Simulation of Glazing Behavior in Fires using Computational Fluids Dynamics and Spectral Radiation Modeling

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ABSTRACT

The performance and behavior of glazing systems have significant impact on fire growth and development. In the typical scenario of a glass pane exposed to fire, radiation is the predominant mode of heat transfer. In previous studies, the present authors have developed and validated a spectral radiation heat transfer model based on the Discrete Ordinates Method (SDOM) which accounts for the glass spectral properties (e.g. emissivity, transmissivity) and the diffuse nature of radiation incident on the glazing. In order to model the dynamic interaction between a glass pane and fire, the SDOM has been implemented in the CFD code FDS 5.0 and the new code (FDS-SDOM) is evaluated. The first part of FDS-SDOM validation study reports a comparative analysis between FDS-SDOM, the original (unmodified) version of FDS (OFDS) and the exact solutions for varying absorption coefficients typical of glass. The comparative study, in terms of radiative heat flux, shows that FDS-SDOM provides results closer to the exact solutions in comparison to OFDS when the absorption coefficient is varied from 0.1 to 100 m^{-1} (maximum error less than 1% for FDS-SDOM against 13 % for FDS). This provides further justification for the need to account for varying spectral properties of material such as glass and the diffuse nature of radiation in calculations. In the second part of the validation study, FDS-SDOM is applied to two experimental fire and glass scenarios with the aim of predicting the transient temperature distribution in the glass. Relatively good agreements are found between the code's predictions and the experimental data. The work demonstrates the good potential of combining the CFD approach with advanced spectral radiation modeling for fire and glazing studies.

KEYWORDS: CFD, FDS, glazing, glass, fire, spectral radiation, discrete ordinates model.

NOMENCLATURE LISTING

c_p	specific heat (J/kg K)	**Greek**	
I_λ	spectral radiation intensity (W/m^{2}srμm)	ε	emissivity
k	thermal conductivity (W/m K)	μ	direction cosine
K_λ	glass spectral absorption coefficient (m^{-1})	ρ	density
N_d	number of directions in SDOM	τ	transmissivity
q_λ	spectral radiative heat flux (W/m^{2}μm)	**Subscripts**	
q	total net radiative heat flux (W/m^2)	b	blackbody
T	temperature (K)	g	glass
t	time (s)	L	ambient side of glass pane
w_m	weight of discrete direction m, in SDOM	m	discrete direction in SDOM
x	dimension into glass (m)	r	radiative
L	thickness of the glass pane	λ	spectral
		0	hot combustion gases
		1	glass pane surface – side exposed to fire
		2	glass pane surface – ambient side
		∞	gases on ambient side of glass pane

INTRODUCTION

Ventilation is one of the major factors that influence fire development. The breakage and fallout of a window or door glass pane affects ventilation and the severity of fires. The early works of Emmons [1] and Pagni [2] have provided an understanding of the glass breaking problems and established a breaking criterion based on the glass temperature increase in the middle of the pane [2]. Many theoretical and experimental studies have been carried out on the performance of window glass in fires (e.g. [3, 4]). Radiation is the predominant mode of heat transfer in fire and glazing studies. Pagni and Joshi [5] have

developed the code BREAK 1 which models heat transfer by treating the glass as a distributed mass that absorbs radiation through its thickness with non-linear radiative boundary conditions. Although the majority of heat transfer models employed in fire/glass studies have their own merits such as the simplicity of implementation, they do not account for the spectral properties of glass (e.g. emissivity, transmissity) and the diffuse nature of incident radiation. To address these shortcomings, Dembele et al. [6, 7] have developed a spectral radiation model based on the discrete ordinates method. The validation studies of the radiation model show that the approach provides good prediction of glass temperatures and time to breakage [6]. Prescribed gas temperatures extracted from experimental data were used in simulations reported in [6] as the flow field was not computed. In the previous studies by the authors, the dynamic interaction between fluid flow, combustion (fire) and the glass pane was not accounted for as it was important to assess the radiation module independently before any coupling with fluid dynamics. With the aim of developing a tool coupling the dynamic interaction between the fire and glazing, the spectral radiation model developed by the authors has been implemented into Version 5.0 of the CFD code FDS (Fire Dynamics Simulator) developed at the National Institute of Standards and Technology (NIST), USA. The work presented in this article mainly reports on the preliminary validation studies of the Kingston University's version of the modified FDS code referred to as FDS-SDOM.

