STUDY OF GLAZING BEHAVIOUR IN FIRE CONDITIONS USING ADVANCED RADIATION HEAT TRANSFER MODEL AND COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

The behaviour of glazing could influence the growth of fires. Radiation is often the most significant heat transfer mechanism and its modelling is critical to an accurate prediction of temperature distribution in the glass and the time to breakage. In the present study a spectral radiation model based on the Discrete Ordinates Method has been developed. The model accounts for the diffuse nature of radiation incident on the glazing and provides a better handling of the boundary conditions. For verification purposes, the model is applied to some typical fires/glazing scenarios from the literature. Good agreements are found between predictions and experimental data. The study also investigates the effects of the glass thickness, thermal conductivity and emissivity on the glass temperature. In order to predict the dynamic behaviour of the glazing in fires, the coupling of the radiation model with the CFD code FDS is explored and some preliminary results reported.

KEYWORDS: Glazing, glass, Radiation heat, Fire

INTRODUCTION

In the event of fire in a compartment, the breakage of a window or door glass pane could affect the ventilation conditions in the room and depending on the stage of the fire development, flashover or backdraft could occur. Heat transfer and mechanical stress are the main physical processes involved when a glass pane in subjected to heat from a fire. In a fire environment, radiation is the main mode of heat transfer and its accurate modelling remains a challenge.

Cuzzillo and Pagni[1] have reviewed some existing heat transfer approaches employed in fire/glazing problems. The simplest heat transfer model treats the glass as a lumped mass and uses constant heat transfer coefficient. Another approach treats the glass as a distributed mass that absorbs radiation through its thickness with non-linear radiative boundary conditions[1]. The original version of the widely used computer code BREAK1[2] is based on such an approach. The vast majority of existing radiation models employed in glass breakage problems do not account for (i) the diffuse nature of radiation from the fire source or the upper hot gas layer in contact with the glass, and (ii) the spectral nature of the problem. Glasses are selective materials that absorb, reflect and transmit radiation within specific wavelengths. In the present study, a spectral radiation heat transfer model based on the Discrete Ordinates Method (DOM), has been developed and is applied to different radiant heat flux/glass scenarios. The model is employed to calculate the radiative intensity and source term in the energy/temperature equation. Comparisons are made between the model predictions and literature experimental data in terms of temperature distribution and time to breakage. A study is also carried out to understand the influence on temperature of parameters such as the glass thickness, thermal conductivity and emissivity. To investigate the dynamic behaviour of the glazing, it is proposed to couple the spectral DOM radiation model with the widely used Large Eddy Simulation-based CFD code FDS developed at NIST in the USA. Some preliminary results are discussed.

MATHEMATICAL MODEL

The transient energy equation for a semitransparent solid such as glass in one-dimensional cartesian geometry is:

$$\rho \cdot c_p \frac{\partial T}{\partial t}(x,t) = k \frac{\partial^2 T}{\partial x^2}(x,t) - \nabla \cdot q_r \qquad [1]$$

where T is the temperature, t the time, ρ, c_p and k are respectively the glass density, specific heat and thermal conductivity. The last term on the RHS of Eq. [1], $\nabla \cdot q_r$, is the total radiative source (divergence of the radiative heat flux, q_r) determined by integration of the spectral radiation intensity.

With the assumption that the glass is a non-grey material, the boundary conditions to solve Eq. [1] are:

$$-k \left.\frac{\partial T}{\partial x}\right|_{x=0} = h_0(t)\left(T_0(t) - T_1^p(t)\right) + \int_0^\infty \alpha_\lambda \cdot q_{\lambda,0} d\lambda - \int_0^\infty \varepsilon_{\lambda,g} \cdot I_{b\lambda}(T_1^p(t)) \pi d\lambda , \qquad [2]$$

$$-k \left.\frac{\partial T}{\partial x}\right|_{x=L} = h_\infty(t)\left(T_2^p(t) - T_\infty(t)\right) + \int_0^\infty \varepsilon_{\lambda,g} \cdot I_{b\lambda}(T_2^p(t)) \pi d\lambda - \int_0^\infty \alpha_\lambda \cdot q_{\lambda,\infty} d\lambda \qquad [3]$$

at t = 0 and $T=T_i$.

