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Experimental study and advanced CFD simulation of fire safety performance of building external wall insulation system

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Abstract. Large scale fire tests of building external wall insulation system were conducted. In the experiment, thermal-couples were mounted to measure the insulation system surface temperature and the gas temperature inside rooms at the second and third floors. Photos were also taken during the fire tests. The measurement provides information of the ignition and fire spread of the external insulation system which consists of surface protection layer, glass fibre net, bonding thin layer, anchor and the load bearing wall.

Comprehensive simulations of the fire tests were carried out using an advanced CFD fire simulation software Simtec (Simulation of Thermal Engineering Complex) [1, 2], which is now released by Simtec Soft Sweden, with the turbulent flow, turbulent combustion, thermal radiation, soot formation, convective heat transfer, the fully coupled three dimensional heat transfer inside solid materials, the 'burn-out' of the surface protection layer and the pyrolysis of the insulation layer, etc, all computed.

The simulation is compared with experimental measurement for validation. The simulation well captured the burning and fire spread of the external insulation wall.

1. INTRODUCTION

With strategic implementation of building energy conservation, external wall insulation system has been widely used in China. Thin plaster external thermal insulation systems (TPETIS), with advantages such as light weight, low thermal conductivity, wall structure protective, simplicity in construction and etc., have become the most widely used type of wall insulation system. Typical insulating materials used in TPETIS are EPS (Expanded Polystyrene), XPS, (Extruded Polystyrene) PUR (Polyurethane) and PIR (Polyisocyanurate). In recent years, however, a number of serious fire accidents of high-rise building are related to TPETIS. This has drawn people's high attention to the fire safety of TPETIS.

The fire performance of TPETIS is mainly affected by factors such as ignition source, system structure and combustion property of the insulation materials. For ignition source factor, Lee [3–5] has analyzed of the spreading mechanism of window fires (the external wall insulation system fire is usually started by window fires) and proposed a new length scale for correlating window fire's flame height, plume temperature and heat flux. Himoto [6] considered pressure gradient effect of window fire plume, and proposed a model for predicting the trajectory of window flame ejected from a fire compartment. For system structure factor, Oleszkiewicz [7] pointed out that laterally projecting structure of building facade can reduce radiant heat flow by 90%, and the vertical extending structure can increase radiation heat flux by 50%. For TPETIS, he also proposed fire-barrier belts to be used between every one or two floors. In recent years, a number of scientists [8–10] have carried out a number of window and corner fire experimental studies and indicated that the systems with improved structure (such as additional

Table 1. Foam plastics for real scale fire tests.

No.	Foam plastics	Thickness (mm)	Density(kg/m^3)
1	XPS	80	24.8
2	EPS	100	18.8
3	PIR	50	40.9
4	PUR	50	42.6

partitions, non-cavity structure and increased protective layer thickness) can effectively reduce fire spreading. In general, the ignition source and system structure factors have been quite extensive studied in recent years. However, the factor of combustion property of insulation material is in lack of systematic investigation.

In a real external wall insulation system fire, fire smoke may enter into the building through openings at floors above the floor where the fire is started. This can cause fire spread inside the building and impose danger to people and property inside. Therefore, it is also very essential and valuable to investigate how the building interior is affected by the external wall insulation system fire.

In this study, a series of full scale fire tests have been conducted to evaluate the fire performance of TPETIS with different insulation materials including EPS, XPS, PUR and PIR. Meanwhile, measurement is also made to investigate the smoke spreading into the building through opening. Furthermore, advanced CFD simulations are also carried out to simulate these fire tests and provide more insight into the burning and fire spread mechanism of the building external wall insulation system. The simulations are compared with tests for validation. With the validation, more simulations can be performed in the future to study and analyze the fire performance of different building external wall insulation systems for different buildings and also in turn provide possible guidance to improve the fire performance of building external wall insulation system in practice.

