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Studies on a novel porous double walled indoor fire facility

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Abstract. The present study discusses evolution of a twin porous wall based indoor air facility to reduce the ambient disturbances on the fire. Natural convection based central exhaust through top opening reduces the dependence on heavy and power guzzling hot gas extraction equipment thus reducing the investment. Facility meets the national standards on emission. Measurements of wall temperatures at the top and the surrounding walls in a 2.1 m square pan fire with n-heptane for 90 s and diesel for 30 minutes show a maximum of 100°C ensuring structural safety. The need for one wall being solid (to connect to the auxiliary laboratory) was examined with FDS calculations on two alternate designs (a) with all sides porous and (b) three sides porous and one side solid to determine whether the fire is symmetrical. Short duration calculations show that the fire grows vertically towards the exhaust. Experimentally, the flame leans towards the solid wall after 45–50 s of heptane fire- attributed to wall heating near top. Based on this experience, a new design for the indoor fire laboratory is suggested.

Keywords. Qualification of fire suppression products; indoor pool fires; fire dynamics simulation; FDS; entrainment.

1. Introduction

Large indoor fire test facilities for testing and validating fire suppression equipment are designed to support industries (construction, transportation, aerospace, automotive industries, etc.) and governments in fire resistance testing, technology development and research. Advancing technologies for improving the fire safety of buildings and transportation systems, enhancing fire detection and suppression systems, and reducing the risks and costs of fire require robust testing. Many of the modern testing facilities are adaptable to a wide range of testing needs to meet industry and association standards including Indian Standards, UL Standards (USA), European Standards and/or other standards for conducting custom tests for research and development purposes.

Such testing facilities typically require an indoor space that has adequate height to take away the incomplete products of combustion of the fires established over a pan fire (2.1 m × 2.1 m) with n-heptane as standard test fuel or large cribs with standard wood specifically for testing fire extinguishing agents. Standard heptane pool fire burns for one-minute consuming about 20 kg fuel and delivers 13 MW generating incomplete products of combustion of ~200 kg, the equivalent volume at the exhaust at the exhaust temperature of 200°C being over 4000 m^3 including mixing induced dilution.

Typically, a 10A crib during its peak power delivers 6 MW with exhaust gases of 2000 m^3 at 200°C. In order that the fires are established properly, air has to be delivered into the system at about 60–70 m^3 per second over one minute. Indoor room sizes vary but are in the range of 13 m × 18 m × 13 m high to 15 m × 15 m × 15 m.

Conventional indoor facilities adapt heavy duty blowers operating at ~300 kWe to deliver the air into the bottom zone all around the room from the bottom region. The uniformity is achieved by supplying the air into large plenum created through channels all around the inner wall from which air enters via louvers. The dirty combustion gases are evacuated from the top region using another blower that has to draw about 20–40 times the volumetric flow, cleaned up for soot and other products of incomplete combustion before they are let out into the atmosphere. Such facilities are designed with very high (~10–15 m) walls. The difference between the rate of exhaust and the rate of hot gas generated leads to accumulation inside the indoor facility with the smoke descending to levels low enough to make normal operation unsustainable even for short durations of test (typically about two minutes).

Alternatively, the air is allowed through louvers around the wall. Such a system needs manual opening of the louvers and is maneuvered to ensure that large winds from one

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side are restricted to minimize the wind effects on the fire. The limitation of such devices is that the ambient winds change directions randomly and the size of higher speed wind streams can vary from very small to large. While the large ones may be tackled, the small ones cause sudden changes in the flame profile and the burn rate.

Many designs for fire testing have proposed to address the challenge. Table 1 lists several facilities developed across globe. Facilities at University of Waterloo and South Korea will be discussed first. The University of Waterloo facility uses fans to generate 40 km/h wind speeds over fuselage like structures with an active exhaust system over the inclined roof. South Korea ship and offshore research institute has created a fire test facility for clearance of several fire safety equipment using an active exhaust system on the inclined roof.

Spain has a fire atrium test facility in Murcia with a pyramidal roof with four roof exhaust fans pumping $\sim 37\ m^3/s$ for testing fires of about 4 MW. China has a fire test atrium at Hefei, Anhui designed to study large space building fires with a combined mechanical and natural ventilation strategies. This system has mechanical ventilation deployed in full or in-part. Use of such mechanical ventilation needs to be accompanied by hot gas clean up strategies even for maintaining the facility in good operating condition, apart from the need to clean up the smoke in the hot gas.

The facility at the underwriter laboratories, Northbrook, USA (UL, for short) was initially reference for the construction of a similar facility at the fire and combustion research laboratory, Bangalore, India. It is also an indoor facility with mechanical exhaust. Table 1 provides the summary of the facilities described above along with the facility at FCRC, Jain (deemed-to-be-university) built in cooperation with UL. The UL-JFL facility is the only facility outside of the USA. Its design features are addressed later in more detail.

2. Materials and methods

2.1 *The facility*

At Jain, early fire qualification tests of firefighting agents like foam concentrates were conducted in pool fires open to the ambient for Underwriters Laboratories, before the indoor facility was built. Fire pan (2.1 m × 2.1 m) was located suitably to reduce the ambient wind disturbances. After some survey of the locations, an area surrounded by trees and buildings-at-a-distance (more than 30 m) was chosen for the fire pan that had a reinforced-concrete construction below it. Due to the considerations of rain and wind, the tests had to be planned carefully. Most experiments were scheduled towards the evening when the ambient currents were below 0.5 m/s. Higher ambient air velocities/precipitation resulted in test postponement.

