential Analog Input Module.

b. Flow measurements

A typical orifice meter is constructed by inserting between two flanges of a pipe a flat plate with a hole.

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Figure 3. Orifice meter equipped with differential pressure measurement and amplifier system.

We design and constructed a assumed a ratio of the hole and pipe diameter, $\beta = d/D$, a small value in order to obtain a large pressure drop over the orifice giving a more clearer reading by the differential pressure transmitter. The differential pressure was measured using Keyence AP-47 Micro-pressure difference sensor head, equipped with AP-V41AW Separate thin amplifier type NPN.

c. Smoke opacity measurements

Smoke opacity measurement is the unique feature of this smoke venting demonstration apparatus. As mentioned earlier, the sensor beam of light to work with the smoke intensity light through the light source and then received by the receiver (photo cell) which read as Io. By the time the smoke from passing through the light beam sensor, the measured intensity values are identified as Ix, the intensity of which was reduced from the initial intensity.

A state of the art laser beam sensor was applied to measure the smoke opacity and visibility, i.e. the Keyence IB-01 Laser Thrubeam Sensor (Sensor head) and IB-1000 Laser Thrubeam Sensor (Amplifier).

Figure 4. Laser beam sensor equipped with amplifier and power supply system.

Since simultaneous opacity measurements are needed, home made opacity measurement apparatus was developed. The source of the laser light was laser pointer with photo sensor to measure light intensity changes.

Before measurement was carried out, the opacity sensors were calibrated using standar glasses having a certified optical density.

Figure 5. Standar glasses having various optical density for sensor calibration.

d. Fans for Stairwell Pressurization and Smoke Extraction

Stairwell pressurization and smoke extraction systems were created using Fan system. The flowrate of the air and smoke flow was control by speed control and an inverter. Measurement of the flow rate was carried out using orifice meter, meanwhile the air velocity was measured using a hot wire anemometer.

e. Smoke source

Smoke source was generated by heating 1 gr of paper using a solder heating element. Smoke source was placed in the third storey of the mock-up.

3.2. Experimental Procedure

A typical experimental run was started by placing the measuring devices and DAQ system in the designated positions, i.e. laser sensors were placed in in 4 positions (2 sensors in main room, 1 sensor in near exit door and the last in the stairway evacuation) and carrying opacity sensors calibration.

The smoke source was prepared and weighted as 1 gram of paper. The paper was rooled around a heating element. After laser sensor shows 80 %, the fans was turned on at the setting rotation speed. Once started the data was taken for every 10 s. pm. The time data was taken from opacity of 80% to 99%. The measurement was terminated after the laser – opacity sensor shows 99 %. After a typical experimental and all data were recorded, the fan was started at full speed to purge the interior of the mock-up. The next experiment can be started when the laser sensor shows 100 %.

4. Results of Experimental Measurement

4.1. Non Pressurised Conditions

Source of smoke in the experiment is the result of the burning of 1 gram of paper is heated using a heater. Smoke opacity was measured from the three main points show the movement of smoke from the source of the smoke to reach the fire stairwell. The third beam sensor was placed on the 3rd floor. Activation of the sensor beam was initiated as soon as the smoke was detected or reading the sensor beam. The heat release rate of the burning paper are assumed constant at 3.4 kW.

In Figure 6 visible smoke density changes with the light beam sensors are increasingly visible. At 30 seconds of the first sensor, beam 1 and the two are starting to look obvious, while the sensor beam 3 on the staircase is still not visible. Then, when it reaches the first minute, the sensor beam 3 is already starting to look sketchy.

At the time shows 1.5 minutes, a window opposite the sensor beam 1 was not seen, indicating the density of the smoke is very high. Furthermore, the sensor beam 1 is becoming clearer. It appears that without pressurization of the stairwell, there is an increase in the opacity of smoke in the stairwell as the fire door is open. After overcoming the smoke barrier, then the smoke freely enter the stairwell.