2. FULL SCALE FIRE TEST OF BUILDING EXTERNAL WALL INSULATION SYSTEM

2.1 Test sample and testing method

2.1.1 Test samples

Table 1 shows information on foam plastics which are used as insulation core materials of TPETIS for full scale fire tests. Figure 1 shows the tested TPETIS and its complete structure. In addition to different insulation core materials, it also consists of plaster (thickness 5 mm), reinforcing mesh (area density 260 g/m^2), anchor bolt and substrate adhesive.

2.1.2 Testing method – full scale test

(1) Testing building: The full scale fire tests of building external wall insulation system were conducted at Sichuan Fire Research Institute of Public Security Ministry, China. The fire test building is shown in Figure 2. A three-storey building unit with an added 1.4 m × 9.3 m side wall was used for the experiment. The experiment building unit has size of 3.6 m (wide) × 5.2 m (deep) × 9.3 m (high). The external wall insulation system is shown in Figure 1, which consists of surface protection layer, glass fibre net, bonding thin layer, anchor and the load bearing wall.

There are total 3 floors of testing building unit, with combustion chamber at ground floor, and observation rooms at the 2nd and 3rd floors. The Combustion chamber has an internal dimension of 2.0 m × 2.0 m × 1.0 m with an opening of aspect ratio 1.0. Opening aspect ratio of combustion chamber has a significant effect on window fire. In the case of natural convection, when opening aspect ratio of combustion chamber is greater than 0.8, the window fire tends to spread along external

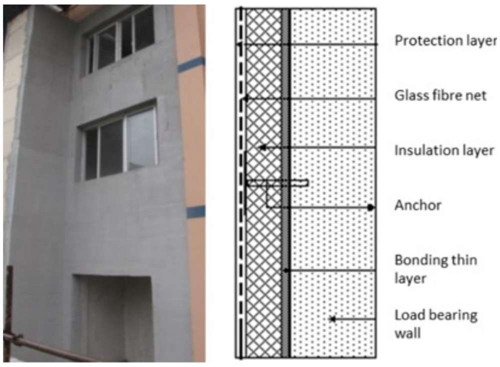

Figure 1. TPEITS and its configuration.

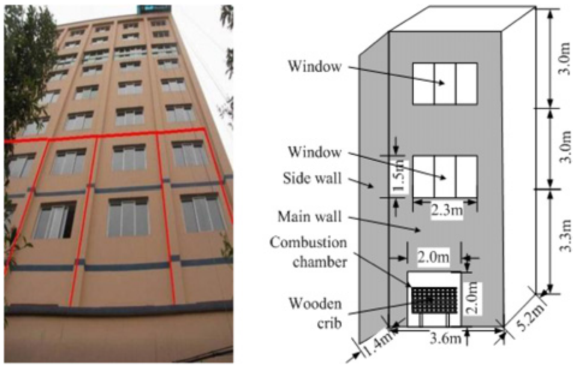

Figure 2. High-rise building fire test tower and full scale fire test model.

wall façade [11]. Woodpile with height of 1.5 m and weight of 420 kg is used as indoor combustible materials for the fire source. This woodpile is built according to BS 8414 [12], using fir stick (size: 50 mm × 50 mm × 1000 mm). In the observation rooms at the 2nd and 3rd floors, there are 2.3 m × 1.5 m window openings, with 3 mm steel single-glazed glass sash at both sides and 0.7 m × 1.5 m vents in the middle. The observation room has the same size as real building room, with the internal dimension of 3.2 m × 4.8 m.

(2) Thermocouple Locations: In the experiment, thermocouples were mounted to measure the insulation system surface and internal temperature and the gas temperature inside rooms at the second and third floors. Photos were also taken during the fire test. The measurement provides information of the ignition and fire spread of the external insulation system.

Specific location of the thermocouple trees is shown in Figure 3, for measuring the surface temperature and the internal temperature of TPETIS and the room temperature. The 5 × 12 thermocouple tree (Fig. 3a) with horizontal distance of 0.8 m, vertical spacing of 0.6 m is for measuring surface temperature. Room temperature was measured along the window edge at 4 edge line central points (Fig. 3c). Inside the each room, 5 thermocouple tree are arranged on the diagonal line (Fig. 3d), with each thermocouple tree consisting of three thermocouples (Fig. 3b).