MATHEMATICAL MODEL AND NUMERICAL DETAILS

The transient temperature distribution is important in predicting the behavior of a glass pane subjected to heat from flames. The temperature is derived from the energy equation:

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

The radiative source term, $\nabla \cdot q_r$, is determined from the solution of the radiative transfer equation using the spectral discrete ordinates method.

Spectral Discrete Ordinates Radiation Method (SDOM)

The spectral radiative transfer equation (RTE) in one-dimensional geometry for glass is:

$$\mu \frac{\partial I_\lambda(x,\mu)}{\partial x} = -K_\lambda(x) \cdot I_\lambda(x,\mu) + K_\lambda(x) I_{b\lambda}[T(x)] \tag{2}$$

The Discrete Ordinates Method (DOM) approach is based on the separation of the angular dependence from the spatial dependence of the radiation intensity in the RTE. For a glass pane exposed to fire radiation, with the SDOM approach, Eq. 2 becomes for a discrete direction m:

$$\mu_m \frac{\partial I_{\lambda m}(x)}{\partial x} = K_\lambda(x) \cdot [I_{b\lambda}[T(x)] - I_{\lambda m}(x)] \tag{3}$$

The boundary conditions to solve Eq. 3 for a glass pane exposed to fire in a compartment for example are:

$$I_{\lambda m} = \varepsilon_{\lambda,g} I_{b\lambda}(T_1) + 2 \cdot (1 - \varepsilon_{\lambda,g} - \tau_{\lambda,g}) \sum_{m'=1,\mu'<0}^{N_d} \mu_{m'} w_{m'} I_{\lambda m'}(0) + \varepsilon_{\lambda,0} \cdot I_{b,\lambda,0}(T_0) \qquad \text{at} \quad x=0 \tag{4}$$

and

$$I_{\lambda m} = \varepsilon_{\lambda,g} I_{b\lambda}(T_2) + 2 \cdot (1 - \varepsilon_{\lambda,g} - \tau_{\lambda,g}) \sum_{m'=1,\mu'>0}^{N_d} \mu_{m'} w_{m'} I_{\lambda m'}(L) + \varepsilon_{\lambda,\infty} \cdot I_{b,\lambda,\infty}(T_\infty) \qquad \text{at } x=L \tag{5}$$

The number of directions, N_d, for DOM applications in 1D geometry is typically 20. The SDOM takes into account the spectral properties of the glass since actual emissivity and transmissivity of glass strongly vary

with the wavelength [8]. The approach also handles the diffuse nature of incident fire radiation on the glass pane.

The spectral and total radiative heat fluxes in the glass 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, $\nabla \cdot q_r$ in Eq. 1, is obtained by differentiation of the total heat flux.

CFD code FDS 5.0 and SDOM Implementation

As underlined above, to predict the dynamic interaction between the glazing and fire, a CFD tool is required. The CFD code used to implement SDOM is the version 5.0 of FDS, the Fire Dynamics Simulator developed at the National Institute of Standards and Technology (NIST) in the USA [9]. FDS solves the Navier-Stokes equations for low Mach number (Ma<0.3). The numerical algorithm employed is an explicit predictor/corrector scheme, second order accurate in space and time, using a direct Poisson solver. Turbulence is treated by means of Large Eddy Simulation (LES), via the Smagorinski sub-grid scale model. For combustion, a mixture fraction model is used. The code has been widely used by the international fire community and undergone various validations for fire applications. The Centre for Fire and Explosion Studies at Kingston University was one of the first university groups to adopt the code for some of its fire research work and has since devoted considerable effort to carry out further development and validations to the code in various applications [10].

