An Educational Laboratory Experiment TO DEMONSTRATE THE DEVELOPMENT OF FIRES IN A LONG ENCLOSURE

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Currently there is enormous pressure to incorporate safety education into the chemical engineering curriculum and this article is dedicated to developing understanding related to fire safety. Fire safety is a complex issue that attracts much public concern and makes up the majority of the requirements in building regulations. Buildings and infrastructures need to be designed against fire risk to provide safety to the occupants and firefighters and in some cases for property and business protection. To meet these objectives, engineers require a knowledge of combustion, fluid dynamics, fire development and propagation, heat and mass transfer, steel structure in fire, etc.

Buildings usually consist of one or more enclosures. Fire growth and development in an enclosure is primarily dominated by ventilation and size and shape of the enclosure as well as by the fuel itself (its amount, properties, and distribution) . Generally four components are required for sustained combustion: (a) fuel to combust, (b) heat to initiate and maintain combustion, (c) oxygen to act as an oxidizer, and (d) chemical chain reactions to sustain the combustion. This is known as the fire tetrahedron. Within an enclosure that has an opening (means of ventilation), fire will travel toward the source of oxygen, in this case toward the opening. This behavior of fire within an enclosure can be clearly observed within a deep enclosure (high depth-to-height ratio) with a single opening and it can be demonstrated and associated theories can be elucidated to students by means of a laboratory experiment.

The importance of laboratory experiments in engineering education has been extensively discussed in References 1 and 2. A total of 13 fundamental objectives of engineering instructional laboratories were set by a colloquy organized in San Diego, Calif., in January 2002.[3] The objectives covered all three domains of learning—cognitive, psychomotor, and affective—and to produce an effective engineer, it is vital to expose students to these three domains.[1] The laboratory experiment proposed in this article is primarily aimed to cover five of 13 objectives mentioned above—Models, Data Analysis (cognitive), Safety, Creativity (affective), and Sensory Awareness (psychomotor). It can be noted that in similar disciplines (combustion, fluid mechanics, heat transfer, etc.), a number of laboratory experiments can also be found in the literature.[4-6]

The intention of the proposed experiment is to observe the effects of restricted ventilation on the motion of a fire over the fuel packages, and to allow observation of the concentrations of fuel within the enclosure with the elapsed time. This type of test can assist with the assessment of the severity of exposure experienced by structural members to the fire within the enclosure and at different locations and times. This understanding can be used to devise strategies to protect structures in case of fire. In addition, this experiment illustrates the triumvirate of heat transfer mechanisms—conduction, convection, and radiation—that occur during real fires. These mechanisms relate to rise in temperature on the one hand, in combustible solids and liquids leading to flame spread through heating, pyrolysis/ evaporation, and ignition, and on the other hand in structural members leading to reduction in their strength.

BACKGROUND

To evaluate fire severity there is a crucial empirical equation used to determine the mass flow rate of air into a fully developed fire in an enclosure. This mass flow rate is required to estimate the maximum heat release rate (HRR) of a potential

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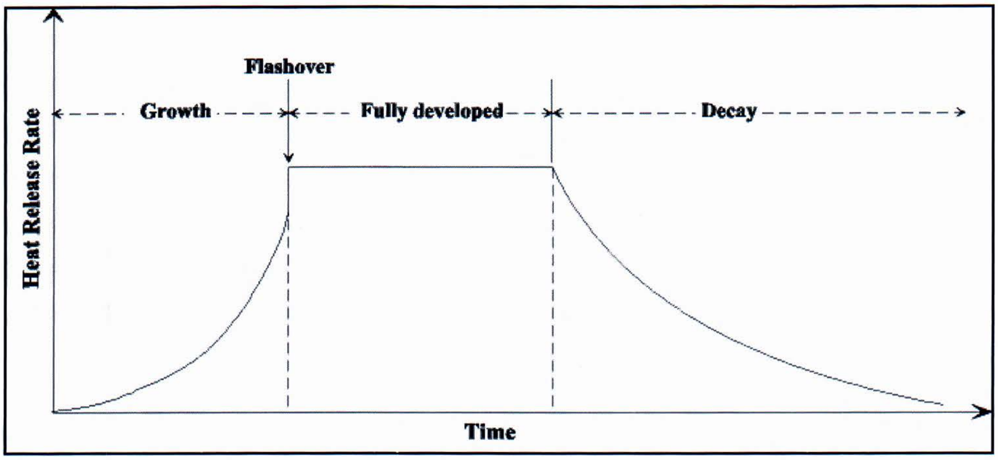