(3) Testing Procedure: The tested TPETIS is constructed by Chengdu Cowan Insulation Materials Co. Construction procedures and processes are conducted according to China National Standards JGJ 144-2004 "Technical Specification for External Thermal Insulation on Walls" and GB 50417-2007 "Code for Acceptance of Energy Efficient Building Construction". Full scale fire tests were conducted 28 days after construction, under environmental condition of temperature of (20 ± 15) °C, air flow less than 2 m/s at height of 3 m above the ground. Test time was 30 minutes. 5 minutes before the test, environmental condition data recording was started. During the experiment, fire spread behaviors of the TPETIS under window fire were observed and recorded. The insulation system surface and internal temperature and the gas temperature inside rooms at the second and third floors were measured.

2.2 Testing results

A series of full scale fire tests have been conducted to evaluate the fire performance of TPETIS with different insulation materials including EPS, XPS, PUR and PIR. Due to space limit, in the following, mainly some representative result from TPETIS test with EPS as insulation materials is presented. In the experimental data plot presented below, the starting time is taken as the time when the monitored temperature inside the combustion chamber started to maintain above 200 °C for more than 60 seconds.

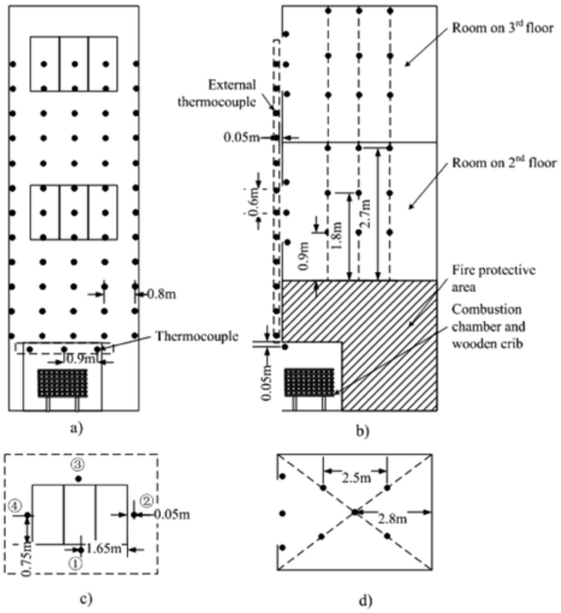

Figure 3. Thermocouple locations: a) front view; b) side view; c) measuring points at windowsill and inside observation rooms and d) top view of observation rooms.

Figures 4 and 5 show the time variation of 2nd and 3rd floor observation room center temperature at different heights in the experiment. For both the 2nd and 3rd floor observation rooms, the hot gas mainly stayed above 0.9 m above floor. The ceiling gas temperature in the 2nd floor observation room is higher than that in the 3rd floor observation room.

Figure 6 shows photos of the fire test scene, before, during and after the EPS experiment. The after experiment photo gives an indication the extent of fire spread over the wall surface. The front wall below the second floor window was essentially all burnt out. The front wall below the third floor window was also partially burnt out.

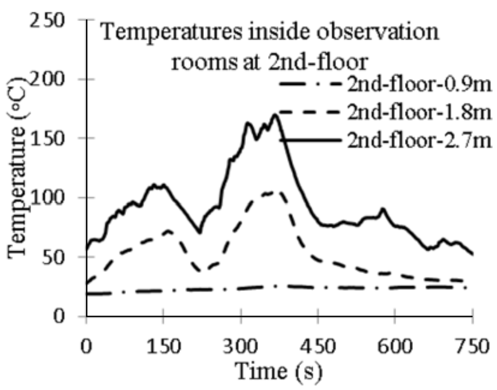

Figure 4. Measured room center temp. at 2nd floor.