Thermal radiation in the flow field is computed in FDS 5.0 by the finite volume technique on the same grid as the flow solver. However in the original version of FDS (OFDS), radiative transfer calculation in solids such as glass is based on a gray "two-flux" model which assumes the radiative intensity constant inside the "forward" and "backward" hemispheres [9]. Although this approximation may be reasonable for some solid materials, for glass it is more problematic for at least two reasons: the spectral properties are not accounted for, and the "two-flux" model has its own limitations mainly due to the assumption of constant intensity in each hemisphere [11]. Work has therefore been undertaken by the authors to implement the 1D SDOM into FDS 5.0 as an alternative to the gray "two-flux" model for glazing studies. The modified code is referred to as FDS-SDOM. For this implementation, the gray diffusive wall boundary condition in the OFDS was replaced with a spectral boundary condition relevant to glass in FDS-SDOM as:

$$I_{w,\lambda}(s) = \varepsilon_\lambda I_{bw,\lambda} + \frac{1-\varepsilon_\lambda-\tau_\lambda}{\pi} \int_{s'\cdot n_w<0} I_{w,\lambda}(s')|s'\cdot n_w| d\Omega + \tau_\lambda I^*_{w,\lambda} \qquad (6)$$

RESULTS AND DISCUSSION

Some Validation Results of the SDOM Approach

The SDOM has been validated independently of the flow field in previous studies by the authors using experimental data from the literature [6, 7]. Among other scenarios, the experiment of Skelly et al. [12] which consisted of a rectangular compartment (1 m x 1.2 m x 1.5 m high) was considered. The glass window assembly measured 0.5 m x 0.28 m. The tested glass was typical window glass of 2.4 mm thick with an unexposed edge measurement of 0.025 m around the entire vent opening perimeter [12]. Burning hexane liquid provided the fire in the compartment. Two different size trays were considered: 20 cm x 20 cm and 30 cm x 20 cm. Figure 1 presents for the 20 cm x 20 cm pool fire, the experimental data and the simulation results obtained with the SDOM approach [6]. The temperature profiles of the hot upper layer are measured close to the central point of the glass window, and used as prescribed input data for the boundary condition in SDOM (T_0 in Eq. 4) – the flow field is not computed. The temperatures denoted by "Tests 4, 5, 6" represent the temperature profiles of the exposed side (fire side) of the glass pane measured in three repeated tests [12]. The calculated temperature profiles of the exposed side of the glass pane are in good agreement with the experimental data. The relative difference or error, between the SDOM predictions and the averaged experimental data do not exceed 3 %.
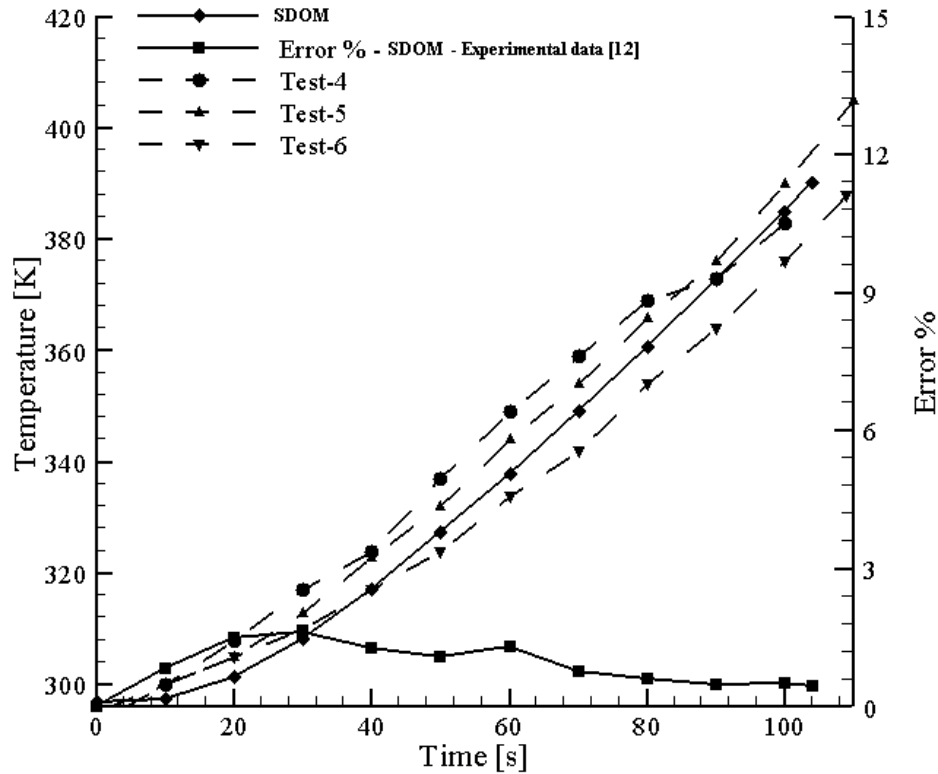
Fig. 1. Glass surface temperature predicted by SDOM and experimental data from [12].