Figure 1 (right). *A schematic representation of typical ventilation-controlled fire in terms of HRR vs. time.*[8]

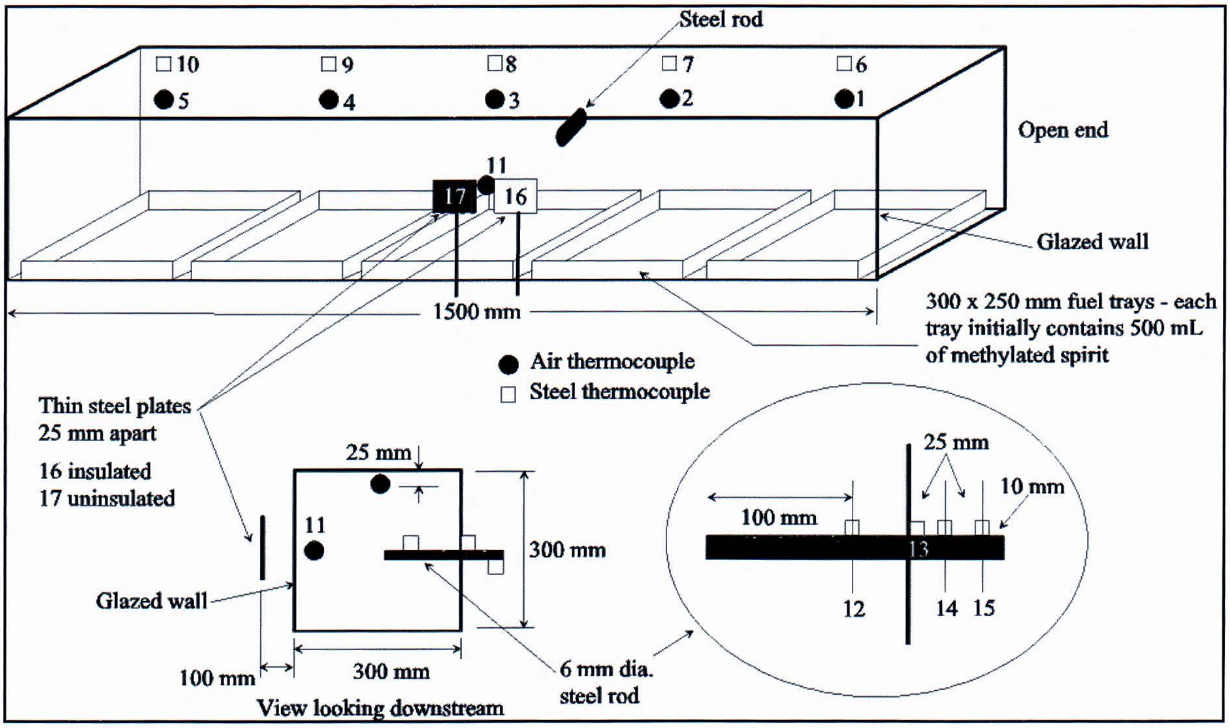

Figure 2 (below). *Schematic diagram of the test set-up and location of the thermocouples.*