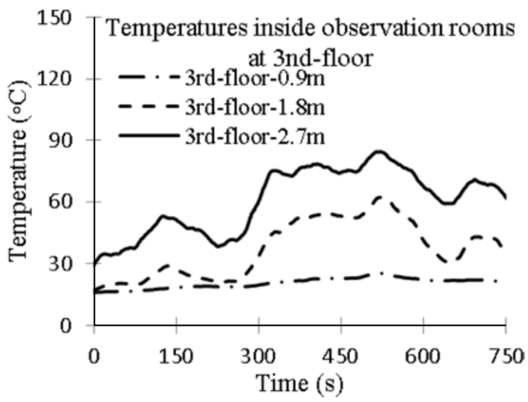

Figure 5. Measured room center temp. at 3rd floor.

a) before experiment b) during experiment c) after experiment

Figure 6. Experiment photos.

3. ADVANCED CFD SIMULATION AND VALIDATION

Comprehensive simulations of the above fire test were carried out using an advanced CFD fire simulation software Simtec (Simulation of Thermal Engineering Complex) [1, 2], which is now released by Simtec Soft Sweden, with the turbulent flow, turbulent combustion, thermal radiation, soot formation, convective heat transfer, the fully coupled three dimensional heat transfer inside solid materials, the 'burn-out' of the surface protection layer and the pyrolysis of the insulation layer (EPS or XPS), etc, all computed.

3.1 Theoretical model

3.1.1 Gas phase model

The analyses are carried out using *Computational Fluid Dynamics* (CFD) simulation. CFD simulation of fires corresponds to numerically solving a set of governing equations which describe the physics of fires.

For the gas phase turbulent combustion in a conventional fire, the governing equations, comprising continuity, momentum, energy and species equations, are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\begin{aligned}\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} &= -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\frac{\partial u_k}{\partial x_k}\right] + \rho a_{gi} \\ &= -\frac{\partial p^*}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\frac{\partial u_k}{\partial x_k}\right] + (\rho - \rho_\infty) a_{gi}\end{aligned} \tag{2}$$

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho u_j h)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu}{\mathrm{Pr}}\frac{\partial h}{\partial x_j}\right) + S_h \tag{3}$$

$$\frac{\partial (\rho Y_i)}{\partial t} + \frac{\partial (\rho u_j Y_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu}{Sc}\frac{\partial Y_i}{\partial x_j}\right) + R_i \tag{4}$$

where $p^* = p - p_\infty + \rho_\infty a_{gi} x_i$, and is the pressure minus its hydrostatic value, x_i the space coordinate vector, t the time, ρ the density, u_i velocity vector, h the enthalpy, μ dynamic viscosity, Sc the Schmidt number, Pr the Prandtl number, Y_i mass fraction for chemical species i, δ_{ij} the Kronecker delta tensor, a_{gi} the gravity acceleration vector, R_i the reaction rate, S_h the energy source term resulting from the radiation, and

$$h = \sum Y_i h_i = \sum Y_i \left(h_{0,i} + \int_{T_0}^{T} c_{p,i} dT \right) \tag{5}$$

in which $h_{0,i}$ is the heat of formation of species i at temperature T_0.

The radiation equation and the thermal state relations provide the necessary auxiliary equations. The thermal radiation is computed by solving radiation transfer equation, with consideration of radiation participating medium including soot, carbon dioxide and water vapor.

3.1.2 Solid wall model

In a fire, the combustible lining material and the walls exposed to the flame and hot gas are heated up through convection and radiation heat transfer. After a certain time, if sufficiently heated, the combustible lining material will start to pyrolyse and burn. Consequently, the flame will spread. In order to properly capture the flame spread, both the heat transfer inside solid material and the possible pyrolysis need to be well computed. Meanwhile, the computation of solid material heat transfer and pyrolysis must be fully coupled with gas phase simulation, because the solid material simultaneously responds and also feeds back to the state variation of its surrounding gases.

(1) Heat transfer in solid wall: Heat conduction inside a wall determines the internal temperature distribution and also provides the necessary coupled boundary condition for the gas phase calculation. For an inert wall, the heat balance is described by the following transient three dimensional heat conduction equations:

$$\frac{\partial(\rho H)}{\partial t} = \nabla \cdot (k \nabla T) = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \tag{6}$$

where H is the solid material enthalpy given by $H = H_0 + \int_{T_0}^{T} c_p dT$. The specific heat c_p and conductivity k are usually temperature dependent and can be represented by polynomial functions.

