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FIRE DRIVEN FLOW WITHIN CAVITIES BEHIND PERFORATED CLADDING – A CFD MODELLING INVESTIGATION

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ABSTRACT

Ventilation cavities and gaps between material layers are common in modern construction. The cavities may provide a pathway for smoke and flame spread in the case of fire; more importantly, the narrowed space may lead to unseeable, accelerated flame and smoke propagation due to the chimney effect. Therefore, the Building Regulations in the UK request the provision of sufficient cavity barriers to close up and/or divide the cavities to control and mitigate the flame elongation and smoke propagation within the ventilated cladding system.

Perforated panels are increasingly used as cladding for buildings of all size and use: it provides a very effective way to enliven the façade. Perforated metal offers the same protection to a structure as other types of metal siding while allowing more effective pressure equalisation between the space behind the panel and the exterior of the building. The chimney effect and thus the flame elongation behind the panel are different from those within the traditional ventilated render system. Therefore, it could lead to a different need in the provision of cavity barriers to prevent the flame and smoke movement within the cavities. Instead of physical testing, Computational Fluid Dynamics (CFD) modelling is used to investigate the fire-driven flow within the cavities behind the perforated panels with the intent to determine the requirements on the cavity barriers within the undivided cavity gaps.

Pyrosim and FDS are utilised for the fire and smoke modelling. Flame height, thermal impact to the interior material surface and airflow velocities are predicted. The panels with different perforation percentages are investigated under the same fire scenario with the purpose to provide guidance on the requirement for cavity barriers within external wall systems with perforated panel cladding.

INTRODUCTION

In the event of a fire, fire spreading within narrow air cavities between material layer of ventilated façades or rainscreen system is considered as a major risk as the chimney or stack effect within the narrow space can accelerate the fire spread over the external wall system.

Following the initiation of a fire inside the building, a fire may develop into a fully developed fire, i.e. flashover, and break out from the fire room through window openings. In accordance with BR 135, a post-flashover fire flame breaking out of a building will typically extend 2m above the top of the opening before any involvement of the external face. At this stage, the fire performance of the complete external wall system, including the cladding, insulation and cavity barriers, etc. is critically important. Once flames begin to impinge upon the external fabric of the building, from either an internal or an external source (such as balcony), there is the potential for the external cladding system to become involved and to contribute to the external fire spread up the building by the following routes:

- Surface propagation: This influences the rate of fire spread up the building envelope by way of the surface of the external cladding system.
- Combustible insulation: Combustible insulation material will provide a bypass for fire spread and accelerate the rate of fire spread over the external wall.
- Balcony: Inappropriate use of the balcony could be an ignition source. The construction material of the balcony could also provide vertical fire spread bypass between compartment levels.
- Cavities: If flames become confined or restricted by entering cavities within the external cladding system, they will become elongated as they seek oxygen and fuel to support the combustion process. This process can lead to a flame extension of five to ten times that of the original flame lengths, regardless of the materials used to line the cavities. Therefore, cavity barriers should be incorporated within an external cladding system.

There has been increased awareness of façade fire safety, especially after the Knowsley Heights and the Grenfell Tower fire accidents. The need to understand the system level fire performance of façades have resulted in literature reviews and experimental studies.

Perforated Cladding system

Perforated metal cladding is increasingly applied to different type of buildings as it provides a very effective way to enliven the façade of a simple structure or building. The perforated cladding also has the ability to add depth, texture and features to an otherwise simple façade since the form of perforation is variable and attractive, e.g. from uniform circular perforation to honey comb-patterned mesh to even three-dimensional forms.

In addition, perforated cladding can control and manage the amount of natural light reaching the inside of the building relaying on the size of perforations, e.g. large perforation allows more natural light to pass through the claddings, but reducing the amount of solar gain especially for the buildings with large glazed elements. Figure 1 illustrates residential building with perforated cladding system as part of the external wall.

Figure 1: Illustration of Residential Building with Decorative Perforated Cladding Panel (*https://www.dezeen.com/2019/03/30/nth-fitzroy-apartment-melbourne-interiors-fieldwork-flack-studio-australia/*)

External wall and cavity barrier requirement

In the UK, the Building Regulations request the provision of cavity barriers within the following locations to divide cavities and to close the edges of cavities:

- At the edge of cavities, including around openings;
- At the junction between an external cavity wall and every compartment floor and wall;
- At the junction between an internal cavity wall and every compartment floor/wall or other wall/door assembly forming a fire-resisting barrier.

