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Numerical Analysis of the Fire Resistive Performance of the Water-Film on a Double-Glazed Curtain Wall

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Abstract **-**As high-rise buildings globally increase, double-layered curtain walls are being preferred for the beauty and natural ventilations. However, when the external cladding of a building comprising glasses or metals is damaged, fire can rapidly propagate to upper levels and it makes loss of lives and property. In this study, we numerically evaluates the thermal barrier effect of the water-film flowing on a surface exposed to a fire at double glazed curtain wall. In the results the water-film effectively cuts off the radiation energy from the hot-gas by absorbing almost radiative heat. Also, when the water-film is used, total heat transfer rate increases at the interface exposed to the hot-gas due to an increases in the convective heat transfer rate in comparison to the case without the water-film. Consequently, it is essential to understand the heat transfer mechanism through the water-film for a design of the thermal barrier system using parameters related with the characteristics of film flows, e.g., thickness, wavy flow at free-surface, uniformity of the film, phase change of water, and so on.

Keywords**:** double-glazed curtain wall; CFD; fire resistive performance; water-film; heat transfer

1. Introduction

As high-rise buildings globally increase, double-layered curtain walls are being preferred for the beauty and natural ventilations. However, when the external cladding of a building comprising glasses or metals is damaged, fire can rapidly propagate to upper levels and it makes loss of lives and property. Thus, it is important to investigate and control distribution of temperature in the curtain wall when fire occurs.

Numerous researches have been conducted to advance the fire resistive performance of curtain walls for decades. Water spray curtain is a representative system to cut off heat. The curtain composed of water droplets is generally located in front of the wall to be protected. It behaves as a filter and can reduce radiative heat flux (Thomas, 1952). Water sprays can provide thermal shielding to maintain the integrity of neighbouring structures in case of reservoir fire (Chen et al., 2010, Hostikka et al., 2006). However, the difficulty lies in the optimal nozzle design and high injection pressure is needed.

Our research team have tried to advance the water curtain system. The final system is that a flowing water-layer is directly laid on the surface of the curtain wall to cut off heat. The greatest advantage of this system is easy to control temperature of the curtain wall by adjusting a flow rate of the water-layer. However, there is a little researches and relational statue globally.

As a basic study, we numerically evaluates the thermal barrier effect of the water-film flowing on a surface exposed to a fire at double glazed curtain wall in a 2-dimensional numerical domain.