Where L is the thickness of the glass pane, h_0 and h_∞ are respectively the heat transfer coefficients of the hot (i.e. surface directly exposed to fire) and cold sides of the glass pane. The term $q_{\lambda,0}$ is the spectral incident radiation on the exposed glass pane from the fire side (e.g. radiation from the walls, upper hot layer and the flame for a compartment fire), and $q_{\lambda,\infty}$ is the spectral incident radiation from the ambient side (e.g. exterior radiant heat).

The spectral emissivity of the glass, $\varepsilon_{\lambda,g}$, is a parameter that depends on the wavelength of radiation and the glass thickness as shown in Fig. 1[3]. The emissivity influences the amount of the total energy emitted and absorbed by the glass.

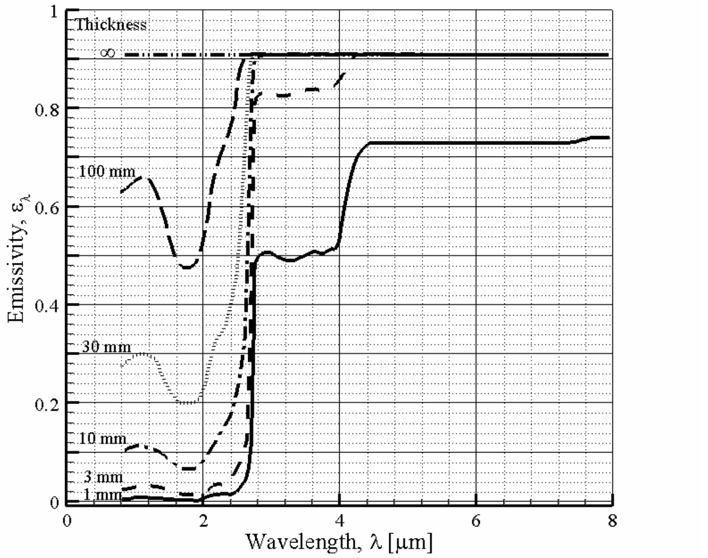

FIGURE 1. Spectral emissivity for different glass thicknesses[3]

The glass breakage criterion used in the present study is that proposed by Pagni[4], based on the temperature difference $\Delta T = \overline{T}_{exposed} - T_{coldest}$:

$$\Delta T \geq (1 + s/H)\frac{\sigma_{max}}{E \cdot \beta} \qquad [4]$$

H is the distance from the top to midpoint of the window, s the dimension of the covered edge, σ_{max} the maximum tensile stress, E the Young's Modulus and β the coefficient of thermal expansion.

The spectral radiative transfer equation (RTE) for azimuthally symmetric condition in one-dimensional geometry for a non-scattering glass layer is:

$$\mu \frac{\partial I_\lambda(x,\mu)}{\partial x} = -K_\lambda(x) \cdot I_\lambda(x,\mu) + K_\lambda(x) I_{b\lambda}[T(x)] \qquad [5]$$

I_λ is the spectral intensity of radiation, μ the direction cosine, K_λ the glass spectral volumetric absorption coefficient, and $I_{b\lambda}(T)$ the spectral blackbody intensity or Planck function

The Discrete Ordinates Method (DOM) approach is based on the separation of the angular dependence from the spatial dependence of the intensity in the RTE[5]. For a glass pane exposed to fire radiation, using the DOM approach, for a discrete direction m, Eq. [5] becomes:

$$\mu_m \frac{\partial I_{\lambda m}(x)}{\partial x} = K_\lambda \cdot \left[I_{b\lambda}[T(x)] - I_{\lambda m}(x)\right] \qquad [6]$$

The boundary conditions to solve Eq. [6] are:

$$I_{\lambda m} = \varepsilon_{\lambda,g} I_{b\lambda}(T_1) + 2 \cdot \left(1 - \varepsilon_{\lambda,g} - \tau_{\lambda,g}\right) \sum_{m'=1,\mu'<0}^{N_d} \mu_{m'} w_{m'} I_{\lambda m'}(0) + \varepsilon_{\lambda,0} \cdot I_{b,\lambda,0} \quad \text{at } x=0 \qquad [7]$$

$$I_{\lambda m} = \varepsilon_{\lambda,g} I_{b\lambda}(T_2) + 2 \cdot \left(1 - \varepsilon_{\lambda,g} - \tau_{\lambda,g}\right) \sum_{m'=1,\mu'>0}^{N_d} \mu_{m'} w_{m'} I_{\lambda m'}(L) + \varepsilon_{\lambda,\infty} \cdot I_{b,\lambda,\infty} \quad \text{at } x=L \qquad [8]$$

$\tau_{\lambda,g}$ is the transmissivity of the glass given by $\tau_{\lambda,g} = 1 - \alpha_{\lambda,g} - \rho_{\lambda,g}$ and w_m the weight of a discrete direction m in DOM technique.