Validation Study 1 - Comparative Study between FDS-SDOM, OFDS and Exact Solutions

The first part of the validation study of FDS-SDOM is based on a scenario for which exact heat flux solutions could be calculated. The scenario consists of a wall with an internal temperature of 1273.15 K and the ambient temperature is 10 K. The wall thickness is 0.1 m and the absorption coefficient is varied to cover a range from 0.1 to 100 m^{-1} (i.e. 0.001 to 1 cm^{-1}). The range covers the bulk of the glass absorption spectrum as shown in Fig. 2 [13], although the wall is not exactly glass. The emissivity, conductivity and specific heat are equal to one and the material density 1000 kg/m^3. For this scenario, the exact solutions for radiative flux in the wall are the analytical solutions of plane layer emission [14]:

$q = I_b[1 - 2E\_3(\tau)]$ where $I_b = \sigma T^4$ $\sigma \cdot T^4$ and $E\_3(\tau)$ $E\_3(\tau)$ is the third-order exponential integral function of optical depth τ

For comparison, the heat flux in the wall was also calculated using the original version of FDS (OFDS) based on gray "two-flux" approach for radiation calculations in solids.
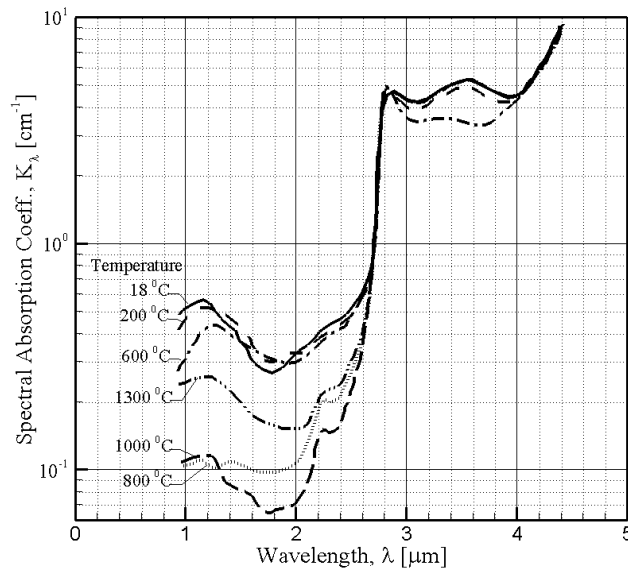
Fig. 2. Spectral absorption coefficient of window glass [13].

Table 1 presents the predicted solutions obtained with FDS-SDOM, OFDS and the exact solutions. FDS-SDOM calculations are based on 100 nodes in the wall and 20 directions in SDOM. FDS-SDOM predictions are consistently close to the exact solutions and are stable. The relative differences between the two sets of data (FDS-SDOM and exact solutions) do not exceed 1 %. In contrast OFDS predictions show large fluctuations compared to the exact solutions with a 13 % maximum relative difference. The better predictions obtained with FDS-SDOM can be explained by the ability of the SDOM approach to account for more solid angles in space to treat diffuse radiation contrary to the "two-flux" approximation based on only two hemispheres with constant radiation intensities in each. In terms of computing times, FDS-SDOM requires 10% more time than OFDS for the scenarios investigated. This validation scenario demonstrates the capability of FDS-SDOM to predict heat flux distributions for different absorptions coefficients relevant to glass, with relatively good accuracy and little computational overhead.

Table 1. Heat fluxes computed by FDS-SDOM, OFDS and exact solutions.

	Absorption Coefficient [m^{-1}]				
	0.10	1.00	5.00	10.00	100.00
Exact Heat Flux [kW/m^2]	2.897000	24.940300	82.945700	116.2891	148.9698
Heat Flux Predicted FDS-SDOM [kW/m^2]	2.902142	25.106795	82.628688	115.72419	148.15574
Relative error FDS-SDOM & Exact solution[%]	0.2	0.7	0.4	0.5	0.5
Heat Flux Predicted OFDS [kW/m^2]	2.949532	26.979710	93.897304	128.41184	148.97023
Relative error OFDS & Exact solution[%]	1.8	8.2	13.2	10.4	0.0003