ventilation-controlled fire. The HRR (expressed in W, kW, or MW) is generally regarded as the most important parameter in a fire because it represents its severity. A fully developed fire is one for which the HRR reaches a maximum. Figure 1 shows three distinct stages of typical ventilation-controlled fire: growth, fully developed, and decay. In a real fire, especially with liquid pool fire, the growth period is very short; a quick transition (known as flashover) to the fully developed stage occurs. At this stage, the fire is essentially controlled by available ventilation through openings and approaches a steady state (as shown in Figure 1). This is the most significant stage as the fire severity is maximum during this period. In this situation, large amounts of unburnt fuel flow out of the enclosure, in the form of a gas layer through the upper portion of an opening. This gas might also be burning. At the same time, cool, ambient air is drawn into the enclosure in the lower portion of the opening, under the hot gas layer.

The classical equation for the mass flow rate into the enclosure is stated in Eq. (1) in which C is an empirical constant 0.4 to 0.61 $kg.s^{-1}.m^{-5/2}$, dependent on the discharge coefficient of the opening[7] and is normally taken to be 0.5 $kg.s^{-1}.m^{-5/2}$, A_0 is the area of the opening (m^2), and H_0 is the height of the opening (m):

$$\dot{m}_a = CA_0\sqrt{H_0} \quad kg.s^{-1} \tag{1}$$

The HRR can be estimated from the consumption rate of oxygen ($\dot{O}_2$) and the energy released per kg of O_2.

$$HRR = \dot{O}_2 \ (kg.s^{-1}) \times \text{Energy released} (J.kg^{-1}) \tag{2}$$

If each kg of air contains 0.23 kg of O_2 and all the O_2 of air that enters in the enclosure is consumed then ($\dot{O}_2$) can be obtained from the following relationship:

$$\dot{O}_2 = 0.23\dot{m}_a = 0.23 \times 0.5 A_0 \sqrt{H_0} \quad kg.s^{-1} \tag{3}$$

It has been empirically found that the consumption of each kg of O_2 releases approximately 13 MJ of energy.[9] The theoretical HRR associated with an enclosure fire can be now be expressed as:

$$\mathrm{HRR}_{\mathrm{theoretical}} = 0.23 \times 0.5 A_0 \sqrt{H_0}\ \left(\mathrm{kg.s}^{-1}\right) \times 13\left(\mathrm{MJ.kg}^{-1}\right) = 1.5 A_0 \sqrt{H_0}\ \mathrm{MW} \qquad (4)$$

To obtain the experimental value of the HRR (assuming a steady state fire with negligible growth and decay periods as is often the case for liquid fuels), Eq. (5) can be used:

$$\mathrm{HRR}_{\mathrm{experimental}} = \frac{\text{Volume of fuel } [\mathrm{m}^3] \times \text{density}[\mathrm{kg.m}^{-3}] \times \text{calorific value}[\mathrm{MJ.kg}^{-1}]}{\text{burning duration}[\mathrm{s}]} \mathrm{MW} \qquad (5)$$

Within an enclosure that has an opening (means of ventilation), fire will travel toward the source of oxygen . . . .

Enclosures in buildings assume a wide variety of sizes and shapes. Many rooms are found to be roughly cube shaped (*e.g.*, length, height, and width are all similar magnitudes) in different types of accommodation. Eq. (1) was developed based on the experimental study of fire in cubic shaped enclosures where all fuels burned simultaneously. In many buildings, however, the spaces can be very wide, long, or both, in comparison to their height. If, in a fire situation, they are ventilated only from one side, then the depth-to-height ratio can be quite high[10] (up to ~20 in open-floorplan offices).

To understand the behavior of a flame front and its movement across the fuel package located within deep enclosures, this experiment is designed to be conducted in a prototype enclosure. As the structural members in a building are exposed to heat during a fire, evidence of all three types of heat transfer processes (conduction, convection, and radiation) will be demonstrated as well.