By definition, the external wall of a building includes:

- anything located within any space forming part of the wall;
- any decoration or other finish applied to any external (but not internal) surface forming part of the wall;
- any windows and doors in the wall; and
- any part of a roof pitched at an angle of more than 70 degrees to the horizontal if that part of the roof adjoins a space within the building to which persons have access, but not access only for the purpose of carrying out repairs or maintenance.

The perforated cladding system is categorised as part of the external wall and the gap between the cladding and the wall is classified as a cavity within the external wall. Therefore, in accordance with Building Regulations requirement, cavity barriers should be provided within the cavity between the perforated cladding and the wall construction. However, in many cases, the provision of cavity barriers is challenging. The primary function of the cavity barrier is to prevent the unseen spread of fire and smoke within the concealed spaces in its structure and fabric.

Fire Safety Issue within Cavity of Cladding System

As discussed above, the open cavity within the wall construction (including any decorative cladding panel) can act like a chimney in the event of a fire. When flames are confined by the narrow cavity, they may be elongated due to seeking oxygen and fuel to support the combustion process. This phenomenon is known as “chimney effect”. The chimney effect, even if the cavity itself is fully non-combustible, could allow the flames to reach the next floor level, where windows and other wall penetrations will allow the fire to re-enter the building and maintain the spreading of the fire. This may enable fire to spread quickly and unseen through the external cladding system, if appropriate cavity barriers have not been provided. The air inflow rate in a narrow cavity scenario is governed by limited space and the chimney effect. Ignition and the efficiency of combustion is controlled by pyrolysis rates and the rate of air inflow. Flame geometry is influenced by cavity width. Heat transfer from flames and radiation effects from the protecting layer (e.g. cladding) will determine the heating rate and heated area of the virgin material.

The current research mainly focuses on the fire performance of ventilated façade systems. Various types of research have been carried out including full scale or reduced scale tests [Kolaitis DI, Bostro¨ m L, Jamison KLT] as well as analytical modelling approaches [María P. Giraldo, Karlis Livkiss]. It has been observed that the flames spreading up through an air cavity space of the building cladding can extend up to ten times higher compared to the flame outside the cavity and increase the burning rate of the cladding system [Bostro¨ m L].

The perforated decorative cladding creates a cavity between the metal cladding and the wall of the building. However, due to the perforation on the cladding, the air flow patterns differ from the cavities within the ventilated cladding system. Very little study has been carried out for the fire driven flow within the cavity behind the perforated metal cladding.

In this study, Computational Fluid Dynamics (CFD) can be used as a tool to study fire-induced flows and flame spread in narrow air cavity configurations. Nevertheless, only limited work has been done to investigate the applicability of CFD for smoke and fire spread in concealed spaces.

CFD MODELLING OF PERFORATED CLADDING SYSTEM

The CFD analysis for this report is conducted utilising Fire Dynamics Simulator (FDS) and Smokeview as released by the National Institute of Standard and Technology (NIST). FDS is a computational fluid dynamics (CFD) model of fire-driven fluid flow. FDS solves numerically a form of the Naiver-Stokes equations appropriate for low-speed (Ma < 0.3), thermally-driven flow with an emphasis on smoke and heat transport from fires. FDS employs Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) solutions of Navier-Stokes equations. DNS approach directly resolves all length scales of turbulence. DNS requires very fine mesh, equal to or less than the Kolmogorov length scale, and therefore large computational and time resources are needed. Nevertheless, DNS has been applied to study boundary layer flow and fame spread in various instances.

MODEL SET UP

In order to investigate the influence of different factors on the fire and smoke propagation within external walls due to the perforated cladding system, a CFD model has been set up for the parametric study. The model consisted of a narrow and long gas burner, which is positioned between two parallel facing non-combustible boards. One of them represents the outer surface of the wall construction and one of them represents the metal decorative cladding. The dimensions of the wall panels measure 1m by 2m. The burner was located next to the inner wall surface. The purpose of this model is to emulate the flame elongation and smoke propagation within a cavity between the wall and the decorative cladding system.