From the spectral radiation intensity, the total intensities are calculated by integration $I_m(x) = \sum_{all\ \Delta\lambda} I_{\lambda m}(x)\Delta\lambda$.

The spectral and total net radiative heat fluxes at any position, x, are respectively given by $q_\lambda(x) = \sum_{m=1}^{N_d} w_m \mu_m I_{\lambda m}(x)$ and $q(x) = \sum_{all\ \Delta\lambda} q_\lambda(x)\Delta\lambda$.

The total radiative source term used in the energy equation, Eq. [1], is obtained by differentiating the total heat fluxes.

RESULTS AND DISCUSSION

Model Verification

The 1D DOM radiation model developed for glazing, is verified by comparing its predictions to two sets of experimental data published in the literature[6, 7]. For the angular discretization in DOM, a set of 20 Gaussian points is employed and 40 nodes for spatial discretisation. Preliminary sensitivity studies have shown that this ensures that the results are not grid or direction-sensitive. Fig. 2 shows the experimental arrangement of Skelly et al.[6] using a rectangular compartment (1.0 m x 1.2 m x 1.5 m high) constructed of iron slats and ceramic fire board. There are three vents in the compartment: an open upper layer exhaust vent, an open vent near the base of the compartment for fire ventilation, and a glass window assembly. The glass window assembly measured 0.50 m x 0.28 m. The tested glass was 2.4 mm thick. The fire consists of a burning hexane liquid in a 20 cm x 20 cm tray. Fig. 3 presents the experimental data and the simulation results obtained with the developed spectral DOM radiation model, referred to as “KU-Glaz model”. The temperatures denoted by “tests 4, 5, 6” represent the temperature profiles of the exposed side of the glass pane measured in three repeated tests[6]. The predicted temperatures of the exposed side of the glass pane are in relatively good agreement with the experimental data. The relative difference or error, between the model’s predictions and the averaged experimental data as shown in Fig. 3, do not exceed 3 %. Table 1 summarises the time for the first crack occurrence in the glass pane. Cracking occurs in the glass because in the window assembly, the glass pane is supported in a frame that shields the border from incident radiative heat flux. The exposed side of the glass heats up as a result of radiant heat absorption while the framed border remains relatively cool. The temperature differences induce stresses and when the glass yield stress is exceeded, the first cracks occur. In Table 1, the averaged experimental[6] crack time for the three tests is 107 s, while the KU-Glaz model predicts 104 s (2.7 % error).

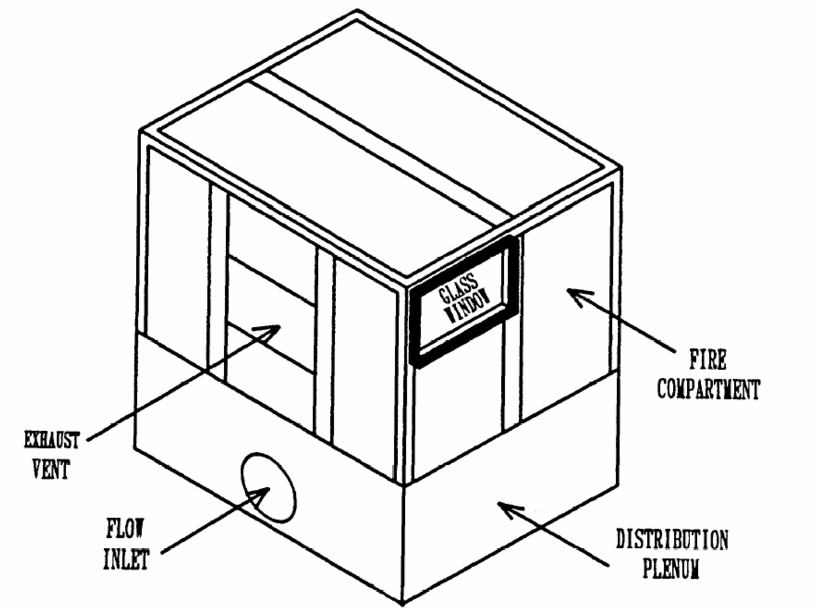

FIGURE 2. Schematic view of the experiment of Skelly et al.[6]