Table 1. Parameters of some major fire test facilities across the World (UL–JFL: Underwriters Laboratories–Jain Fire Laboratory in Bangalore, India) [1–3].

Facility	Size m × m × m	Vol. m^3	Air flow m^3/s	Use	Comments
UL, Northbrook	18 × 12 × 7	1425	13	Active fire suppression	Large mechanical ventilation
Waterloo, Canada	20 × 17 × 12	4000	310	Aircraft fire Tests, R &D	Sloped roof
Murcia, Spain	20 × 20 × 17	6800	37	Fire R & D	Pyramidal roof, large mechanical ventilation
Kosori, South Korea	30 × 25 × 16	12,000	–	Passive, active fire tests	
Hefai, China	22 × 12 × 27	7200	59	Fire R & D	Natural + mechanical ventilation
UL-JFL	18 × 12 × 11	2600	–	Active fire tests, Fire R & D	Natural ventilation

About a hundred tests were conducted in two years before shifting to indoor fire bay. The studies during this period gave inputs of ambient wind structure. Though there were a few occasions when the wind speed went higher, on the average it was below 0.5 m/s.

Figure 1a shows the basic design for the in-door fire laboratory came from underwriter laboratories (UL). This design had to be accepted unless argued otherwise as it was based on more than hundred years of experience of UL. In this figure, the supplementary laboratory is meant for auxiliary tests and experiments on fire suppression equipment. The fire bay has a top exit aided by a chimney zone of 3 m × 3 m area and 3 m height. A canopy 4 m wide prevents rain ingress due to some cross wind. It was important to get the pollution board clearance for the design that discharges the smoke. A submission was made that the fire qualification tests last about 3 minutes and their frequency is at best once a day. The facility was located far from the city in an environment surrounded by fields. The pollution control board clearance was obtained in view of the above features. While this feature eliminated rooftop air handling equipment load and need for large power back up to maintain uninterrupted fire tests, there is of course adequate power back up and uninterrupted power supply for critical test and auxiliary equipment and instrumentation.

Figure 1b shows one alternate design in which the four walls of the fire bay would be replaced by porous walls. It was decided that the active blower supply be replaced by air drawn from the sides due to free convection caused by the fire. The three sides (south, east and west) would be staggered double porous walls arranged so that the oncoming wind with a gust or swirl would be diffused by the outer wall and led into the fire bay through the staggered inner wall. The north wall would be porous with a plenum behind it. Air could enter from the sides all over the height through this porous wall into the fire bay.

Figure 1c shows a second alternate design evolved to meet the requirements of management teams in which the north wall was set out as solid. It was enquired if there would be differential flow into the fire if the north wall was made solid instead of porous. Among other relevant questions are: Is the height of the roof adequate enough to contain the smoke without interference to operations within the fire bay? Are the velocities inside the fire bay below the acceptable limits? Are the increased wall temperatures that become attained during the fire tests within acceptable limits for structural safety? These will be considered for examination

For a standard 2.1 m × 2.1 m n-heptane fire, visible flame (persistent fire zone) is below ∼4 m, the intermittent fire zone is below ∼6 m and the plume goes beyond. The height of the roof portion of the facility that is set at 11 m is adequate to receive the hot gases such that all of the visible flame is very much below the roof and the smoke and hot gases emanating from the fire are drawn away from the top region via. a chimney above the pool fire location. And, if this rate is not adequate, the gases can flow out of the porous walls. In one of the early conceptions, it was suggested that the region around the top exit be made sloped to enable the gases to be focused to exit from the top. This idea was replaced by an RCC roof around the central exit