The model is constructed within a computational domain of 1m by 2m by 0.2m. Two parallel facing obstructions with an area of $2m^2$ were set-up with the same distance of cavity depth being studied. The burner was modelled in the space below the obstructions to represent the fire. In order to investigate the impact of the perforation on the pressure difference and air supply between the cavity and atmosphere, the air flow upward velocity, temperature, flame height and incident heat flux within the narrow cavity along the height of the wall were investigated.

The simple chemistry combustion model (default in FDS) was used in simulations for the burner fire. The fire is represented by the burner and the HRR of the burner fire that have been investigated are 15kW/m, 30kW/m and 150kW/m, which are comparable with the available fire tests (Karlsson, Ingason, and Livikiss) where the fire intensity ranges from 16.5 kW/m to 125kW/m.

The wall of the system is assumed to be of brickwork construction and the perforated metal cladding is assumed to be of steel material. The relevant thermal properties of the materials are incorporated in FDS. The material properties used in simulation are presented in Table 1. Wall temperature, convective and radiative heat fluxes were measured with the respective devices in FDS.

Table 1: Property for the material for the wall and the perforated cladding

Material	Brick-wall	Perforated Metal Cladding
Specific Heat (kJ/(kg°C))	1.04	0.46
Conductivity (*W/m K*)	See Figure 2	45.8
Density (kg/m^3)	750	7850
Emissivity	0.8	0.95
Thickness (mm)	120	10

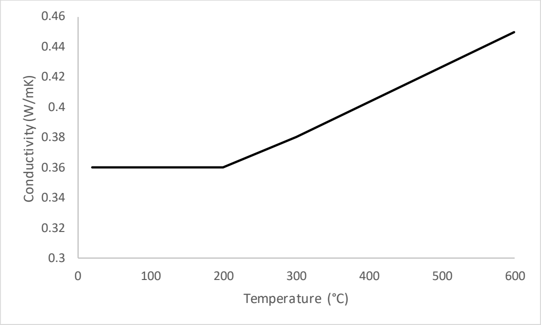


Figure 2: Conductivity of Wall

In this study, the following parameters are investigated by the numerical analysis:

1. Cavity Depth
2. Perforated Ratio of Metal Cladding
3. Intensity of Fire

In addition, the system without the perforated metal cladding was also investigated, where the obstacles from the cavity arrangement model were removed. This free burning case serves as the basis for comparison.

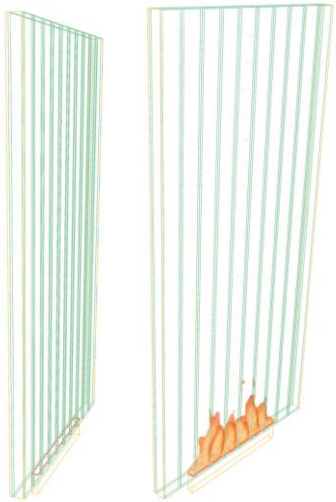


Figure 3: CFD Model for Wall System Studied

It is acknowledged that the perforation configuration, e.g. the size, location and shape of the perforations may also have impact on the fire/smoke propagation within the cavity. However, the study presented in this paper focuses on the metal claddings with vertical perforations.

RESULTS

Mesh Size Sensitivity Study

In the use of computer modelling systems such as FDS, the resolution of the meshes may have an impact on the results obtained. Reducing the grid size does not automatically mean a significantly better precision, but it does considerably increase the runtime of the simulation. Therefore, it is important to find a balance between the desired precision and keeping the simulation time at a level acceptable to the user.