Validation Study 2 - Application of FDS-SDOM to Experimental Glazing-Fire Scenarios

The second validation study is based on the experimental scenarios of Harada et al. [15] and Skelly et al. [12]. The experiments in [15] were carried out to predict the time to first crack occurrence and/or breaking time of a glass pane. Different heat fluxes in the range 2.7 to 9.7 kW/m^2 were imposed to the glass by changing the distance between the glazing pane and a propane-fired radiant panel. In the independent validation of SDOM (uncoupled with fluid flow), for the heat flux of 5.48 kW/m^2, the experimental and predicted times to first crack occurrence were the same (207 s) [6]. The measured and SDOM predicted times to first crack were respectively 144 s and 147 s (2 % difference) for 6.69 kW/m^2, and 90 s and 94 s (4 % difference) for 9.11 kW/m^2 [6].

FDS-SDOM is employed to simulate the scenario of Harada et al. [15]. In calculations, the spectral range [0.1 - 200 μm] is considered and the spectral emissivity, absorption coefficient and transmissivity of glass are used. Figure 3 shows the transient temperature distribution on the exposed glass surface for an incident heat flux of 6.69 kW/m^2 obtained with FDS-SDOM. Transient temperatures profiles were not presented in [15], SDOM transient predictions [6] are used instead as "reference" data. The predictions of FDS-SDOM are in relatively good agreement with the reference temperatures when the spectral radiation model is coupled with FDS.

It is of interest to investigate how OFDS based on gray "two-flux" model would predict temperature distribution on the glass surface. As calculations in solids by OFDS are gray, gray calculations are carried out by varying the absorption coefficient assumed gray in the range 0.01 – 1000 m^{-1} (i.e. 0.0001 to 10 cm^{-1}) to encompass the whole glass absorption coefficient spectrum (Fig. 2). OFDS predictions are shown in Fig. 3 with different absorption coefficients (k=0.1 to 1000 m^{-1}). Transient temperature predicted by OFDS show strong fluctuations with the different absorption coefficients and do not agree with the reference data. This implies that the application of OFDS is clearly problematic for real fire/glazing scenarios where spectral glass properties should be included in calculations for accuracy. For the same experimental scenario in [15], Fig. 4 presents the glass surface temperatures obtained with FDS-SDOM as well as the reference data for three different fire heat fluxes: 5.48, 6.69 and 9.11 kW/m^2. Overall the two sets of data are in a relatively good agreement for the three heat fluxes considered.

The second scenario considered for the validation analysis of FDS-SDOM is based on the compartment fire experiment of Skelly et al. [12]. In contrast to the independent radiation model application of SDOM (Fig. 1), the fluid dynamics calculations are performed by FDS and dynamically coupled with SDOM for radiative source terms and temperature calculations in the glazing. Figure 5 depicts the geometry adopted for this scenario. For the computations, a total of 30 (X) x 30 (Y) x 30 (Z) meshes were employed in 90% of the compartment volume. For the remainder of the volume, a more refined mesh based on 30x30x90 grids is used close to the glass window for more accurate predictions of the gas temperature distribution near the wall and glass window. The mesh resolution inside the glass window is 20 points across the glass thickness. A preliminary grid sensitivity analysis has shown that simulations solutions are grid independent for the mesh structure adopted for this particular scenario. The burning fuel is hexane and two different pool sizes are considered in the simulations: 20 cm x 20 cm and 30 cm x 20 cm.