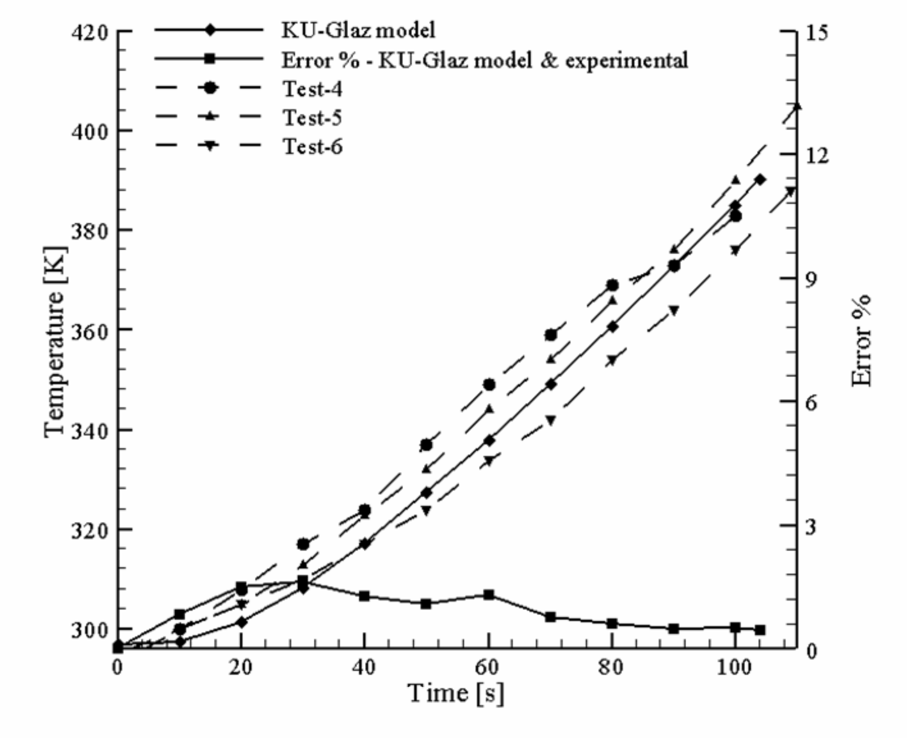

FIGURE 3. Temperature predicted by the KU-Glaz model and experimental data[6], error between KU-Glaz model and average experimental data

The second set of data considered for the model verification is based on the experiments conducted by Harada et al.[7] on a float glass to predict the glass cracking and/or breaking by imposing a variation of heat flux between 2.7 and 9.7 kW/m^2. This was achieved by changing the distance between a propane-fired radiant panel and a 3 mm thick glass pane. The 0.5m^2 glass pane was non heat-treated, and the physical characteristics of the experimental apparatus were input directly into the code developed in the present study. The experimental and predicted times of the first crack occurrence are presented in Table 2. Experimental data are averaged over a series of tests, e.g. 1 to 3. For the heat flux of 5.48 kW/m^2, the experimental and model predicted times are the same (207 s). The experiment and model predicted times are respectively 144 s and 147 s (2 % difference) for 6.69 kW/m^2, and 90 s and 94 s (4 % difference) for a heat flux of 9.11 kW/m^2. These results also confirm the relatively good agreement between the spectral DOM model predictions and experiments for a range of incident heat flux typical of fire scenarios.

TABLE 1. Time of the first crack occurrence in the glass window

Cases	Time [s]	Error [%]
Experimental -Test - 4[6]	100	-
Experimental -Test - 5[6]	112	-
Experimental -Test - 6[6]	109	-
Experimental - Average	107	-
KU-Glaz model	**104**	**2.7**

TABLE 2. Time to first crack - Comparisons between predictions by the KU-Glaz model and the experimental data[7]

Test series[7]	Heat Flux[7] [W/m^2]	Time of first crack [s]	
		Experiment[7]	**KU-Glaz**
1 to 3	5480	207	**207**
7 to 9	6690	144	**147**
15 to 17	9110	90	**94**