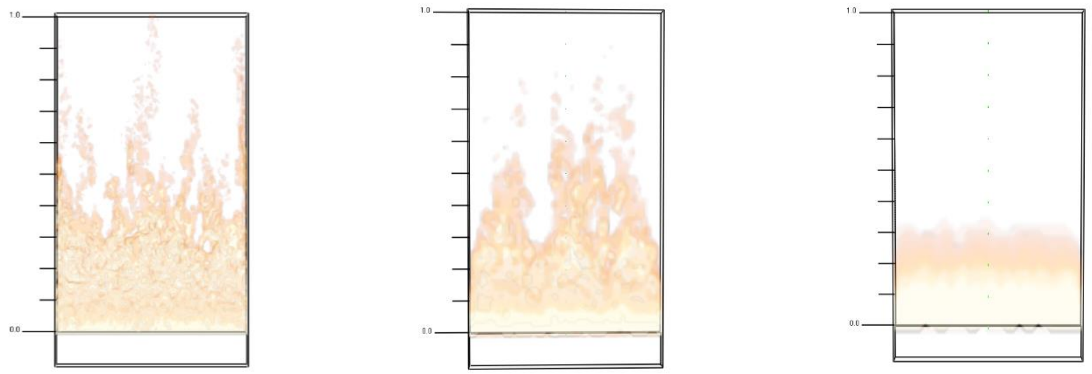
A sensitivity analysis was undertaken to compare the results obtained when using varying mesh sizes: 5mm, 10mm, and 20mm. The analysis is to demonstrate that the selection of a 10mm for this study is appropriate and provides a valid result, given the limitations of computational processing. A model of reduced size was used in this comparison as the absolute values of the results are not significant, only any differences in the results between the mesh sizes. The model has a height of 1m, a cavity depth of 40mm, and no perforation on the outer cladding layer.

Table 2: Grid Sensitivities

	5mm	10mm	20mm
Average Temperature at 0.2m above fire (°C) Deviation	690 -	760 **10%**	491 28%
Average Temperature at 0.6m above fire(°C) Deviation	467 -	497 **6%**	324 29%
Average Temperature at 0.8m above fire(°C) Deviation	402 -	430 **7.5%**	278 31%
Average Velocity at 0.2m above fire(m/s) Deviation	2.1 -	2.2 **5%**	2.7 28%
Average Velocity at 0.6m above fire(m/s) Deviation	2.0 -	2.1 **5%**	2.7 35%
Average Velocity at 0.8m above fire(m/s) Deviation	2.0 -	2.1 **5%**	2.6 30%
Average Incident HF at 0.2m above fire(kW/m^2) Deviation	18.7 -	16.2 **13%**	11.9 36%
Average Incident HF at 0.6m above fire(kW/m^2) Deviation	5.1 -	5.2 **3%**	2.7 46%
Average Incident HF at 0.8m above fire(kW/m^2) Deviation	3.7 -	3.9 **5.3%**	2.34 36%

Table 2 illustrate the values of the peak temperature, average radiant heat flux, and average velocity, respectively, for the three different mesh sizes used in the model. It can be seen that the deviation from a 10mm and 5mm mesh size is less than 10% with the exception of the average radiative heat fluxes, for which the absolute different is not considered as significant. It can be reasonably stated that the 10mm provides an appropriate level of accuracy and is acceptable to be used in this study which aims to preliminarily understand the impact of the perforation on the metal cladding on the fire drive flow by a comparative study.

The flame heights within the FDS simulation also show a good similarity between the 5mm and 10mm meshes, whereas the 20mm mesh is too large to illustrate any localised variations – illustrated in Figure 4.



5mm 10mm 20mm

Figure 4: Flame height at 10 seconds for 5mm, 10mm, and 20mm meshes

Impact of Perforation Percentage

The primary focus of the results will be on the 40mm cavity depth model, with perforation percentages of 0%, 10%, 25%, and 50%. These will be also compared to the free burning model which has no outer cladding layer.