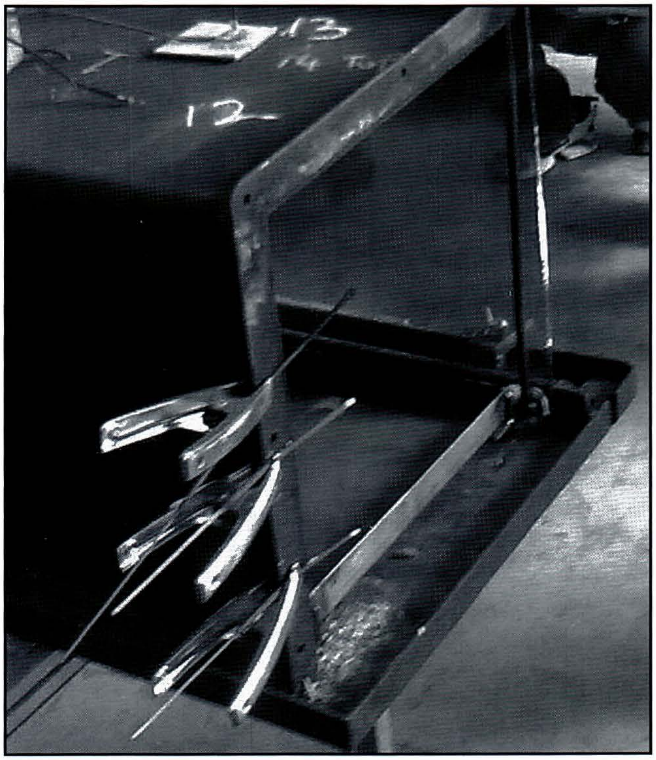

Figure 3. *Incense sticks are placed to assist the observation of the behavior of air currents moving in and out of the opening.*

APPARATUS

The enclosure used for this experiment is 1.5 m long, 0.3 m wide, and 0.3 m high and is primarily constructed of sheet steel. One 0.3m × 0.3m side of the enclosure (Figure 2) is used as the opening (to enable air flow inside the container since fire requires oxygen to burn). The other sides are completely enclosed. To assist observation, one 1.5 m × 0.3 m side is constructed of fire-resistant glass to allow details of the fire behavior to be safely viewed. Fire-resistant glass is recommended as a safety precaution as the inside gas temperature may rise above 800 °C.

Five fuel trays are placed within the enclosure, as shown in Figure 2. The fuel trays are 0.3 m × 0.25 m and are constructed of sheet steel. Each tray contains 500 ml of methylated spirit (calorific value 26 $\mathrm{MJ.kg^{-1}}$, density 780 $\mathrm{kg.m^{-3}}$).

Type K thermocouples are placed just above the center of each tray and 25 mm below the enclosure ceiling (numbers T/C1 – T/C5). Tray 3 has an additional air thermocouple (T/C11) located ~170mm below the roof and positioned toward the glass wall. These thermocouples are used to record gas temperatures. Additionally, one thermocouple is spot-welded to the steel on the enclosure roof above each tray (numbered T/C6 – T/C10) and these are intended to measure the temperature of the steel.

One 6 mm diameter steel rod is penetrated through the middle of the longitudinal steel sidewall of the enclosure which is ~150mm above the enclosure floor. Four thermocouples are spot welded to the rod, one (T/C12) being within the enclosure, and the other three (T/C13- T/C15) outside.

Two thin steel plate targets are placed 25 mm apart at half the longitudinal distance and 100 mm outside the glazed wall of the enclosure, directly opposite to T/C11. These are directly exposed to the radiation caused by the burning fuel. Of these two plates, one has insulated backing while the other has been left exposed. One thermocouple is spot welded to each of these plates: T/C16 on the insulated plate and T/C17 on the uninsulated plate. Thermocouple (T/C18) measures the ambient temperature.

All thermocouple readings are recorded using a data-logger at an interval of 5 seconds.