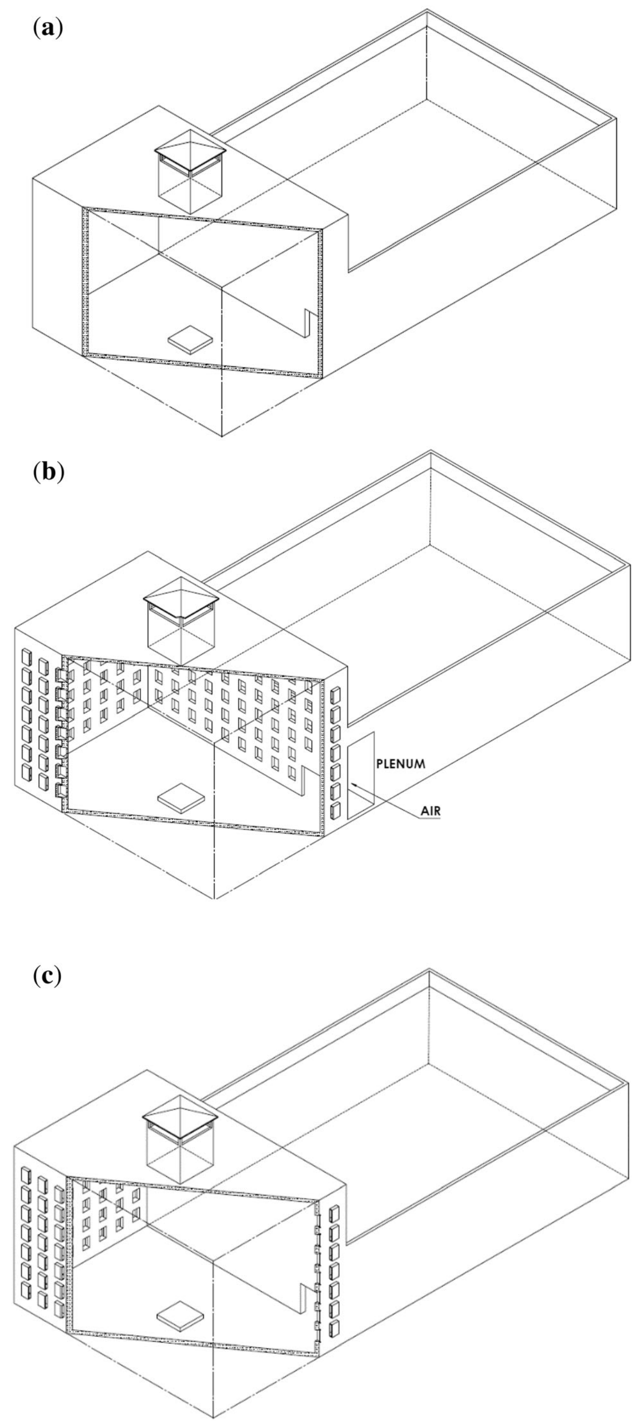


Figure 1. Options for the fire laboratory—(**a**) along the lines provided by underwriter laboratories, (**b**) modification with porous wall—double on three sides and with a plenum on north side, and (**c**) the porous wall replaced by solid wall on the north side.

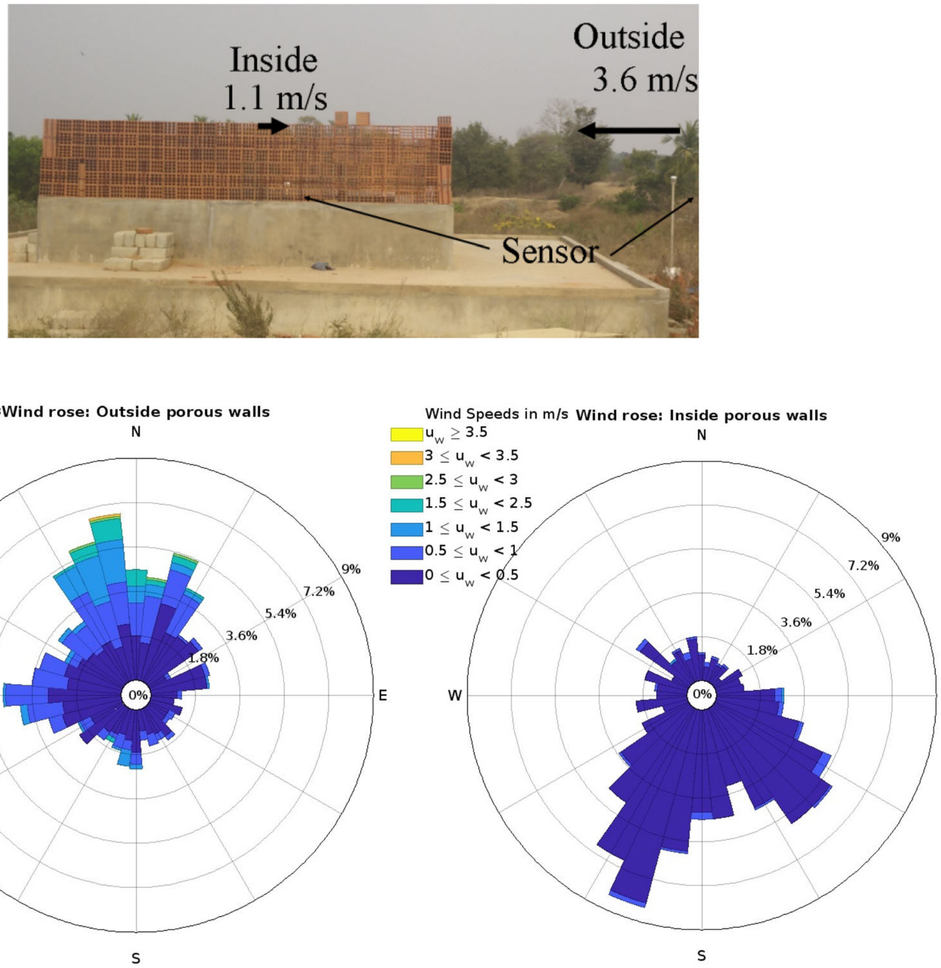


Figure 2. Open field simultaneous measurements of wind speeds outside and inside of a porous wall.