Influence of the Glass Thickness, Thermal Conductivity and Emissivity on Temperature

In this section the 1D DOM spectral radiation model (KU-Glaz model) is employed to investigate the effects of the glass thickness, thermal conductivity and emissivity on the temperature distribution. The geometry of the sceanario is the same as in the experiments conducted by Harada et al.[7]. A constant radiative heat flux of 5.48 kW/m^2 is imposed on one side (exposed) of 3, 6, 10 and 30 mm thick glass. Fig. 4 shows that the temperatures are lower as expected for thicker glasses as the thicker glass needs more energy to reach the same temperature as a thinner one. However the fraction of incident radiation absorbed by the 30mm glass is more than that of the 3mm; the thicker glass absorbed 71 % of the incident radiation while the thinner just absorbed 59 % (assuming that the radiation source has a temperature of 1250°K and the spectral emissivity shown in Fig. 1).

The effects of the thermal conductivity on the glass temperature is shown in Fig. 5 for the 3 mm thick glass. The temperature of the glass increases rapidly when the thermal conductivity is lower. The lower the thermal conductivity, the larger the temperature gradient between the side of the glass exposed to heat and the unexposed side. In fire protection, to avoid the glass breakage its temperature should be kept lower, it is therefore more beneficial to use glass with high conductivity and low diffusivity. Radiation remains the most significant mode of heat transfer since increasing twelve folds the conductivity (from 0.1 to 1.2 W/mK) results in a temperature difference between the unexposed sides of only 60 K after 200 s.

Glass surface properties such as the transmissivity are important in the analysis. Depending on the surface treatment (e.g. coating) the glass could become transparent or opaque to radiation. The KU-Glaz model is employed to investigate the influence of the surface transmissivity on the temperature. The simulation conditions are: heat flux of 5.48 kW/m^2 imposed on one side (exposed) of a 3 mm thick glass. Two surface properties are considered: the first one is based on normal glass properties ($\rho_{\lambda,g} = 0.1$, $\varepsilon_{\lambda,g}$ from Fig. 1, $\tau_{\lambda,g} = 1 - \varepsilon_{\lambda,g} - \rho_{\lambda,g}$) and the second surface is opaque with $\tau_{\lambda,g} = 0$ and $\rho_{\lambda,g} = 0.1$. As shown in Fig. 6, for a given side of the glass pane, the temperatures obtained with opaque surfaces are lower than those of normal glass. The explanation is that semi-transparent surfaces such as normal glass allow more radiation heat storage in the glass and the subsequent temperature rise in comparison to opaque surfaces for which almost all of the radiant heat is absorbed, reflected and emitted at the surface. For opaque surfaces the temperature rise of the glass bulk is mainly due to conduction. In terms of preventing the glass breakage it is clearly beneficial to use coating that make the glass surface opaque to radiation in the visible and infrared.