Figures 6 & 7 show the transient temperature distribution of the exposed glass surface, predicted by FDS-SDOM, respectively for the 20 cm x 20 cm and 30 cm x 20 cm pool fires. The repeated experimental data denoted by "Tests 4, 5, 6, 1, 2, 3" [12] are also presented for comparison. FDS-SDOM predictions are closer to temperatures measured in "Test 6" (20 cm x 20 cm pool) and "Test 1" (30 cm x 20 cm pool) although there is a slight temperature under prediction in the first 20 s. As the measurement errors were not provided in [12] it is difficult to discuss further these under-predictions and more scenarios should be investigated. FDS-SDOM calculations are overall in good agreement with the measured temperatures.
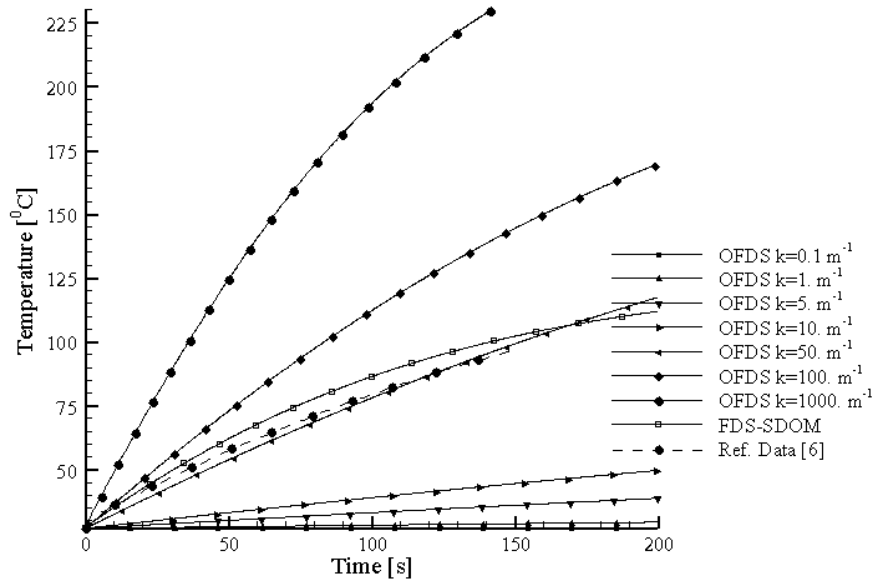
Fig. 3. Glass surface temperature predicted with FDS-SDOM, OFDS for the experimental scenario in [15] - Heat flux of 6.69 kW/m^2
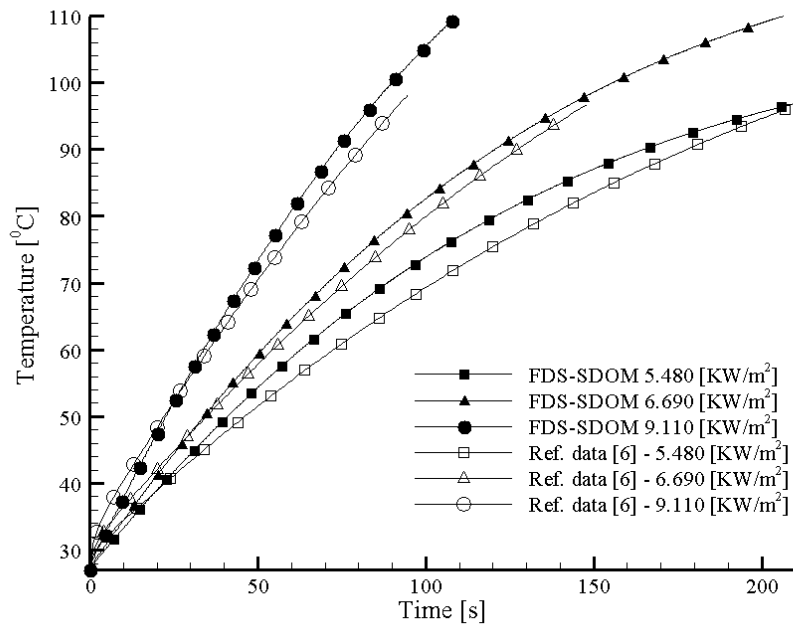