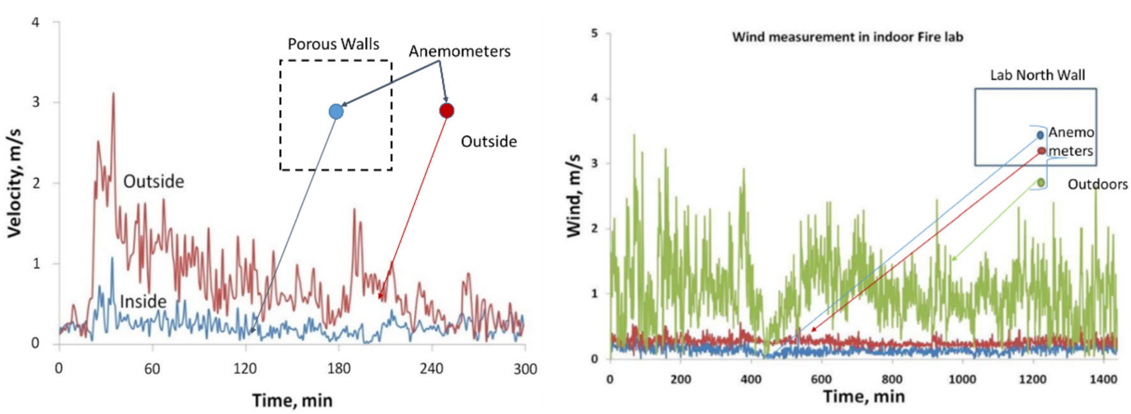
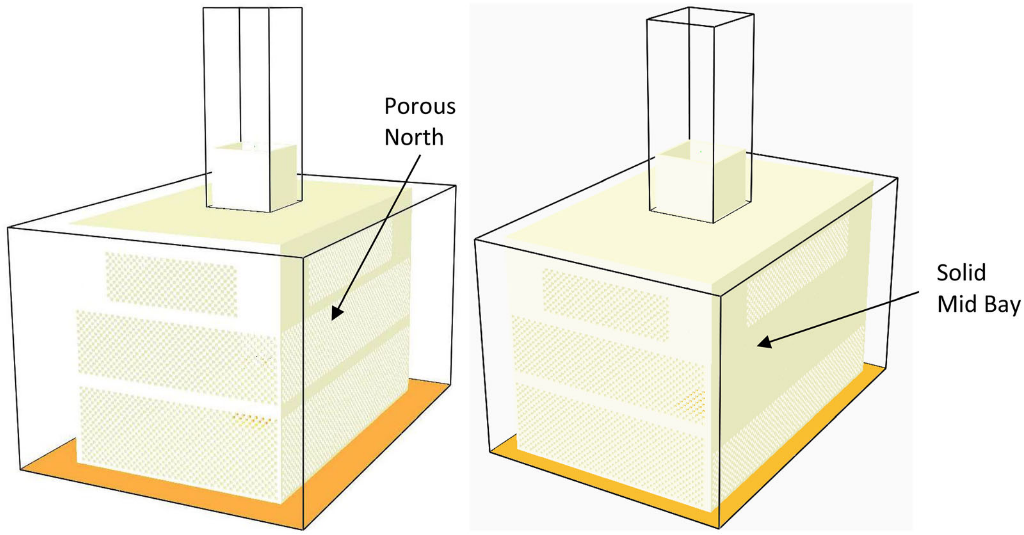


Figure 3. Results of measurement of wind speeds over long durations in the indoor test facility. The left side refers to open porous wall measurements. Right side diagram refers to the results at three points, with two of them inside the fire bay over a day.

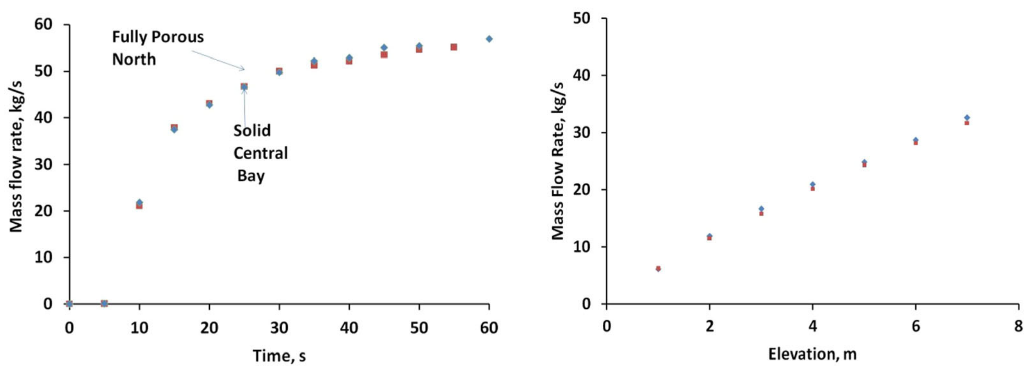
zone and it could only be expected that the hot gases exit from side porous walls. It was inferred that cross wind effects would make the gas exit asymmetric and this was accepted as such.

An estimate of the transverse velocities was obtained from the earlier work due to Koseki and Yumoto [4]. For a 2.1 × 2.1 m pan fire, the air entrained is 15–20 times the fuel flow rate at a height of 0.5 m. Measured burn rates



(**a**) Porous North Wall (**b**) Closed North Mid Bay

Figure 4. Computational features of calculations for porous north and partially porous north with solid mid bay.



(**a**) (**b**)

Figure 5. (**a**) Entrained mass flow rate comparison and (**b**) Vertical flow rates at 60 s.

peak to 0.3 kg/s in about 75–85 s. This leads to an air ingestion of 4.5–6 kg/s. If air is drawn from the side walls with a porosity of 50% (say), then the air flow velocities into the inside of the fire bay will work out to 0.3–0.4 m/s and on the outside of the wall half this value (because the entry cross section becomes doubled. While this wind speed may be acceptable, the local wind speed may increase to larger values, if there is a gust in any segment. In order to assess this aspect, it was decided to measure wind speed both outside and in a zone close to the pan simultaneously for a long period of time, both during the day and night.