To assist the observation of the behavior of air currents moving in and out of the opening, a number of incense sticks at different heights (usually at 1⁄4 H_0, 1⁄2 H_0, and 2/3 H_0) from the enclosure floor are positioned as shown in Figure 3.

The sequence of events is to be recorded manually using a stopwatch.

PROCEDURE

Job safety analysis

The instructor needs to apply project risk analysis (PRA) first to ensure that the students have assessed the experiment's safety aspects before igniting the fuel. A laboratory protocol on risk assessment including a plant inspection checklist, and materials' safety data sheets (MSDS) for its hazards should be in place. The relevant laboratory protocols of the author's laboratory[11] can be obtained on request.

Based on an area tour and plant inspection, using the checklist and reviewing the MSDS, students will assess the hazards and risks of this experiment before it begins. This part of risk assessment needs to be documented by the students. This practice of risk-based approach will develop students' awareness of safety.

During the experiment the ambient temperature should be below 20 °C to avoid any flash flame movement. Above this temperature (vapor pressure is 4 cm Hg or 0.0526 atmosphere and lower flammability limit is 3% volume of air at 20 °C), flammable mixture is produced. If this guidance is not followed, a flash fire may develop upon ignition that can blow flame out of the open end of the enclosure and/or may shatter the glass. For safety precaution, the students should be at least 2m away from the rig at the start of the test.

Experiment

The trays are filled with fuel and placed within the enclosure at least 15 minutes prior to ignition (allowing liquid to settle down to avoid eye and skin injury of students from splashing of liquid). The fuel is ignited in the rearmost tray (*i.e.*, Tray 5) through a small hole, which needs to be closed immediately after the ignition. An electronic match or gas lighter can be used to ignite the fuel. The minimum ignition energy required for methylated spirit is approximately 0.65 mJ.

The movement of the flame front needs to be carefully observed. Initially the flame front will likely move quickly from left to right (Figure 2) jumping from tray to tray establishing a fire in Tray 1 and subsequently slowly in the other trays from right to left. The explanation can be obtained from Reference 10. The times when jumping of the flames from tray to tray during the rearward movement is observed should be recorded using the stopwatch to observe the variability of the burning duration over various trays. The incense sticks should be placed after the flame front is established at the second tray. It will be observed that during the test, fresh air is entrained into the enclosure through the lower portion of