2. Materials and Methods

2. 1. Modeling and Grid Generation

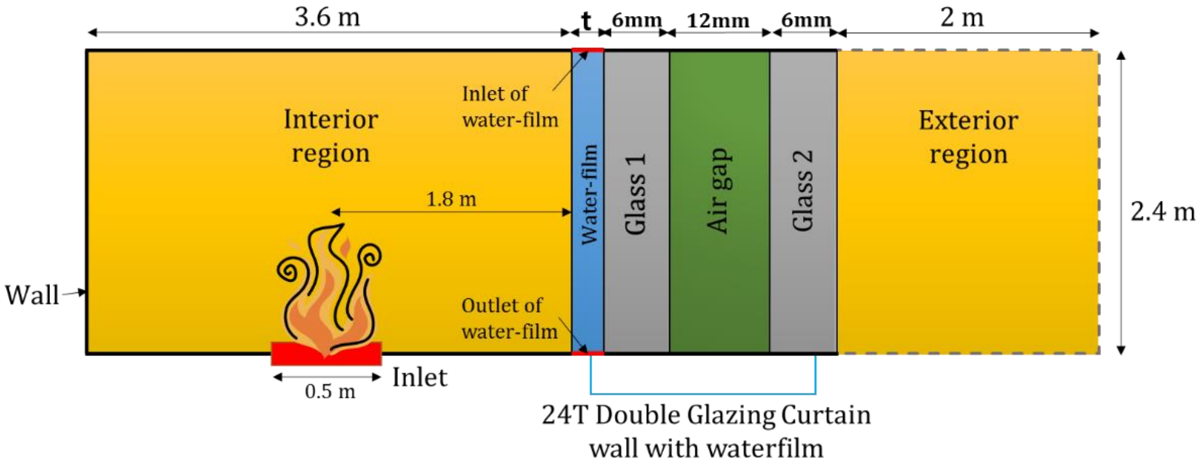


Fig. 1. Schematic of the numerical domain

Generally, a double glazed curtain wall glass comprises two glass panels and a space between both panels is filled with air, and then it is sealed. In this study, the double glazed glass except curtain wall frames is modelled as shown in Fig. 1. The 2-dimensional numerical domain is divided to three main regions including interior region (room), double glazed curtain wall region and exterior region. There is no leakage in the interior region which size is equivalent to a regulation of ISO 9705 room fire test. In order to study the thermal barrier effect of water-film, two numerical cases are considered as presented in Table. 1. Grids are generated with ANSYS ICEM V14.5 and comprise square cells. In case 1, the interior region is expanded to a region of water-film, whereas the thickness of water-film is 2 mm in case 2. Consequently, start point of a region of glass 1 is equal in both cases. The y+ value of first nodes from walls of the hot gas region remains within 100 for using the standard k-e turbulence model. The number of cells selected by grid independent test is shown in Table. 1.

Table. 1. Numerical cases

Case No.	Thickness of water-film	Number of grid cells
1	No	39,940
2	2mm	41,940

2. 2. Governing Equations

For modeling a hot plume, the ideal-gas model is used for density of a mixture of chemical species. Also, the water-film falling along the curtain wall glass is heated up by the hot-gas stream in the interior region. Mass transfer during the evaporation of the film is not considered in this study. The thermodynamic equilibrium is assumed at the interface between the hot-gas and the water-film. The standard k-ε turbulence model (Launder et. al., 1979) considering buoyancy effects is used for turbulent flows and discrete ordinates (DO) model for non-grey radiation is used to consider the transparency of the curtain wall glass. The reflection of incident radiation at the surface is isotropic with respect to the solid angle Conjugate heat transfer is calculated interfaces between two regions, e.g., hot-gas and water-film, curtain wall and ambient air. For calculating thermal fluid flows, continuity equation, momentum equation and energy equation are as shown in Eqs. (1) – (3).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\vec{u}(\rho E + p)\right) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \vec{J_j} + \left(\bar{\bar{\tau}}_{eff} \cdot \vec{u}\right)\right) + S_h \tag{3}$$

The first three terms on the right-hand of Eq. (3) represents energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. S_h includes the heat of chemical reaction. Species transport equations with eddy-dissipation combustion model are used to model a compartment fire. It is assumed that CH_4 gas from the inlet completely combusts in the interior region. Local mass fractions of chemical species are calculated by a convection-diffusion equation for each species. Also, reaction rate is controlled by a turbulent time scale and only one step heat-release mechanism is considered.

2. 3. Numerical Details

Absorption coefficients of water-liquid and glass are 5101.0 m^{-1} and 40.3 m^{-1}, respectively. The absorption coefficient of glass is obtained from measured transmittance data by using the Beer-Lambert law. Refractive index for hot gas and water is 1.0 and 1.33 regardless of variations in temperature and flow conditions, respectively. Methane gas flows from the fire inlet into the interior region with a mass flow rate with 0.0024 kg/s. and complete combustion is assumed.

At the region of water-film in case 2, water flows in the inlet of water-film with 0.1 m/s uniformly and the thickness of water-film is 2 mm. The pressure-outlet condition with static pressure 0 Pa is applied to the outlet of water film. Also, temperature of water is fixed to 300 K at the inlet of water-film. Also, moving wall condition is applied to the interface between the hot-gas and the water-film in case 2, and the wall velocity is 0.2 m/s.