Figures 2 and 3 show two sets of measurements—one in open field and one directly outside and inside of the indoor fire bay. These measurements were made using a sonic anemometer (Range: 0–30 m/s, Resolution: 0.01 m/s, Accuracy: the greater of 0.3 m/s or 3% of measurement). The wind measurements show that while outside values vary up to 1.5 m/s on the basis of a local mean, the inside the porous wall are about a third in the mean. The results inside the fire bay are better. The wind speeds close to the pan are clearly between 0.2 and 0.3 m/s.

In order to determine the differences between the north wall condition (porous or non-porous), it was necessary to make fire growth and flow calculations for the cases. For this purpose, FDS software was employed.

2.2 *The calculation procedure*

A recently released FDS 6.1 [5] is used for the calculations. Calculations are run on a mesh size of 0.1667 m along *X* direction, 0.175 m along *Y* direction and 0.1667 m along Z direction are chosen based on heat release rate criterion

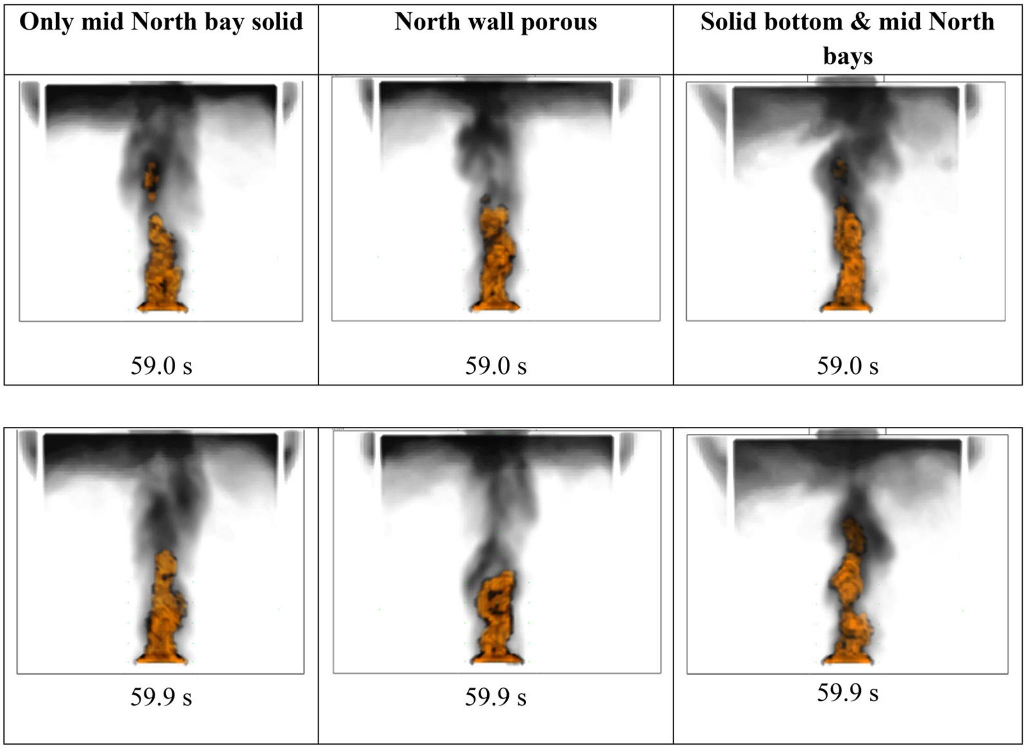


Figure 6. Instantaneous flame-smoke pictures at two instants in one pulsation cycle.