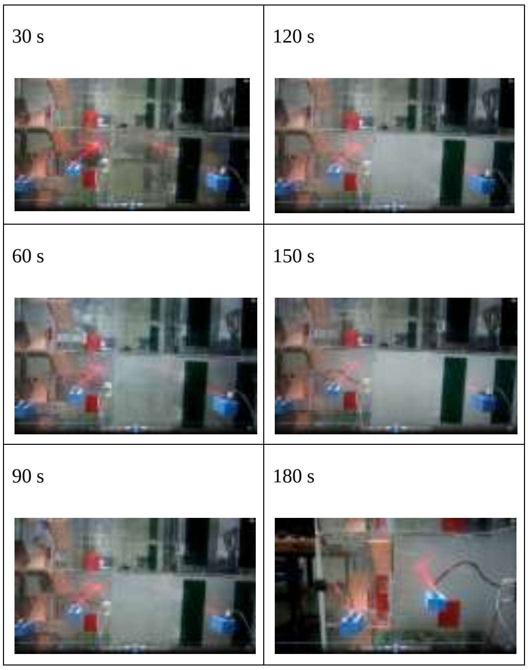

Figure 6. Changes in opacity of the smoke
on the stairwell without pressure

In a system where there are two types of fluid adjacent to where there is a density difference it will greatly affect the buoyant force on the fluid. Fluid with a lower density will float on the state of the environment in which there is a fluid that has a density greater. The relative magnitude that occurred between the two styles is the ratio of buoyancy to drag viscosity expressed in Grashof number [Drysdale, D., 2003], namely:

$$Gr = \frac{gl^3\left(\rho_0 - \rho\right)}{\rho v^2} = \frac{gl^3 \beta \Delta T}{v^2} \qquad [11]$$

Grashof number is the ratio between the buoyancy force due to the barrier effect of the fluid density. In a stream of smoke, Grashof number determines the type of flow of smoke.

Opacity values obtained by measuring the intensity of a beam of light caused by the passage of smoke particles with a value of Io and Ix. The relationship between Io and Ix are described in bouger's Law is useful for calculating the value of the optical density of smoke [Drysdale, D., 2003]:

$$OD = \log_{10}\left(\frac{I_o}{I_x}\right) = KL \qquad [12]$$

To determine the value of light transmission and light passing through the smoke opacity can be determined by the equation:

$$T = \frac{I_x}{I_0} = 1 - \frac{N}{100} \qquad [13]$$

Thus the two equations obtained optical density value of a property, namely:

$$OD = \log_{10}\left(\frac{1}{T}\right) \quad [14]$$

The following graph show the plot of the experimental data of obtained optical density with the condition without pressurization in the fire stairwell.

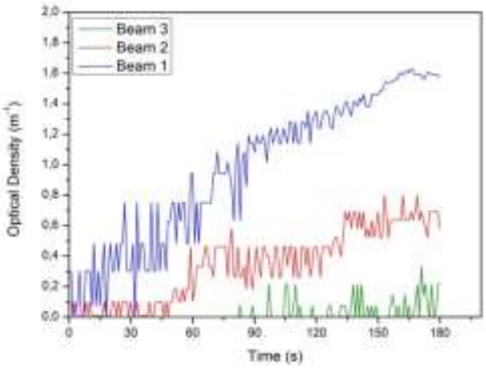

Figure 7. Data opacity in the stairwell without pressurization, HRR 3.4 kW.

Just as the images of the video, the graph of the experimental results (Figure 7) show that the fire origin space, has the highest optical density of about reached 1.6 m^{-1} , because the smoke almost covers the entire light beam sensor 1. The outcome for the second beam sensor also show the evident that the opacity of the smoke was thick in this area, reaching about 0.8 m^{-1}. Without pressurization of stairwell, smoke is able to enter the stairwell, as detected by the sensor beam 3. After 70 s to 3 minutes, the optical density of the stairwell was measured at 0.3 m^{-1}.

4.2. Pressurised Conditions

The second experiment was conducted with the similar parameters as in the first experiment. However, in this case stairwell pressurization was provided through the use of fan installed on the top of the high-rise building models. Injection system is used to put pressure on the staircase representing a multiple injection close each door of the stairwell. Air capacity provided through the fan was 0.0016 m^3/s. As in the experiment without the pressure of a staircase, with the source of the smoke on the pressurization experiment was the result of the combustion of 1 gram of paper.