Flame height

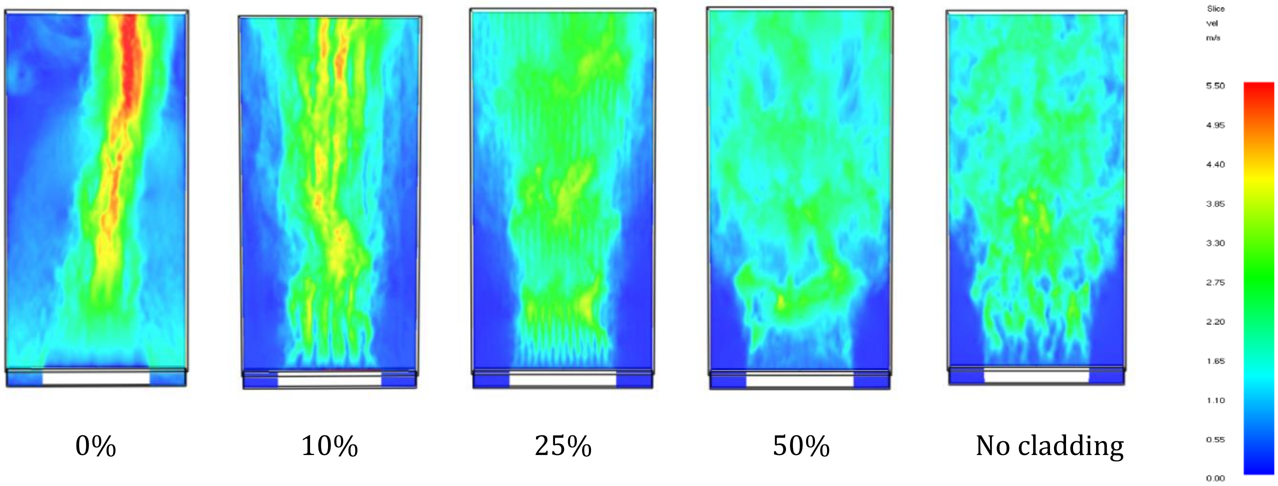
The indicative flame heights for each arrangement have been taken from the Smoke-View output file and show the flame (HRRPUV) for t=20s, with the flame being in a relatively steady-state from 10s to 40s. It can be seen that the flame height is reduced significantly due to the perforation on the cladding and it can also be seen that the flame can be elongated within the enclosed cavity.

0% 10% 25% 50% No cladding

Figure 5: Flame height at 20 seconds for arrangements with 0%, 10%, 25%, and 50% perforation and free burning case

Upward flow velocity

Figure 6 shows the velocity contour at 20s for the cases with different perforation ratio within the cladding. It can be seen that the velocity within the air flow is clearly reduced as the perforation ratio increases. With the perforation ratio of more 50%, the velocity of the fire driven flow within the cavity is very similar with the case with no cladding.



0% 10% 25% 50% No cladding

Figure 6: Velocity slice file for 0%, 10%, and 25% arrangement, taken at t=20s

Incident heat flux to the near wall

The incident heat fluxes for each arrangement have been taken as the sum of the average radiant and convective heat flux measured at each measurement device along the wall height between 10s and 40s where the system is considered to be in a relatively steady state. The results are displayed in Figure 7.

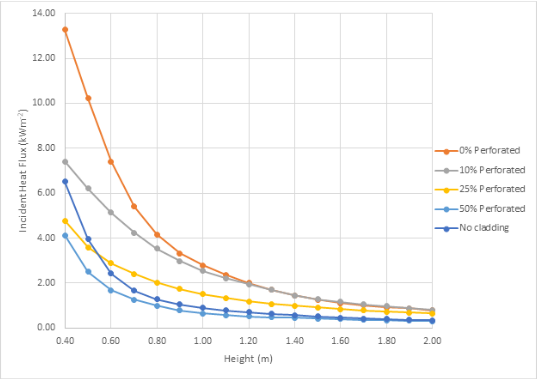


Figure 7: Average Incident heat flux values for arrangements with 0%, 10%, 25%, and 50% perforation and free burning case

The incident heat fluxes for each arrangement follow an extremely similar trend over the height of wall, with the no perforation case providing radiative heat flux values much larger than all other cases. This is likely due to the effect of re-radiation from the outer cladding panel (with no perforations) as well as the increased temperatures within the cavity where there are no perforations providing heat dissipation to the outside. Within the cavity behind the cladding with perforation over 50%, the incident heat flux along with the height is very similar with the case with no cladding.

Temperature

The temperatures for each arrangement have been taken as an average of the temperature measured at each thermocouple device (0.2m, 0.3m, 0.4m, 0.5m, …) between 10s and 40s where the system is considered to be in a relatively steady state. The results are displayed in Figure 8. With the cladding perforation ratio increases, the temperature within the cavity is gradually decrease. With a perforation ratio over 50%, the temperatures within the cavity space are very similar to the no cladding scenario.