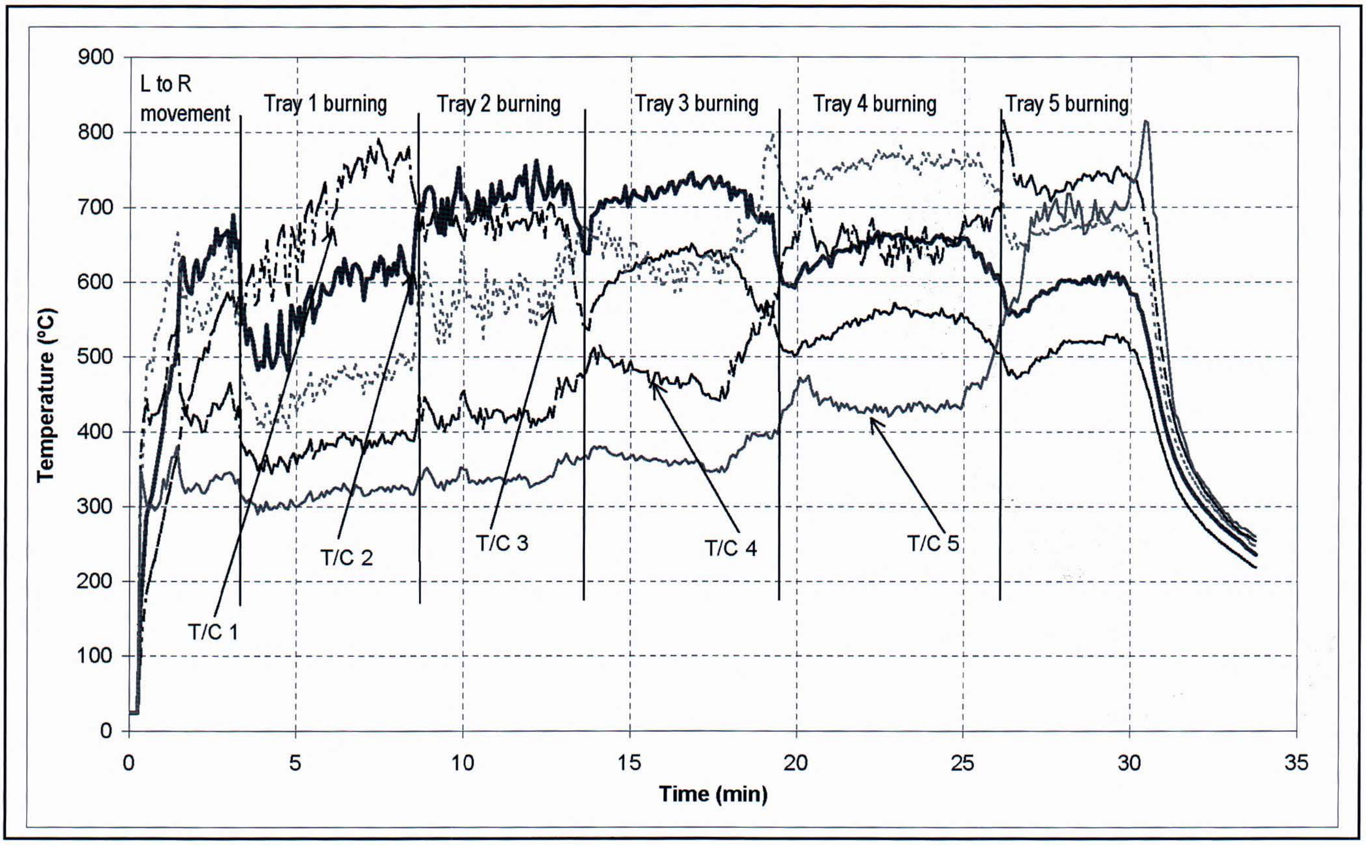

Figure 4. *Air/combustion gas temperature above each tray for the entire duration of the fire.*

the opening and hot gases flow out through the upper portion of the opening. The location of the neutral plane above the floor should be identified (expected to be located 1/3 to 1⁄2 opening height below the top surface) and recorded.

RESULTS AND DISCUSSION

The logged temperature data, particularly the recordings of T/C1 to T/C5, will provide evidence of the sequence of tray ignitions. In the first few seconds after ignition, the air/combustion gas temperature within the enclosure will begin to rise, with the thermocouples above the burning tray demonstrating the highest temperatures. When the temperatures of T/C5, located above the last burning tray, fall below 500 °C, it will be considered that the burning duration is ended. The graphical evidence (the rise, steadiness, and fall of the temperature-time profiles) will need to be correlated with the times recorded by a stopwatch. An example of the presentation of the results of an actual experiment is given in Figure 4. It is to be noted that in the given time scale of Figure 4, the evidence of left-to-right movement could not be clearly observed. The slowest rise of the temperature recorded by T/C1 can be noticed, however. The figure also shows that while the burning duration over Trays 1-4 does not change much, a shorter duration over Tray 5 is observed. The likely reason is that while the fuel was burning in Trays 1-4, hot gases rise and on reaching the top surface (ceiling) develop an inward ceiling jet behind the flame front. This ceiling jet on reaching the cooler back wall drops down. As the fire continuously generates heat, the cooler fluid that flowed in from the back of the enclosure (entrained fluid) to replace the rising warmer fluid will warm up and also rise. Thus a convection current becomes established that draws fuel from the back to the front.