Outer walls around the room and the curtain wall are no-slip condition and adiabatic condition for flow and heat transfer calculations, respectively. Conjugate heat transfer including conduction and convection is calculated interfaces between two regions, e.g., hot-gas and water-film, glass and ambient air.

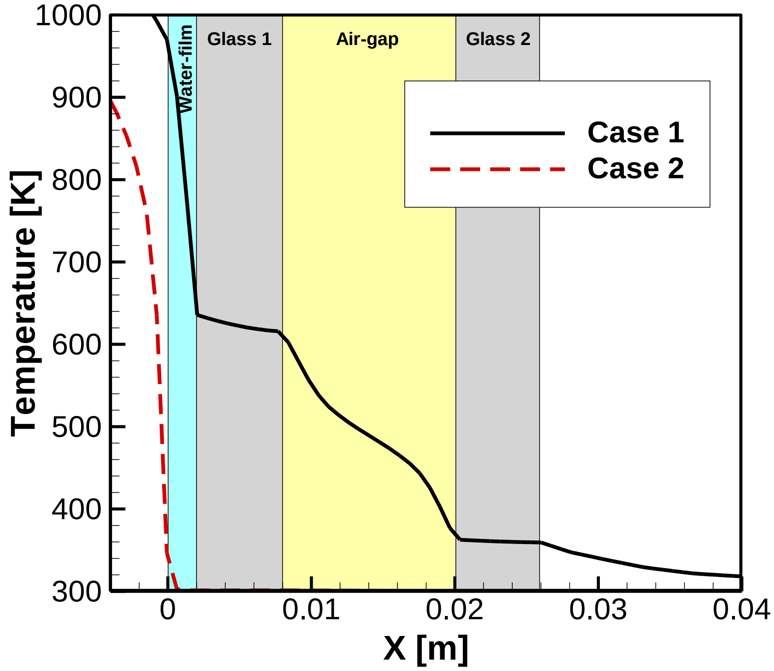
The CFD simulation is performed with the commercial tool, ANSYS FLUENT v14.5. The pressure implicit with the splitting of operators (PISO) algorithm with 2nd order discretization for the spatial variables is applied for more accurate results. The residual criterion for all variables is set to 1E-4. The time-step size is fixed to 0.005s.

3. Results and Discussion

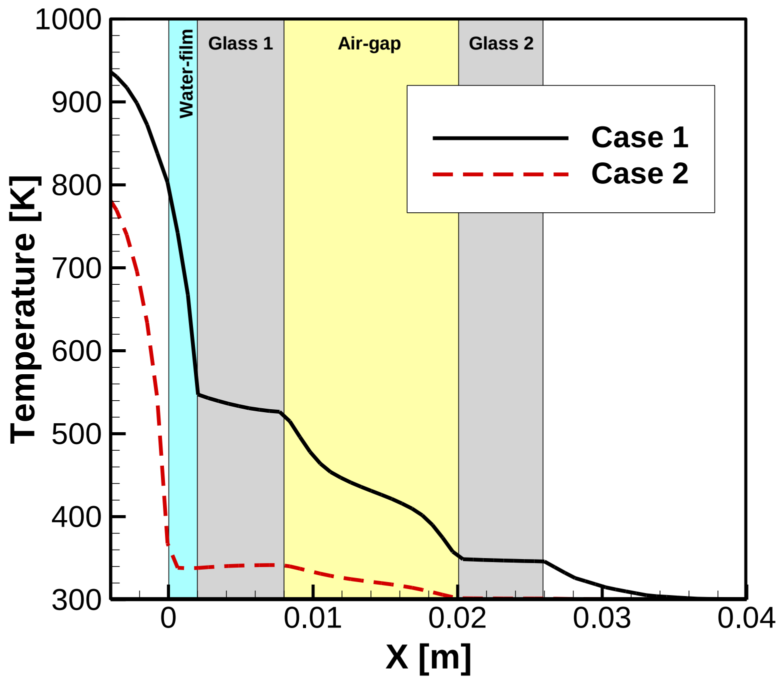
After about 180s, hot plume flows and heat transfer rates through the curtain wall region reach a quasi-steady state and temperature decreases due to depletion of oxygen in the interior region after 230s. Therefore, numerical results at 200s are analysed for a comparative study.