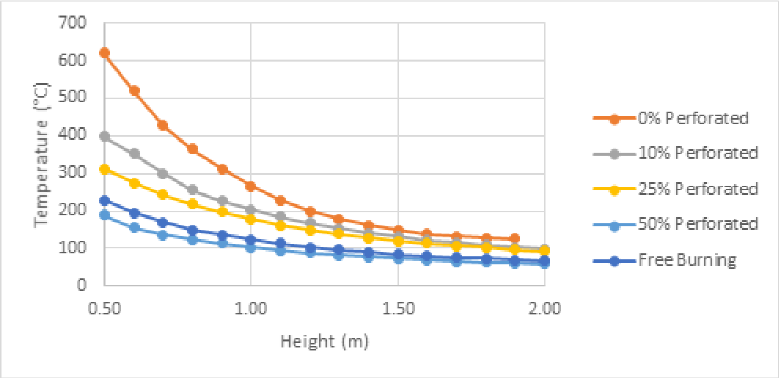


Figure 8: Average temperature values for arrangements with 0%, 10%, 25%, and 50% perforation and free burning case

Impact of Cavity Depth

Flame height

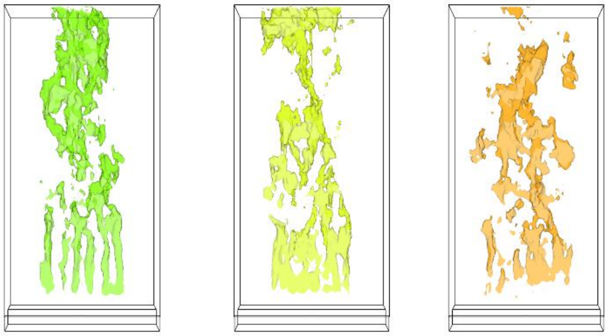
As the cavity depth increases, the distance between the two walls becomes less relevant to the behaviour of the fire within the cavity and it can be seen that by 80mm, the flame heights within the cavity are approximately the same, regardless of the level of perforation on the outer cladding layer. This suggests that the impact of the perforations on the fire behaviour become more significant as the cavity depth decreases.

Table 1: Flame heights taken at t=20s for different cavity depths and perforation levels

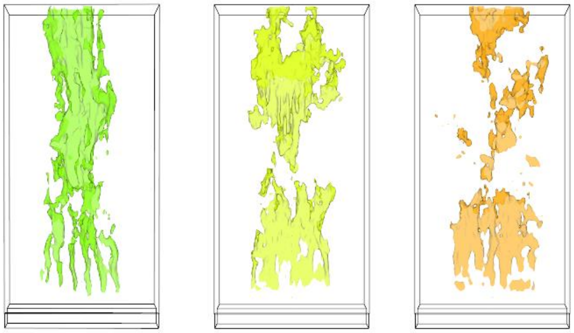
		Perforation Level				
		0%	10%	25%	50%	No Cladding
Cavity Depth (mm)	40	0.9m	0.4m	0.4m	0.4m	0.4m
	80	0.5m	0.4m	0.4m	0.4m	0.4m
	120	0.4m	0.4m	0.4m	0.4m	0.4m

Upward flow velocity

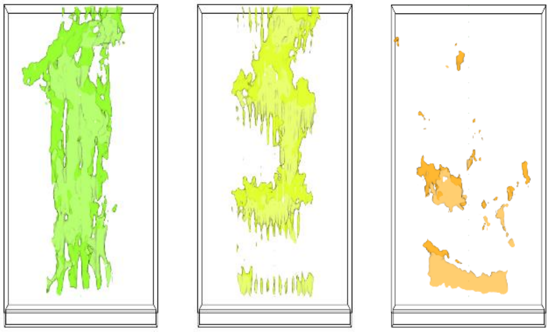
Figure 9 illustrates the different in upward flow velocity profile (represented by the isosurface of velocity 1.5m/s) within the gaps with different cavity depths. It can be seen that in general, the impact of the cavity depth on the velocity of the air flow within the cavity is less significant than that of the perforation ratio. This is due to that the perforation has more direct influence on the air supply to support the combustion with the cavity space.



120mm (10%, 25%, 50% perforation)



80mm (10%, 25%, 50% perforation)



40mm (10%, 25%, 50% perforation)

Figure 9: Velocity profile (1.5m/s isosurface within the cavity of different depth)

Incident heat flux to the near wall

The incident heat flux for two perforated cases (25%, and 50%) are compared with different cavity depths; these are illustrated in Figure 10. It is shown that the incident heat flux along the height within the cavity doesn't vary too much if the perforation ratio is over 25% and the cavity depth is more than 80mm.