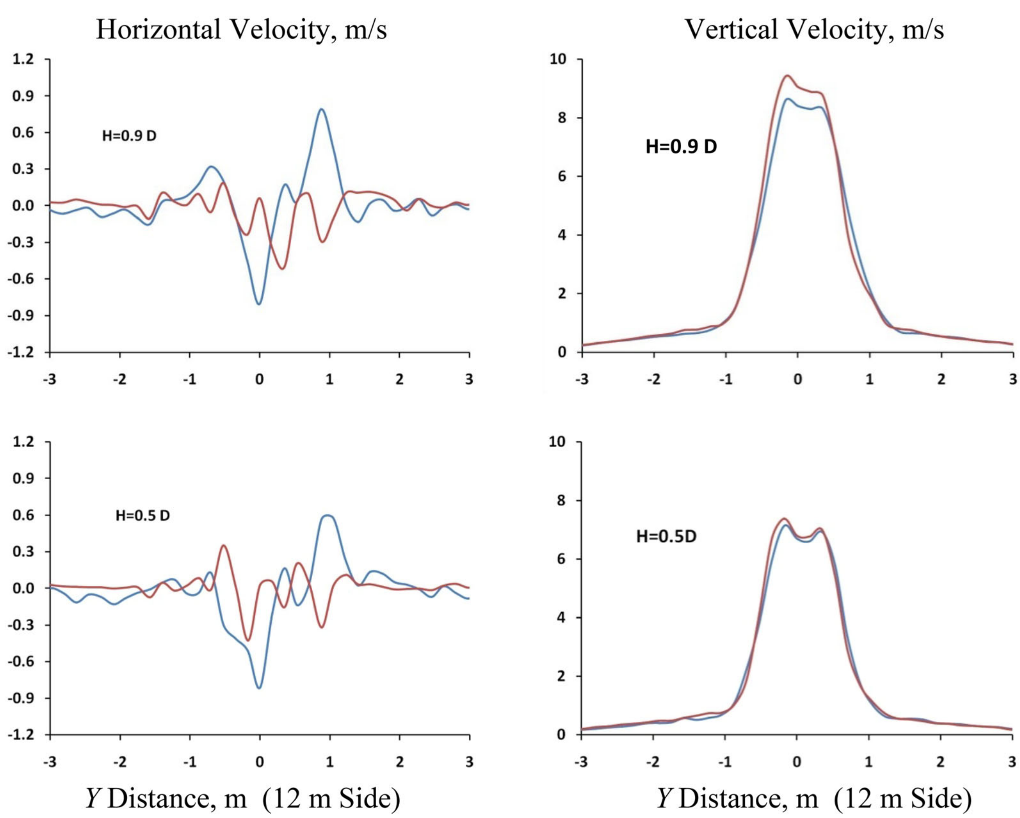


Figure 7. Velocities: 12 m side, 0.5 and 0.9 D (1.6 and 3.2 m high) at 59 and 60 s and 0.28 kg/s (HRRPUA: 63.5 g/m^{2}s).

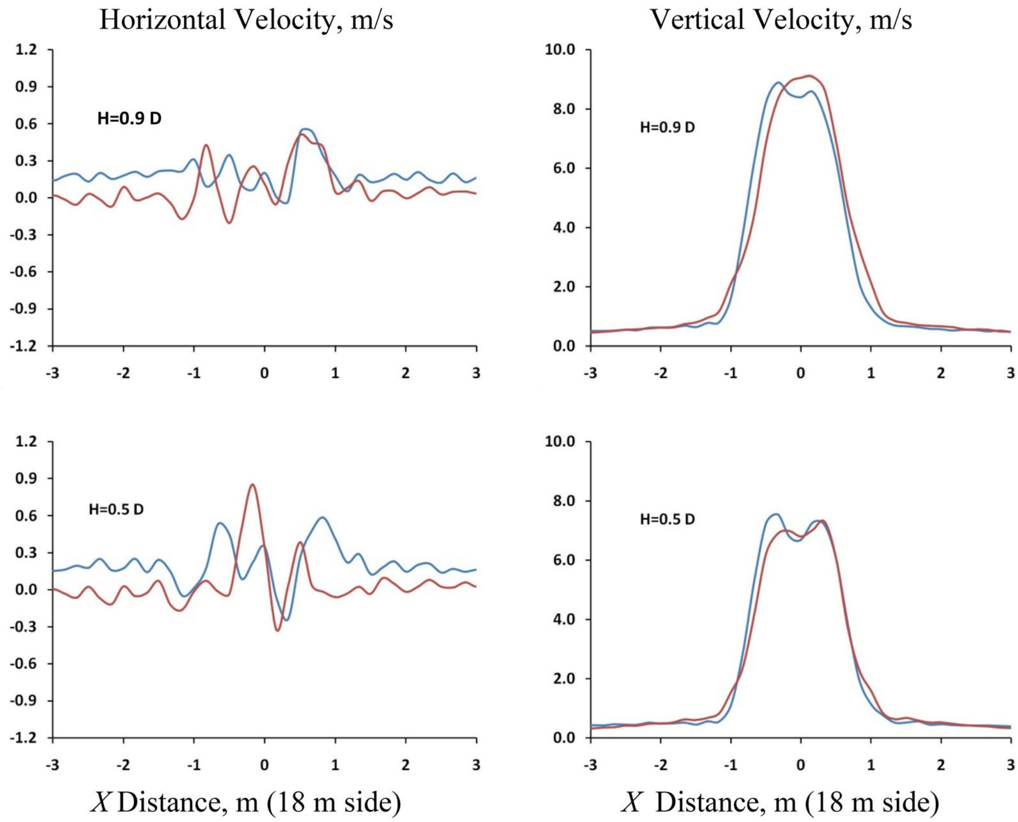


Figure 8. Velocities at two heights along 18 m side at 59 and 60 s—0.28 kg/s fuel (HRRPUA: 63.5 g/m^{2}s).

giving a minimum of 13 nodes across the pan. Wall porosity is modeled by creating a hole on every alternate mesh surface on the lab wall. Room dimensions are approximated as 12 m × 18 m × 12 m high. A zone outside of the porous was chosen to provide the ambient boundary condition. A rectangular domain consisting of 1,257,984 cells (78 × 112 × 144 cells) were employed in the calculation. 1 m additional region was computed all round to ensure boundary disturbance is minimized. Porous wall was approximated by blocking alternate cells at the East, South and West walls. Beam area and column areas were blocked completely. 2.1 m × 2.1 m size fuel surface was located centrally at a height of 0.32 m to approximate fuel layer in the pan. Additionally, height of domain above chimney was increased by 8 m to allow for reduction of upward smoke momentum before it crosses the boundary. Figure 4 shows the three-dimensional framework used for the calculations. A fixed 35% radiation fraction is assumed. Fire is modeled with a heat release rate per unit area (HRRPUA) of 3.178 MW/m^2 with suitable ramp to achieve peak heat release in 50 s to mimic the real fire.