Fig. 4. Glass surface temperature predicted with FDS-SDOM for the experimental scenario in [15] for different heat fluxes.
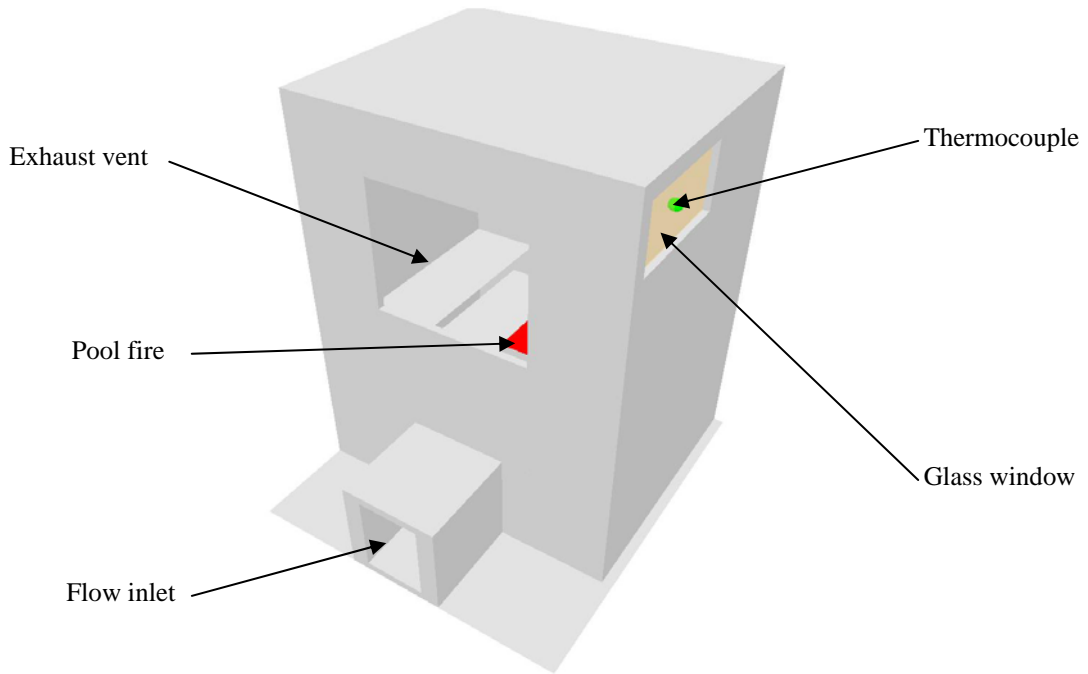
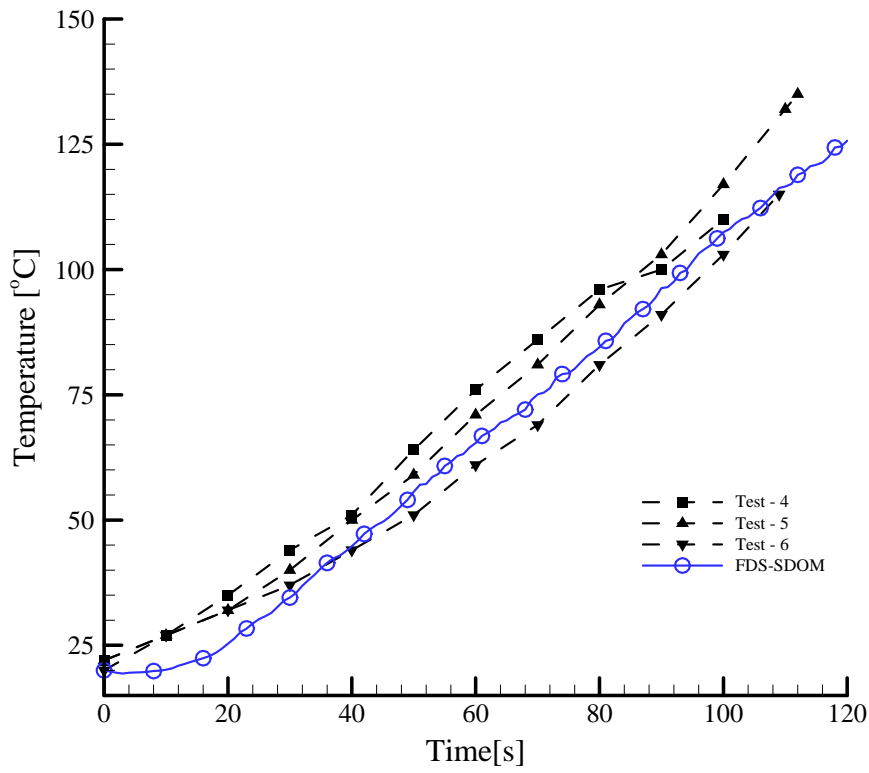Fig. 5. Geometry for FDS-SDOM application to the compartment fire scenario in [12].