In a typical conventional fire such as a building fire, the walls of interest are usually connected and each wall is exposed to gas on two surface sides. When a solid wall is exposed to fire, it may be subject to intensive heating. Meanwhile, most practical solid wall materials are not very good heat conductors. Along the direction perpendicular to the wall surface, the temperature gradient in a solid can be very high, particularly near the wall surface. The accuracy requirement of the numerical solution of this heat conduction equation necessitates adoption of a grid which can be much finer (typically around 1.0 mm) than that used in the gas phase computation. Therefore, the presently affordable gas phase numerical grid cannot be directly adopted for solid phase computations and a separate grid system is needed for the solid phase calculation.

In Simtec, the three dimensional solid phase heat transfer is computed using a separate solid phase mesh.

(2) Pyrolysis modeling: In conventional fires, many involved solid walls are combustible. When sufficiently heated, these combustible walls start to degrade and pyrolyse. In this study, the pyrolysis reaction is described as

$$Virgin\ material \rightarrow volatile\ products + Char. \tag{7}$$

For EPS which can be considered as non-charring material, char will not be produced during the pyrolysis.

It is noted that EPS may also melt and drop as liquid droplet. For simplicity, this process is not considered in this study.

3.2 Simulation setup

Simulations were made to simulate the above large scale fire tests. The simulation was setup according to the best available information about the experiment. The major setup parameters directly available from the experiments include the geometry, the wall material type and overall configuration. Due to the complexity and nature of the experiments, some critical parameters which are very essential for CFD simulation are in lack. These lacked critical parameters include the heat release rate of the fire ignition source and the thermal property data of the wall material. In the experiment, woodpile of 420 kg is used as indoor combustible materials for the fire ignition source. Due to the complexity and lack of woodpile property, it is difficult to also simulate the ignition and burning of the woodpile in detail. Therefore, in the simulation, the ignition and consequent growing burning process of woodpile is ignored. Instead, the woodpile combustion is treated as an overall fire source with constant heat release rate and the simulation gave focus on how the external wall insulation system could be ignited by the woodpile fire source. Since there is no measurement data on the heat release from the woodpile in the experiment, estimation of 1.5 MW was made to approximate the heat release rate from the woodpile fire source. Obviously, this can cause big difference between the simulation and the experiments. Another important lacked setup parameter is the thermal property of the insulation material. The thermal property of the insulation material has big influence on how the wall material can be ignited and how fast the fire will spread. To obtain a best reliable thermal property of the insulation material, extensive search was made through internet and the data from different sources were combined together to give and derive a full set of the thermal property of the insulation material. In the experiment, tests were made with different insulation materials. The simulation presented in this paper will only for the EPS case. For EPS, the collected thermal property data are $\rho = 18.8\,\mathrm{kg/m^3}$, $combustion\ heat = 4 \times 10^7\,\mathrm{J/kg}$, $c_p = 1000\,\mathrm{J/kgK}$, $k = 0.03\,\mathrm{W/mK}$, $pyrolysis\ heat = 1.2 \times 10^6\,\mathrm{J/kg}$, $pyrolysis\ temperature = 237\,^\circ\mathrm{C}$. The big difference between simulation setup and the experiment will make the quantitative comparison between simulation and experiment measurement rather difficult. As a result, the simulation results will largely be validated in a general sense.

Figure 7 shows the simulation geometry model. The front surface and the side wall are assumed to be covered by the insulation material. As in the experiment, a fire barrier of 0.3 m wide and 3.6 m long was placed at 2.0 m above the ignition fire source chamber, across the building front surface. In the simulation, the insulated external wall is represented by three layers which include the protection layer, the insulation layer and the load bearing wall body. Due to its very thin thickness, the bonding layer and the glass fibre net are not explicitly considered. Meanwhile, the anchor is also ignored.