3. Results and discussion

The temporal power rise (fuel heat release rate increase resulting in entrained mass flow rate throughput at room exit) that is set out in the calculations is shown in Figure 5a. The mass flow rate entrained by the flame at various elevations is shown in Figure 5b. This increases nearly linearly with height and reaches 33 kg/s at a height of 7 m. The air flow rate ingested is about 8 times the stoichiometric air flow needed. The amount of air ingested at the exit is about 60 kg/s, nearly double the value at 7 m height.

This dilution helps keeping the roof temperatures below 200°C. Also, the effect of having the north wall solid or porous is not significant on entrained mass flow rates.

The instantaneous pictures of the smoke and fire are set out in Figure 6 for three sub-cases of the porous wall facility: (a) Partially porous North wall with only middle segment solid (left column), (b) Entire North wall porous (central column) and (c) North wall has only the top region porous with solid bottom and middle region (right column) to examine the fire behavior. The duration chosen is for one pulsation cycle time of 0.9 s. Images are presented at 59th s and 59.9th s. If we examine the pictures, it will not be possible to identify one or the other from them.

We now turn to predictions of velocities, pressures and temperatures. Horizontal and vertical velocities along the 12 m side as well as 18 m side are set out along the two axes passing through the pan in Figures 7 and 8 at two heights, 0.5 D and 0.9 D at two instants of time—59 and 60 s. Blue lines indicate calculations with blocked central bay while red lines indicate fully porous north region. The horizontal velocities are small ∼ ± 0.3 m/s. Since it is a

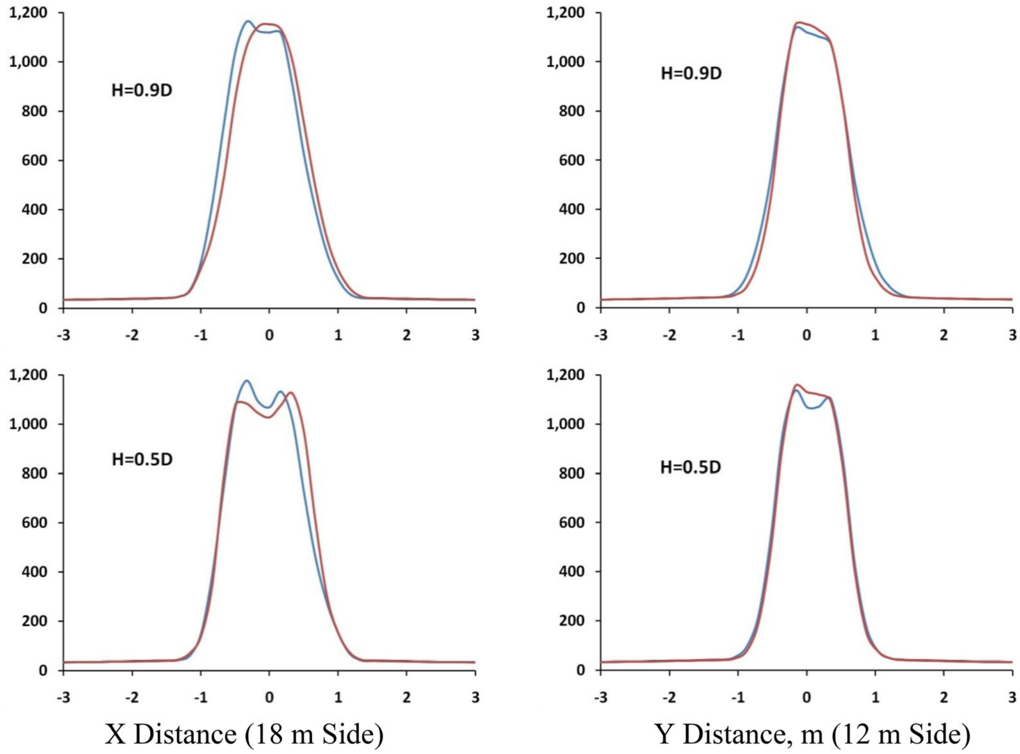
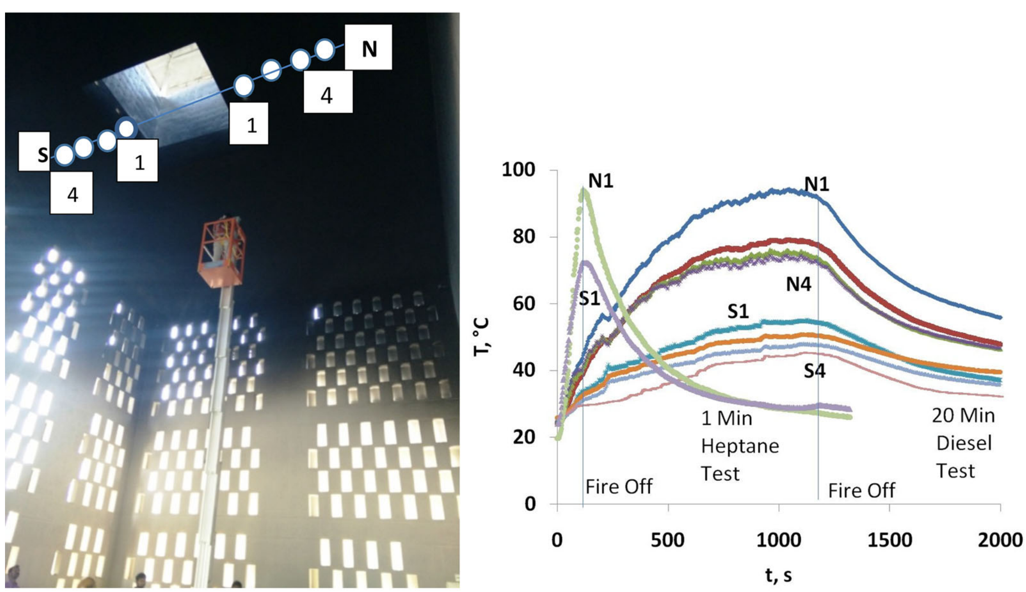