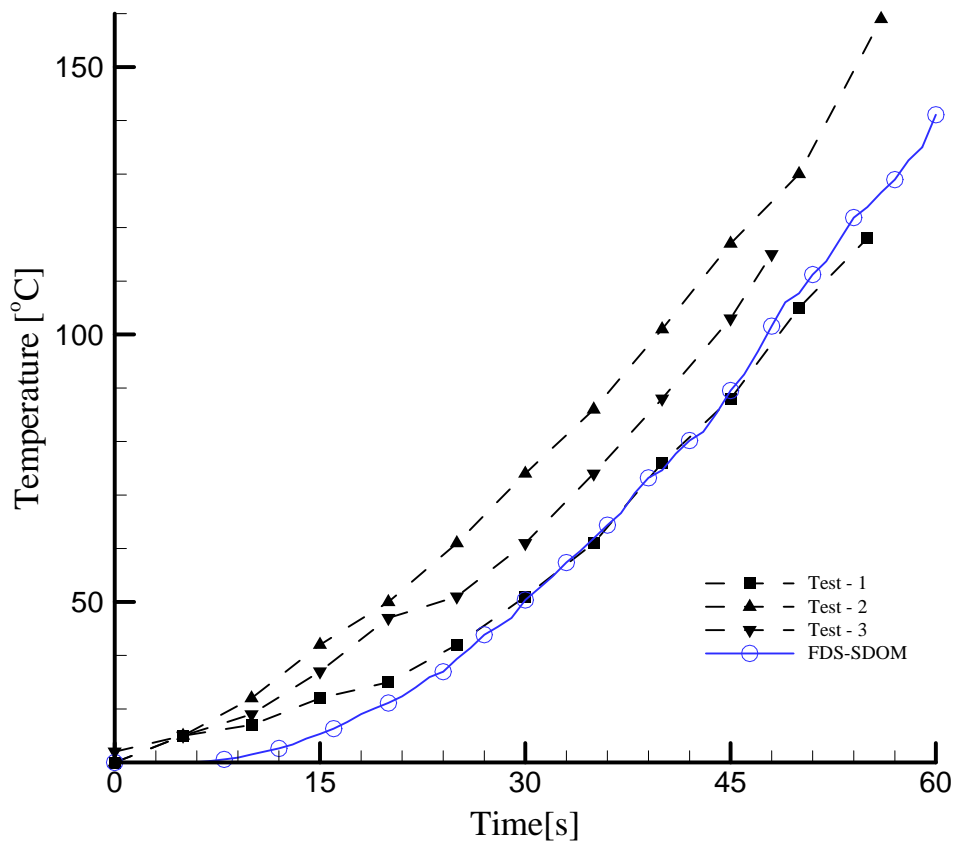Fig. 6. Glass surface temperature predicted by FDS-SDOM and experimental data from [12]. Pool fire 20x20 cm.

Fig. 7. Glass surface temperature predicted by FDS-SDOM and experimental data from [12]. Pool fire 30x20 cm.

CONCLUSIONS

A spectral radiative heat transfer model based on the discrete ordinates method (SDOM) previously developed by the authors has been implemented into the CFD code FDS 5.0 to predict the dynamic interation between glazing systems and fires. The paper has mainly reported the preliminary validation results of the new tool (referred to as FDS-SDOM) for some scenarios.

In the first validation study, FDS-SDOM is employed to predict the radiative heat fluxes in a wall with varying absorption coefficients typical of glass. The exact solution for this scenario has been reported in the literature. A comparative study between FDS-SDOM and the exact solutions shows that the code's predictions agree within 1% with the exact solutions. Simulations were also carried out for the same scenario using the original (unmodified) version of FDS (OFDS) which treats radiation in solids such as glass with a gray "two-flux" approach. OFDS solutions show large fluctuations with a maximum error of 13 % in comparison to the exact solutions for the absorption coefficients investigated.

In the second validation study, FDS-SDOM is applied to the experimental scenarios of Harada et al. [15] and Skelly et al. [12]. In the first scenario where a glass pane is subjected to fire radiant heat [15], FDS-SDOM predicts with a relatively good accuracy the glass surface transient temperature distribution. Application of OFDS is problematic for such a scenario where the glass spectral properties are to be accounted for. The second scenario considered is based on the compartment fire experiment of Skelly et al. [12]. A comparative study between FDS-SDOM and the experimental data [12] in terms of glass surface transient temperature show a relative good agreement between the two sets of data.

The preliminary validation study presented shows the good potential of FDS-SDOM to predict the glass behavior in a fire environment. Work is in progress to apply the code to more fire/glazing scenarios for a better evaluation.

ACKNOWLEDGMENTS

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