A plot of the gas temperature histories recorded by T/C1 (located above the front tray) and T/C5 (above the rear tray) during the test, should be produced. From this, observations should be drawn of whether the temperature near the ceiling above the front tray is higher for the majority of the test duration than the temperature above the rearmost tray. This will indicate whether the severity of exposure of structural members at a particular location in a building is equal throughout the fire duration. If the area under the temperature-time curve is taken as indicative of severity of exposure, then the difference of severity experienced at the front tray will need to be determined, compared to the rear tray. Alternatively, if the duration of high recorded temperatures (above 600 °C), which can cause structural weakening, is used as the criterion, the difference in exposure duration needs to be calculated. A plot of T/C6 and T/C10 recordings representing corresponding steel temperature will substantiate this finding.

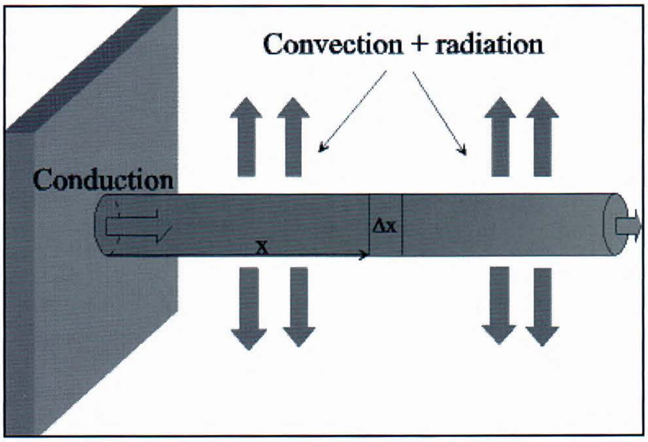

Figure 5. *The protrusion of the rod as a fin-like arrangement and heat transfer mechanism in and out of the rod.*

As this is a liquid (pool) fire, the growth and decay periods are negligibly small, hence HRR can be determined using Eqs. (4) and (5), separately, and the results of these equations should be compared. Based on these findings, it is expected that the students should comment on the validity of the classical formula used for long enclosure fires and look for a more appropriate formula in Reference 10.

For the heat transfer calculation, it is expected that a comparison of the steel rod temperature, at the rod-enclosure junction, with those outside of the enclosure, throughout the burning duration, will be presented. This will include calculations to illustrate that a temperature difference is expected. The protrusion of the rod can be considered similar to a fin arrangement as shown in Figure 5.

Using the concept of conservation of energy, Eq. (6) can be derived for the above arrangement:

$$\frac{d^2T_s}{dx^2}-\frac{P}{kA_c}\left\{h+\sigma\varepsilon\left(T_s^2+T_\infty^2\right)\left(T_s+T_\infty\right)\right\}\left(T_s-T_\infty\right)=0 \qquad (6)$$

An analytical solution of Eq. (6) can be obtained using a set of boundary conditions (see Reference 12).

$$T_s=\left(T_{13}-T_{18}\right)\frac{\cosh m(L-x)+\frac{h}{mk}\sinh m(L-x)}{\cosh mL+\frac{h}{mk}\sinh mL}+T_{18} \qquad (7)$$

where:

h= convective heat transfer coefficient (38 W.m^{-2} K^{-1}- overall value calculated based on the formula given in Reference 13)

k= thermal conductivity of steel (46 W.m^{-1} K^{-1} – variation with respect to temperature difference is ignored)

$m=\sqrt{\frac{2\times h}{k\times D}}+m_{rod}$ with D= rod diameter and $m_{rod}=\sigma\varepsilon(T_s^2+T_{18}^2)(T_s+T_{18})$

L = rod length (outside the enclosure)

TABLE 1
Spreadsheet format.
All temperatures must be in Kelvin.

time	T_{18}	T_{13}	$T_{s\text{-analytical}}$ (T_{14} or T_{15})	$T_{s\text{-iteratiaon}}$	$T_{s\_experimental}$ (T_{14} or T_{15})

P = perimeter of the rod

A_c = cross-sectional area of the rod

x = longitudinal location on the rod where the temperature is calculated

σ = Stefan-Boltzmann constant ($5.67\text{x}10^{-8}$ W.m^{-2} K^{-4})

ε = emissivity factor, taken as 0.9 for the steel rod

For the spreadsheet format, see Table 1.