Figure 9. Temperature in °C along 18 m and 12 m side at two elevations.



(**a**) (**b**)

Figure 10. (**a**) The fire laboratory instrumented with thermocouples at the inner part of the roof four on either side of the top exit, N = North—towards the non-porous wall., The double ended arrow indicates the extent of smoke deposits due to escape of hot gases from the sides, typically about 1.5 m. from the top. (**b**) Roof bottom temperatures along S1–S4 and N1–N4 for n-heptane test lasting for 1-minute burn and diesel test lasting for 20 min. burn in 2.1 m × 2.1 m pan.

large eddy simulation, the instantaneous values can fluctuate. These values are comparable to those obtained by Xin *et al* [6] in the large eddy simulation of an open one-m methane pool fire.

Vertical velocities are about the same as height increases. This is because the fluid flow is averaging out the differences in source of the gases as distance increases from the pan. Temperature distributions are presented in Figure 9. As can be seen, there is very little to choose between the two cases. Many more details of the flow and thermal behavior have been extracted from the calculations. These reaffirm the broad conclusion that there is not much to choose between the geometries from the point of view of the fire behavior. *Any choice of making specific segments of the wall porous as proposal 1 or 2 needs to be made based on considerations other than fire behavior.*

Subsequent to the construction of the fire test buildings in 2016, more than 300 fire-foam qualification tests with n-heptane and other tests have been conducted. In all the tests conducted under widely varying wind and rain conditions, the exhaust going from the top region was limited to a height about 1.5 m below the roof. This would leave a clear 9.5 m space for observations of fire during any tests. This result is in conformity with the FDS simulation results. In order to determine the validity of the design from the view point of structural integrity, two experiments were conducted. The bottom region of the roof was instrumented with thermocouples at four locations on either side of the exit as shown in Figure 10a. Two tests were conducted with simultaneous measurement of roof top temperatures. The temperatures at locations S1–S4 and N1–N4 have been set out in Figure 10. Peak temperatures reached do not exceed 100°C and the peak temperature lasts for a short time. It is also inferred that the wall temperatures fall off as one moves away from the exit port as may be expected.

An interesting observation made during the tests was that the flame was vertical with the hot gases going upwards towards the exit over the forty-five seconds of a typical 1 min pre-burn expected of n-heptane tests. Beyond this period, the flame would bend towards north-west for the next fifteen seconds before the foam is switched on. This puzzling feature was inferred to be due to the north wall heating up to 60–65°C while other three sides would go up to 50–55°C. This temperature difference caused buoyancy driven differential pressure drawing the fire towards the north wall. This feature could not be obtained in FDS simulations since they were completed before the fire facility was built and the wall heating was not simulated.

In view of the above situation, it is a considered view of the authors that the fire bay should be built with porous walls all round. It would be better if it is circular. If this cannot be achieved, it could be in hexagonal or octagonal shape with one side connected to the supplementary laboratory. This would ensure the central movement of the fire from the pan to the exit.

4. Concluding remarks

This paper is concerned with studies on a novel and new design of the fire bay of an indoor fire test laboratory (it is important to note that the relevant patent application is currently pending). In consideration of the need to have as many passive elements as possible, the free-convective exhaust of the product gases of fire was adopted. This feature allowed a new approach to be taken for the design of the civil structure—with twin staggered porous wall design. The facility was tested for compliance of ambient wind disturbances and structural safety. The ambient wind disturbances would be 1 m/s on the mean with sporadic sharp fluctuations up to 3 m/s. Yet, the wind speeds measured close to the pan was below 0.3 m/s and has been considered acceptable for all weather operation. Measurements of inner roof temperatures showed values up to 100°C and a drop off beyond the test duration, which with n-heptane is typically 1 minute of pre-burn. FDS calculations up to 60 s showed that the fire was unaffected even if one of walls was made non-porous. However, initial observations up to about 45 s followed this behavior; however, beyond that the fire had a tilt towards the direction of the wall. This was inferred to be due to the wall heating leading to buoyancy driven pull that causes the bending over. A recommendation that emerges from this finding is that all the four walls of a rectangular fire bay should be made porous. A better solution would be to adopt a circular geometry or many-sided polygon (say hexagon or octagon) with a suitable link to the supplementary laboratory to have fire behavior unaffected by the geometry of the fire bay or wind disturbances.

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