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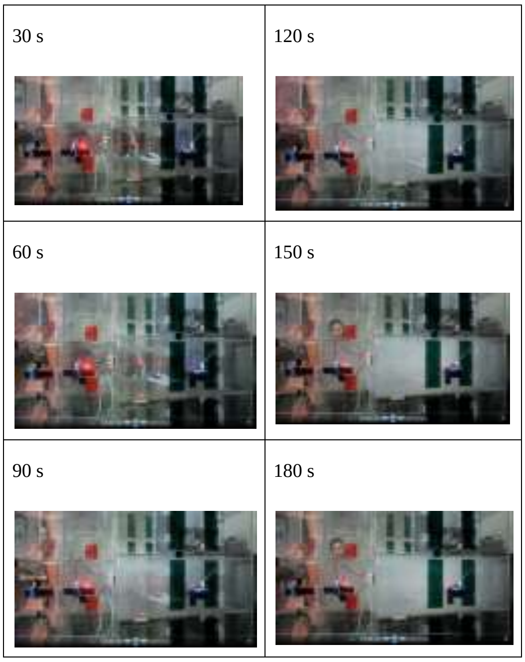

Figure 8. Changes in opacity of smoke in the pressurised stairwell with 3.4 kW heat release rate.

As shown in Figures 8 and 9, pressurization of the stairwell could maintain low obtical density measured by beam No. 2 and 3. The most significant effect are no sightings of smoke in the fire stairwell, although there was slighly visible red beam sensor 3 occured.

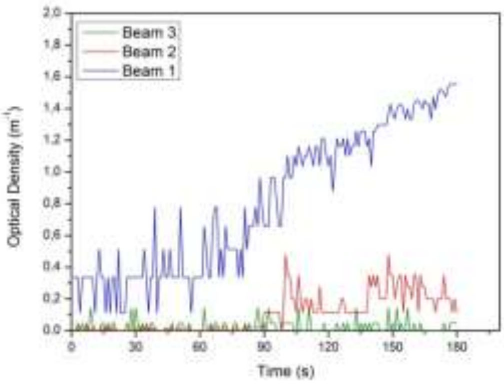

Figure 9. Data opacity in the stairwell pressurization, HRR 3.4 kW

4.3. Smoke Extraction Conditions

Using the smoke management demonstration apparatus, one can also study the effect of smoke venting / smoke extraction system to the optical density in the fire compartment (third floor in this case). By measuring the pressure difference in the flow measurement apparatus operating at various fan speed, one can estimate the flow rate of smoke extraction. In this work, the speed of fan was varied by setting the frequency of the power supply at 40, 45 and 50 Hz. At these frequencies, we can calculate the flow rate of smoke extraction as 2.84, 3.12, and 3.41 m^3/h. As the volume of the third floor of the model is 0.4 m^3, then the air change per hour are approximately 7, 8 and 9.

The results of the measured optical density of the fire compartment by operating the smoke extraction fan are shown in Figure 10. Increasing the air change per hour (ACH) shortens the period for optical density recovery (the period to gain good visibility). Nevertheless, higher ACH may not automatically lower the maximum optical density values.

5. Concluding Remarks

1. The demonstration apparatus designed for simulating smoke management in buildings works well in accordance with the background theory.
2. Stairwell pressurization can reduce measurable levels of smoke density.
3. Simultaneous measurement of optical density using laser beam sensors are helpful to explain the changes of smoke opacity in different areas of the building, including the effect of smoke management effort.
4. Increasing the air change per hour (ACH) shortens the period for optical density recovery.

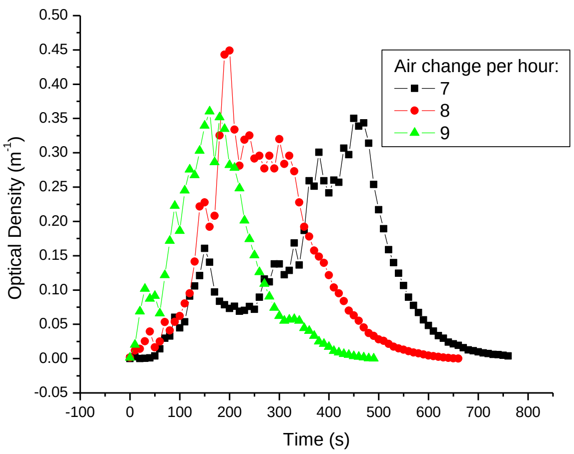

Figure 10. Effect of Air change per hour to optical density

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Acknowledgement

The authors would like to thank ASHRAE for providing Senior Undergraduate Project Grant 2012.