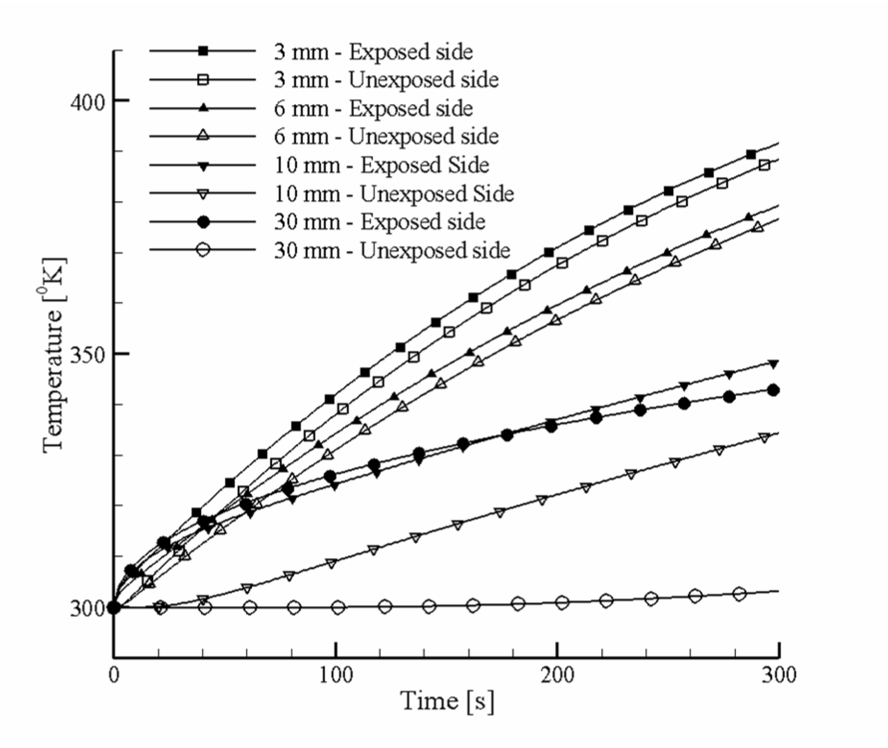

FIGURE 4. Influence of the glass thickness on temperature, using the KU-Glaz radiation model

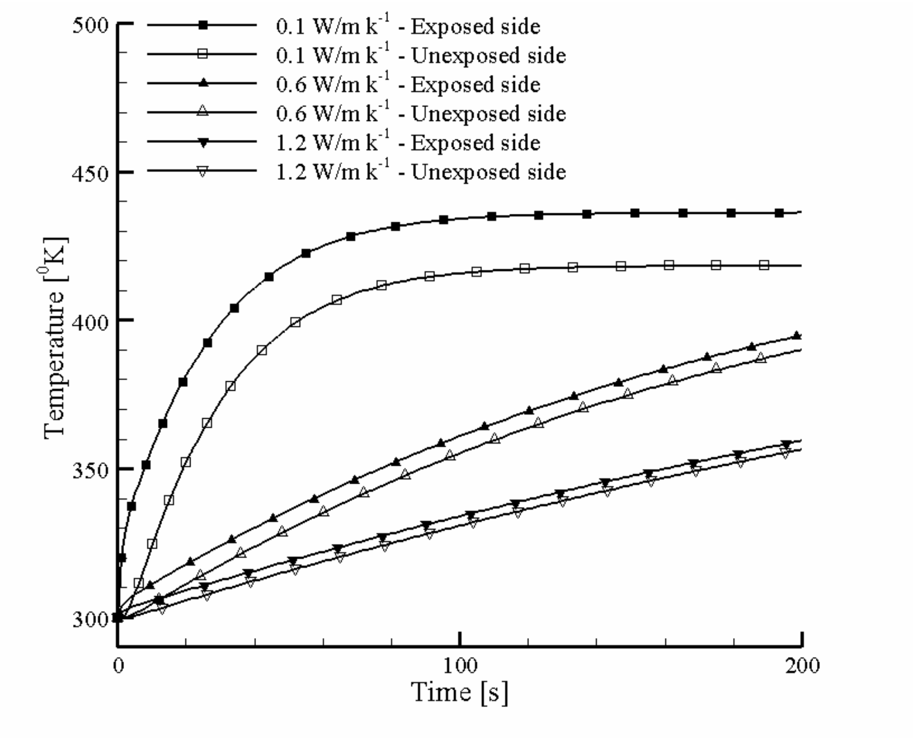

FIGURE 5. Influence of the glass thermal conductivity on temperature for the 3 mm thick glass using the KU-Glaz radiation model