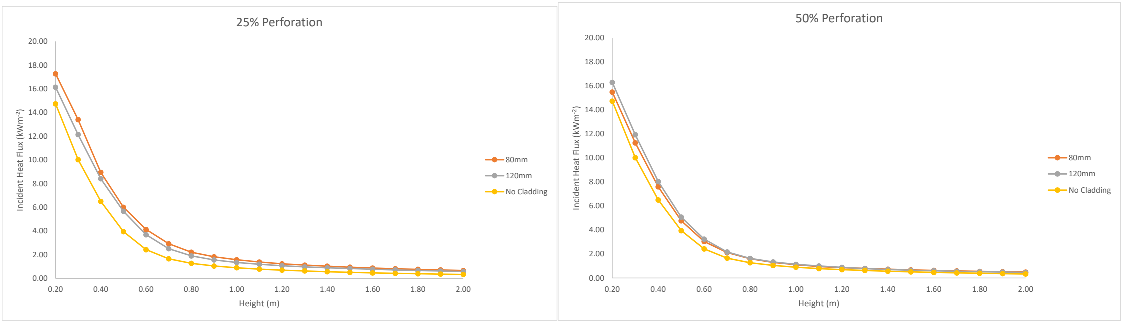
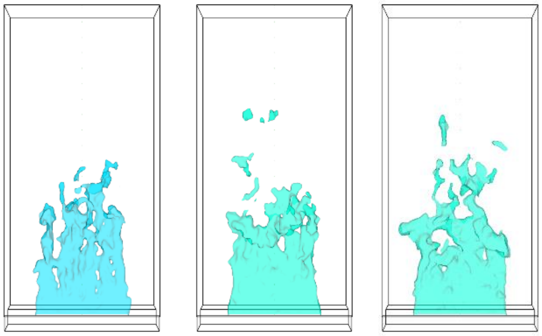


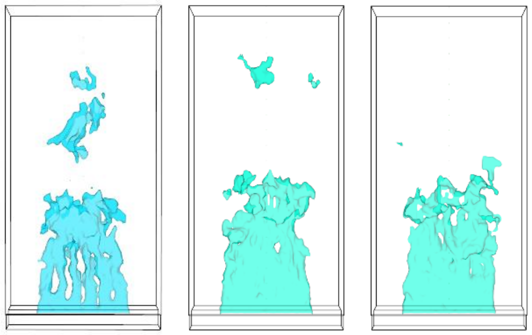
Figure 10: Average Incident heat flux for 25% (left) and 50%(right) perforation case, comparing three cavity depths (80mm, and 120mm)

Temperature

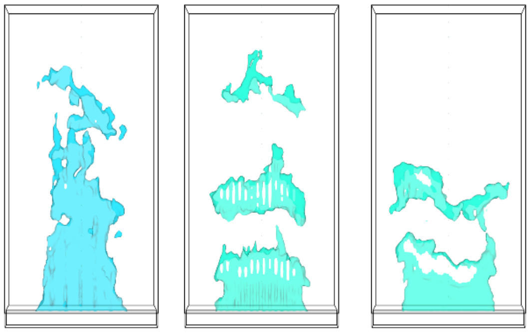
Figure 11 shows the influence of the cavity depth on the temperature within the cavity. The impact of the cavity depth is less significant than that of the perforation ratio, especially when the cavity depth is over 80mm.



120mm (10%, 25%, 50% perforation)



80mm (10%, 25%, 50% perforation)



40mm (10%, 25%, 50% perforation)

Figure 11: Temperature profile (200°C isosurface within the cavity of different depth)

Impact of Fire Intensity

Figure 13 shows the influence of the fire intensity on the fire driven flow within the space, clearly, the velocity, temperature and incident heat flux are increase with the fire intensity increase. However, it is also observed in Figure 14 that when the perforation is over 50%, the fire drive air flow within the gaps is similar with the case with no cladding.