In Simtec simulation, non-uniform gas mesh was used with a fine mesh size of about 2 cm clustered to high gradient region. Meanwhile, a separate solid mesh of about 1.0 mm thickness is used to capture the fully coupled three dimensional heat transfer inside the building walls. This solid mesh is further divided into a moving refined mesh to capture the pyrolysis of the combustible layer. The simulation was made on a desktop PC using 6 hyper-threading cores.

3.3 Simulation results

3.3.1 Heat release rate

Figure 8 shows the variation of computed heat release rate with time. Since no experimental measurement on heat release rate is made, no comparison can be made between simulation and experimental measurement. In the simulation, the ignition fire source in the fire chamber was assumed to start with 1.5 MW and keep the same value all the time, without considering the time variation of

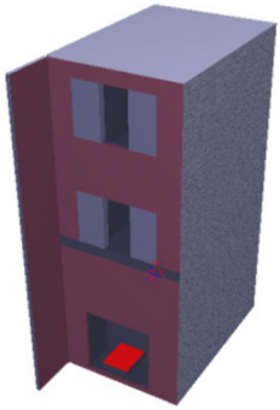

Figure 7. Simulation geometry.

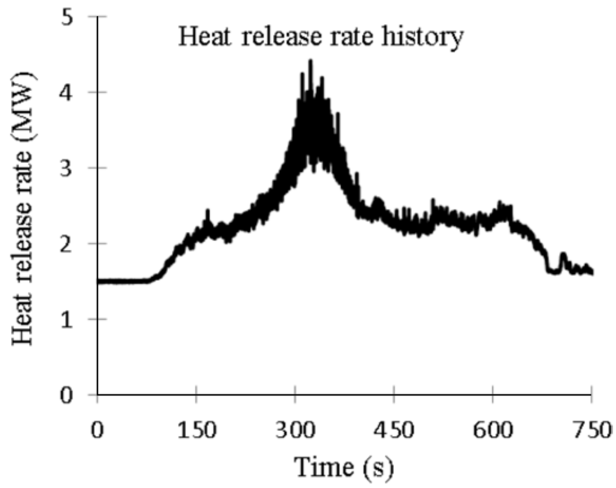

Figure 8. Heat release rate in the simulation.

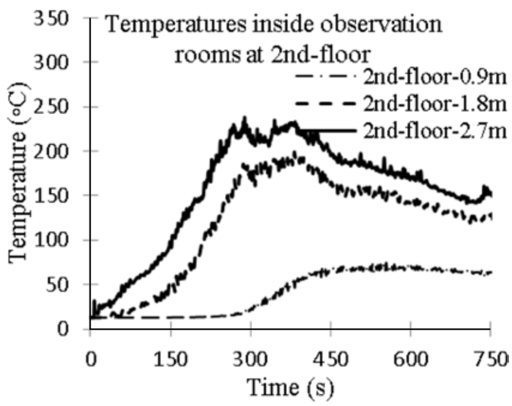

Figure 9. Computed room center temp. at 2nd floor.

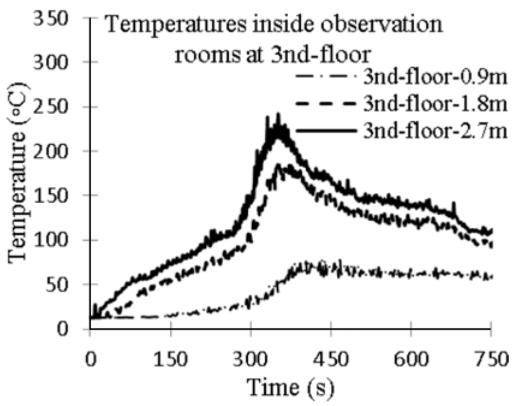

Figure 10. Computed room center temp. at 3rd floor.

ignition fire source power. As shown in Figure 8, the heat release starts to grow after a short period and reached a peak of about 4 MW. This indicates that the insulation system has been ignited, particularly the front wall above fire source (as indicated in Fig. 11). After the peak, fire on the front wall starts to decay because some ignited wall has been burnt-out. Meanwhile, the side wall has not yet been ignited in large area. Therefore, the total heat release starts to go down.