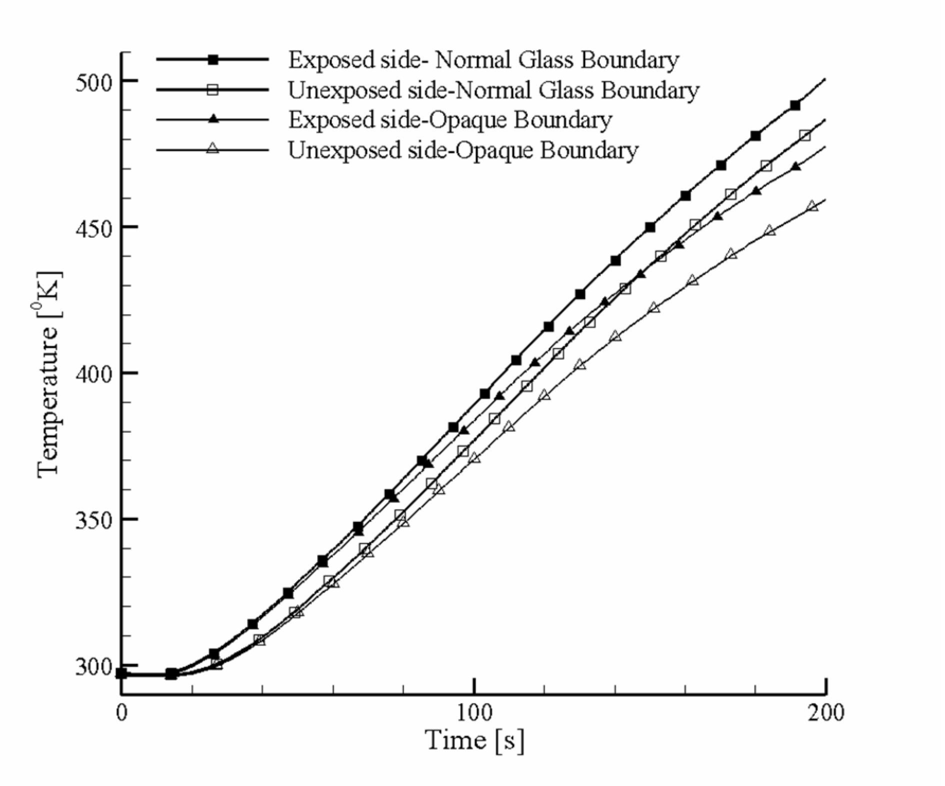

FIGURE 6. Effect of the glass surface transmissivity on temperature

Coupling the DOM Glazing Radiation Model with the CFD Code FDS

In the previous sections the radiation model was employed in isolation without any coupling with the fluid dynamics phenomena. For a better description of the glazing dynamic behaviour in fires it is important to couple the radiation model with fluid dynamics and turbulence models. To this end the authors have investigated the possible implementation of the spectral DOM radiation model in the CFD code FDS[8] (Fire Dynamics Simulator) developed at the NIST in the USA. FDS employed large eddy simulation (LES) concept and is designed for fire simulation indoors and outdoors. In FDS the temperature calculation in solids is treated as one-dimensional and as a grey medium. This methodology simplifies the calculation and reduces the simulation time compared with a 3D spectral scenario. The boundaries are considered opaque in FDS and the emissivity grey. This is a major shortcoming in the treatment of semi-transparent and spectrally dependent emissivity materials such as glass. To analyse the effect of grey emissivity on the glass temperature and also assess whether the code is suitable for spectral glazing calculations, simulations have been carried out with the original FDS code (as provided by developers)[8] using the scenario of Harada et al.[7]

A heat flux of 5.48 kW/m^2 is imposed on one side of the 3 mm thick glass pane (exposed surface) and the simulations with FDS, as shown in Fig. 7, employ propane as fuel and 20 nodes in the thickness of the glass pane. Fig. 8 presents the temperature predicted by the original FDS code based on grey emissivity. For comparison purposes, results obtained with the spectral 1D DOM radiation model (KU-sub) that provide results close to the experimental data[7] are also shown. The non-modified FDS over predicts the temperatures on both sides on the glass and this is mainly because the code does not consider spectral emissivity for the glass (grey emissivity assumed). The grey assumption influences the amount of radiation absorbed by the glass, i.e. if the grey emissivity of the glass is equal to 0.9 this means that 90% of the incident radiative flux will be absorbed. By contrast if actual spectral emissivities shown in Fig. 1 are considered with a flame temperature of 1250^{0}K, a 3 mm thick glass pane will actually absorb around 58% of the total incident radiative flux (32 % less than FDS). This preliminary investigation has shown that for the simulation of the dynamic behaviour of the glass pane in fires, the grey emissivity in FDS should be replaced with a more realistic spectral emissivity prior to coupling the spectral DOM radiation model with FDS. This task was recently carried out by the authors and the 1D DOM spectral radiation model has now been implemented into FDS. The verification and validation tasks are in progress.