Fig. 2. shows temperature profiles along the horizontal line at two positions from a floor of the curtain wall region. As shown in Fig. 2. (a), there is a little change in the temperature of the glass 1 in case 2 because a temperature of water is kept about 300K immediately after flowing in the inlet of water-film. On the contrary, in case 1, the temperature of the surface exposed to a fire increases about 650K due to a heat transfer from the hot-gas at the glass 1. At 0.1m from the floor, temperature of the water-film and the glass 1 increases by about 350K as shown in Fig. 2. (b). This is because heat consistently transfers from the hot-gas into the water-film while water flows along the surface of the glass 1. Consequently, the water-film effectively cuts off the heat transfer from the hot-gas into the glass 1 in terms of temperature.

In addition, it is essential to analyse the heat transfer mechanism for investigating the fire resistive performance of the water-film. Table. 2. shows radiative and convective heat transfer rates at two interfaces located in the front and the rear of the water-film.



(a)



(b)

Fig. 2. Temperature profile along the horizontal line at each height from a floor; (a) 2.3m, (b) 0.1m.

Table. 2. Heat transfer rate at interfaces.

Case name	Heat transfer rate, [W]	AW*	WG1*
Case 1	Total	-	71,271 (100%)
	Radiative	-	45,154 (63.4%)
	Convective	-	26,117 (36.6%)
Case 2	Total	76,780 (100%)	1,414 (100%)
	Radiative	39,500 (51.4%)	22 (1.6%)
	Convective	37,280 (48.6%)	1,392 (98.4%)

*AW: interface between regions of the hot-gas and the water-film
*WG1: interface between regions of the water-film and the glass 1

Radiative heat transfer rate of case 2 is lower than that of case 1 at the interface exposed to the hot-gas, that is, WG1 is for case 1 and AW is for case 2. The reason is that the temperature of the hot-gas is lower due to the water-film as shown in Fig. 2. Also, the water-film cuts off almost radiation energy from the hot-gas into the glass 1. This is because the absorption coefficient of water is very high, namely the water-film effectively absorbs the radiation energy and removes it from the domain.

On the other hands, convective heat transfer rate of case 2 is about 50% higher than that of case 1 at the interface exposed to the hot-gas because the flowing water-film accelerates the velocity of the nearby hot-gas, and then the convective heat transfer coefficient increases. Consequently, total heat transfer rate through the interface of case 2 is higher than that of case 1, and the fraction of radiative and convective heat transfer rate is similar. This phenomena could influence a phase change process of water in real, e.g., vaporization or boiling, which although are not considered in this study. Consequently, it is essential to understand the relation of the water-film to the convective heat transfer at the interface for a design of the thermal barrier system using the water-film.

4. Conclusion

In this study, we numerically evaluates the thermal barrier effect of the water-film flowing on a surface exposed to a fire at double glazed curtain wall.

(a) The temperature of glass temperature with the water-film is kept below 350K, whereas the temperature without the water-film increases by 650K.
(b) When the water-film is used, total heat transfer rate increases at the interface exposed to the hot-gas due to an increases in the convective heat transfer rate in comparison to the case without the water-film.
(c) The water-film effectively cuts off the radiation energy from the hot-gas by absorbing almost radiative heat.

Therefore, it is essential to understand the heat transfer mechanism through the water-film for a design of the thermal barrier system using parameters related with the characteristics of film flows, e.g., thickness, wavy flow at free-surfaces, uniformity of the film, phase change of water, and so on.

Acknowledgements

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