3.3.2 Room temperature

Figures 9 and 10 show the time variation of 2nd and 3rd floor observation room center temperature at different heights in the simulation. Essentially, the room temperature rise follows the heat release rate curve shown in Figure 8. The room upper layer temperature starts to rise from beginning and then reaches at peak value at time of about 300 seconds when the heat release rate comes to its own peak value. The ceiling gas temperature in the 2nd floor room is somehow higher than that in the 3rd floor room. Because of fire spread, the peak value time for the 3rd floor room also has some delay after the peak value time for the 2nd floor room. The room lower part has some temperature rise, but essentially stays cool. The simulation results have good general consistence with experimental measurement.

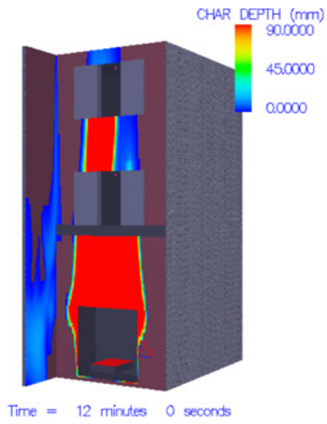

Figure 11. "Char depth" distribution.

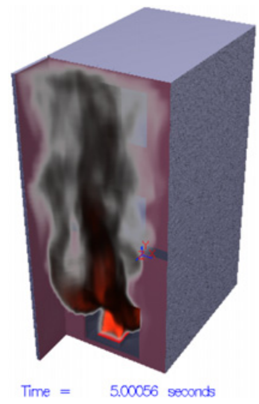

Figure 12a. Fire pattern at time of 5 seconds.

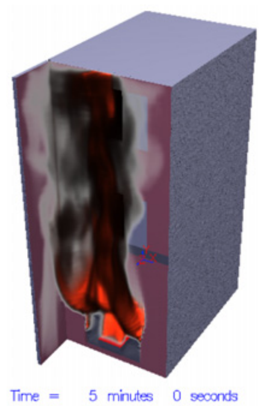

Figure 12b. Fire pattern at time of 5 minutes.

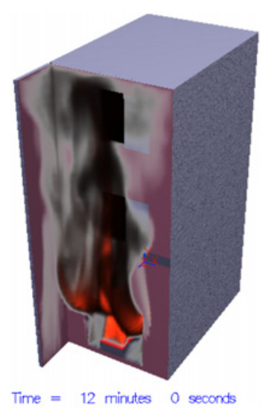

Figure 12c. Fire pattern at time of 12 minutes.

However, the temperature in simulation is generally higher than the measured. As mentioned before, due to lack of accurate input data, the simulation setup may have some substantial difference with experimental setup. Therefore, it is difficult to make direct quantitative comparison between simulation and measurement.

3.4 Fire spread

This computed heat release rate curve also shows a fire spread over the insulation system. Figure 11 shows the "char depth" distribution on the front wall and side wall after 12 minutes. The "char depth" represents the material burn-out depth when the material is a non-charring material. This burning pattern is in generally good consistence with the observation in the experiment, as shown in Figure 6. At this time, the burning of side wall is still growing and not fully developed yet.

Figure 12 gives overall fire pattern at different time stages. It clearly shows that the fire spread over the front wall within the first a few minutes. At time of 12 minutes, the front wall fire has quite much decayed, largely due to the burn-out of the ignited wall part. Meanwhile, the side wall burning is developing.

4. CONCLUSION

Large scale fire tests of building external wall insulation system were conducted. In the experiments, fire spread to upper floor was observed with all the 4 tested insulation materials. This indicates space to improve fire safety performance with these tested wall external insulation systems by further research. The experiment results also show that the fire safety performance of the external wall insulation systems is very much affected by the insulation materials. With different insulation materials, the fire spread behaviour is different.

Advanced comprehensive CFD simulations of the fire test were carried out using Simtec software. The simulation is compared with experimental measurement for general validation. Due to lack of some important accurate input data, the simulation setup cannot fully follow the experiment setup. However, with approximation of the missed input data, the simulation well captured the burning and fire spread of the external insulation wall.

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