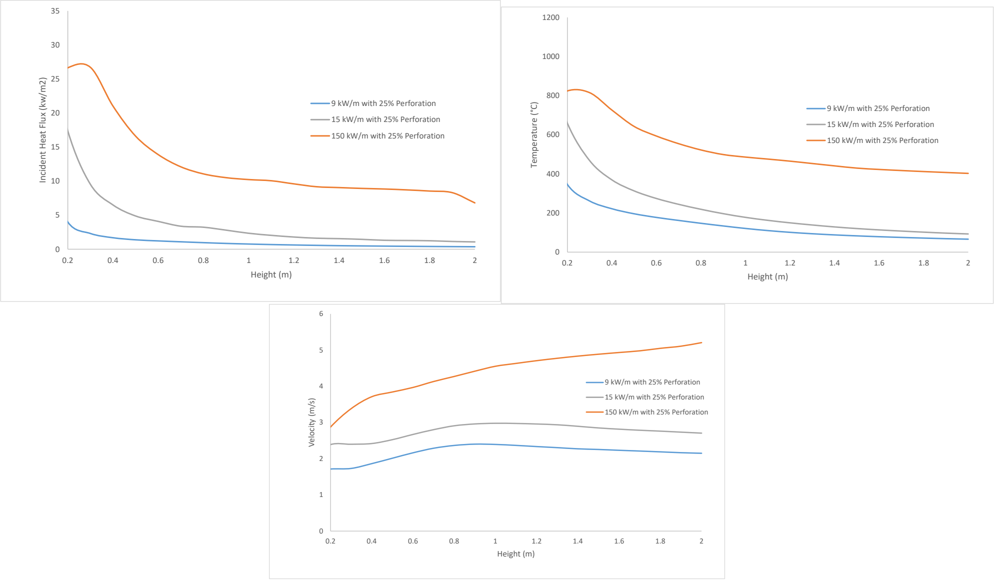
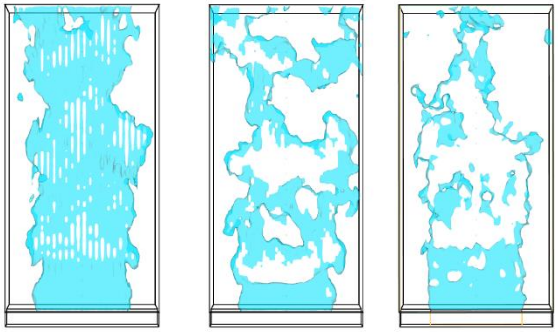
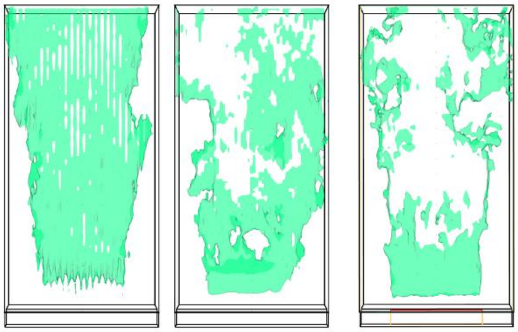


Figure 12: Influence of fire intensity on temperature, velocity and incident heat flux for the case with 25% perforation



150kW/m (25%, 50%, 100% perforation) Velocity



150kW/m (25%, 50%,100% perforation) Temperature

Figure 13: Velocity and Temperature profile (2m/s and 200°C isosurface repective)

FURTHER STUDY

The study presented in this paper is a preliminary study on the influence of the cladding perforation on the fire-driven air flow within the cavity. The study is based on an assumed fire scenario with its size in line with fire tests. It is aimed to investigate the performance of the cladding system further by carrying out CFD modelling with a full cladding system under a post-flashover fire from the compartment. In addition, a cladding system with a different perforation geometry will also be investigated.

CONCLUSION

A numerical study using CFD techniques has been carried out to investigate the fire-driven air flow within the cavity with perforated cladding. The fire intensity investigated are 15 kW/m, 30kW/m and 150 kW/m, in line with other fire tests. The followings have been observed:

1. Perforation ratios have a significant influence on the fire-driven air flow within the cavity space. For the considered fire size, flame height is reduced significantly due to the perforation on the cladding and it can also be seen that the flame can be elongated within the enclosed cavity;
2. With the perforation ratio of 50% or greater, the velocity, temperature and incident heat flux of the fire-driven flow within the cavity is very similar to the case with no cladding;
3. A narrower cavity generally induces higher flame height and higher upward air flow within the cavity. However, if the cavity depth is over 80mm and the perforation is over 50%, the flame height, the incident heat flux and temperature within the cavity are very similar;
4. With the fire intensity increasing, the temperature, velocity and incident heat flux within the gap increases.

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