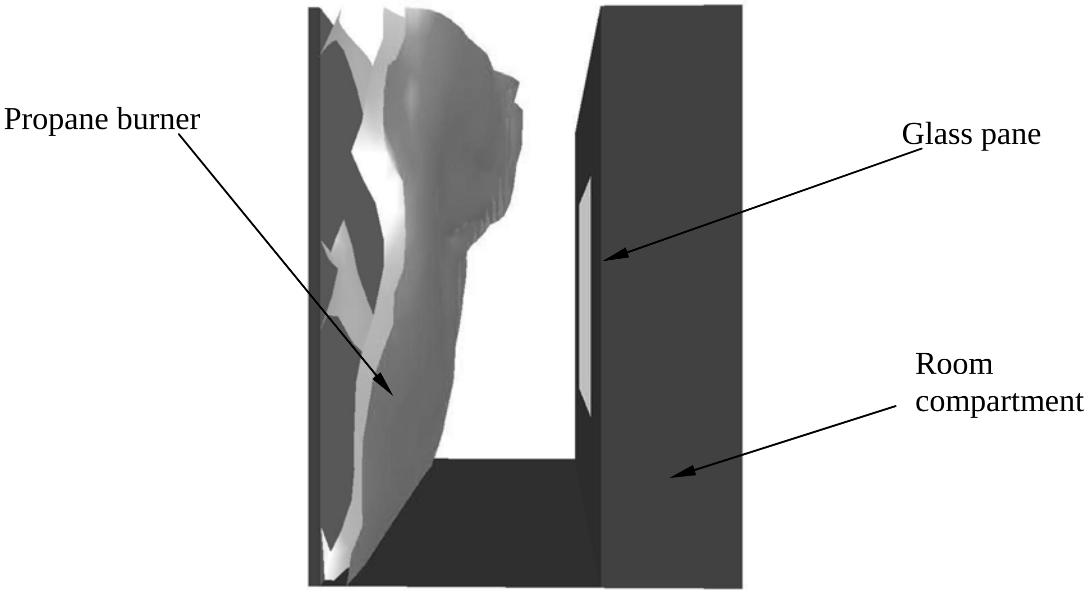

FIGURE 7. Simulation scenario with FDS

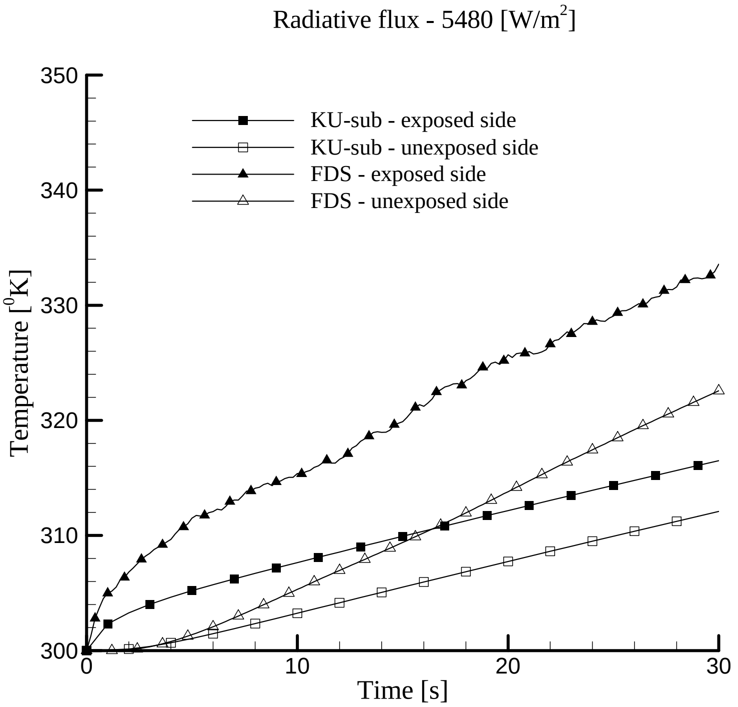

FIGURE 8. Temperature prediction with original FDS code with gray emissivity and the KU spectral radiation model (radiative heat flux 5.48 kW/m^2)

CONCLUSIONS

Numerical simulations have been carried out in order to verify the accuracy of a 1D spectral radiation model based on the Discrete Ordinates Method. The approach presented in the study remedies the shortcomings of some existing radiation models used in glass breaking analysis as it is spectral and accounts for the diffuse nature of incident radiation. The model's predictions agree reasonably well with the experimental data, in terms of temperature profiles of the glass surface and the time of the first crack occurrence. The implementation of the spectral radiation model in the widely used CFD code FDS is explored. Some preliminary results show the necessity of replacing the grey emissivity concept used in the original FDS code by more rigorous spectral emissivity data. The 1D spectral DOM radiation has been coupled with FDS and the verification is in progress.

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