As m_{rod} contains T_s, iteration is required to obtain the correct value of $T_{s\_analytical}$. Spreadsheets are required to be developed (one each for T_{14} and T_{15}) as shown in Table 1. Values under the heading $T_{s\_iteration}$, close to the values of $T_{s\_analytical}$ need to be included, which will be used as T_s to calculate m_{rod}. As a result, $T_{s\_analytical}$ will change. The values of $T_{s\_iteration}$ will need to be changed until $T_{s\_iteration} = T_{s\_analytical}$. Columns $T_{s\_analytical}$ and $T_{s\_experimental}$ should be compared graphically for validation.

Finally, a plot comparing temperatures of T/C16 and T/C17 in one graph should be presented to determine which external target is hotter. It is expected that both targets should receive the same amount of radiative heat flux from the enclosure. The likely primary reason for one target to be hotter than the other is related to its slower heat loss via convection and radiation from target to ambient.

UNCERTAINTY

The outside part of the steel rod, in addition to conduction, will receive some radiation from the hot enclosure wall. As a result $T_{s\_experimental}$ is likely to be slightly higher than $T_{s\_analytical}$.

Bare-bead thermocouples are expected to be used for this experiment to measure gas temperatures (T/C 1-5 and T/C 11) as these are inexpensive compared to aspirated thermocouples. Although air temperature readings using this type of instrument can be significantly altered by radiation errors, these thermocouples will be used for qualitative observations. Details of the radiation correction are beyond the scope in this experiment.

QUESTIONS FOR STUDENTS

1. Document the understanding of the potential hazardous events related to the project before experimental work begins.

2. Describe the burning sequence of the trays of fuel. Offer an explanation for this phenomenon.

3. In what region of the opening does air appear to flow into the enclosure? Give a reason for this.

4. Determine whether the severity of exposure of structural members, at a particular location in a building, is equal throughout the fire duration for a long-enclosure fire.

5. Check the validity of the classical formula for long enclosures by comparing the HRR determined using Eqs. (4) and (5), separately.

6. Undertake some basic calculations (by developing spreadsheets) to illustrate that the steel rod temperature difference outside the enclosure is valid. Calculate for T/C13 to T/C14, and then T/C13 to T/C15.

7. Considering the two external targets (T/C16 and T/C17), explain why one target is hotter than the other. You will need to provide a qualitative explanation of this difference (based on heat transfer principles).

CONCLUSION

The laboratory experiment provides students an understanding about fire and process safety that can be translated to engineering practices in the areas of building design, industrial safety, etc. The intended learning aspects of the cognitive, affective, and psychomotor domains are elucidated by performing this flame propagation experiment.

The test showed that the fires tend to move toward the opening and are not at all uniform through the depth of a deep enclosure. As a result, the severity of exposure of structural members varies at different locations. The test method can be used for preventative design using scaling consideration as given in Reference 10. Last but not least, it illustrates how the heat transfer mechanisms in practical fire scenarios can be quantitatively and qualitatively analyzed.

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NOMENCLATURE

A_0	m^2	opening area
H_0	m	opening height
HRR	W, kW, MW	heat release rate
H_C	$MJ.kg^{-1}{}_{-1}$	calorific value of the fuel
h	$W.m^{-2}\ K^{-1}$	convective heat transfer coefficient
K	$W.m^{-1}\ K^{-1}$	thermal conductivity
T	K	temperature
σ	-	Stefan-Boltzmann constant
ε	-	emissivity factor
ϱ	$kg.\ m^{-3}$	fuel density ❐