CFD analysis of the heat transfer of fire doors under the standard time-temperature curve

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Abstract

The fire resistance of the construction materials is traditionally measured by the fire resistance test method in accordance with the international standards, i.e. ISO 834-1, BS476-20, and ASTM E119, etc. In fire resistance door test, a full-scale test door is fitted into a standardized furnace for testing and then the test report is issued to ensure how long the door can resist the fire. A single leaf wooden door was tested in this study. During the 1-hour test, the temperatures inside the furnace and six measured points on the unexposed surface were recorded with the thermocouples. COMSOL Multiphysics®, was used to develop a three-dimensional heat transfer model for the fire door under the fire resistance test. In results, it showed that the curve trends of the simulated unexposed temperature of the six measured points (three thermocouples place on the door frame and three thermocouples place on the door) generally agreed with the experimental data. For the door leaf, the maximum temperature error between the experimental data and the simulated data was within ± 25%. For the door frame, the maximum temperature error between the experimental data and the simulated data was within ± 35%. The larger difference on the door frame was calculated because the practical smoke passing through the door crevice between the leaf and frame, due to the door sealant failure, was not simulated in this model.

Keywords: Heat Transfer, Fire Resistance Test, CFD Method

Introduction

In the fully developed fire, the temperature can be up to 1100°C [1]. To avoid the fire passing through an opening of a compartment to another, the separating elements such as fire door should have the sufficient "fire resistance" performance. The fire resistance of the elements is traditionally measured by the fire resistance test method based on the international standards, such as ISO 834-1, BS476-20, and ASTM E119. In fire resistance door test, a full-scale test door is fitted into a standardized furnace for testing and then the test report is issued to ensure how long the door can resist the fire. The furnace is heated up to 1100°C according to the standardized time-temperature curve. Test report relates only to what has been tested and allows very little in the way of variations. Changes to a construction require either another fire test or an assessment. Since the additional fire test is time and cost consuming, an accurate and scientific assessment tool is an alternation to address this issue. The assessment tool is capable to analyze the heat transfer accurately through a fire door under the standard test.

Some researchers have used the numerical method to analyze the thermal performance of the specimens of the fire resistance tests. Welch and Rubini [2] applied the CFD method to simulate a full-size 14-burners fire-resistance furnace with a steel specimen following the ISO-834 time-temperature curve. The results showed that radiation heat transfer was dominant, especially for the steel specimen. Moreover, that study stated that CFD method had potential for investigating the thermal behavior of fire resistance furnace and might be able to assist the harmonization of fire resistance test procedures. Chow and Chan [3] predicted the fire resistance of building materials based on finite element analysis program. The results showed that the numerical prediction of aluminum sample agreed with the experimental results done by an electric furnace with the temperature following the standard fire curve of BS 476. However, the prediction of the other two samples made of hardwood and cement mortar was not good due to the burning of the material of hardwood and the changes of moisture evaporation from the cement mortar. Ferreira et al. [4] studied the fire resistance of the tabique wall experimentally and numerically. The experimental tests were tested in a fire resistance furnace according to ISO 834 standard fire curve. The experimental results showed the tabique wall panels fulfilled the requirements of the European fire resistance test standard. Also, the numerical model was developed by ANSYS software and the numerical temperatures showed good agreement with the experimental results.

Based on the literature survey, it can be summarized that the numerical method is suitable to simulate the fire resistance tests done with the practical fire test furnace. Therefore, the objectives of this study are to (1) conduct the fire resistance experiment~~s~~ conducted in the gas-fired furnace with the temperature following the standard firer curve of BS 476 : Part 20 and (2) apply the CFD method (COMSOL Multiphysics) to simulate fire resistance experiments for the analysis of heat transfer.

Fire Resistance Experiment and CFD Modeling

In this study, the fire resistance test was conducted in a gas-fired furnace. During the test, the furnace temperature rose on a time basis according to the standard curve of BS 476: Part 20 [5] (see Figure 1). A fire resistant door was used as a test specimen. For testing of the insulation of the fire door, the six Type-K thermocouples were placed on the unexposed side of the door.

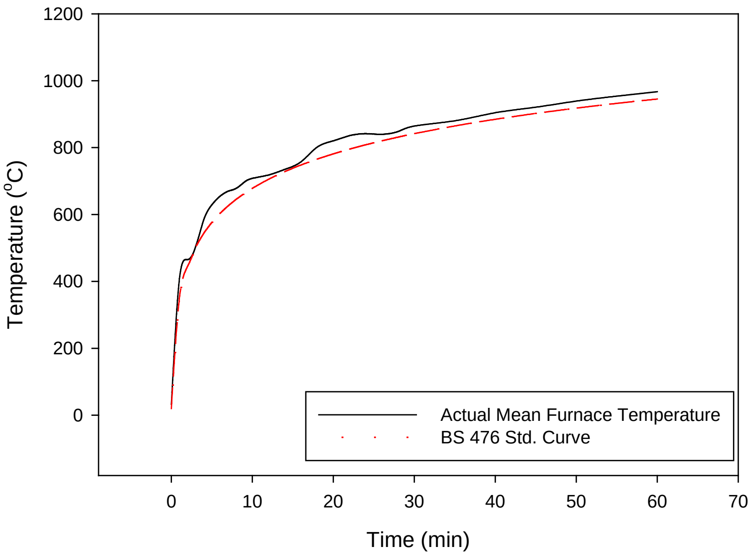


Figure 1. Comparison of the standard time- temperature curve and the mean furnace temperature during the test

Figure 2 shows the wooden door embedded in a concrete wall mounted in a steel frame. In the figure, three thermocouples (labeled as "1", "3", "5') were adhered by the adhesive aluminum foil on the door frame and the other three thermocouples (labeled as "2", "4", "6") were adhered by the adhesive aluminum foil on the door leaf. Since the structure of the wooden door was symmetric and the pressure at the same horizontal level was basically the same, heat transfer through the two horizontal positions (point 2' and point 2 ; point 6' and point 6) should be the same. This assumption was also verified by the COMSOL simulation. After the simulation, the temperature difference between the symmetric positions (point 2' and point 2 ; point 6' and point 6) was calculated of less the 0.04%.

Figure 2. Single leaf - door installed on the furnace

Figure 3 depicts the dimension of the tested wooden door. The outer dimension for the door frame is 2398 mm (H) × 970 mm (W) × 101 mm (D) and that for the wooden door is 2360 mm (H) × 900 mm (W) × 59 mm (D), respectively. The wooden door is composed by sandwiching an acoustic layer into the two pieces of laminated wood boards. Because this study was performed for research purpose, the door components such as door lock, handle, and closer were not installed on the tested door.

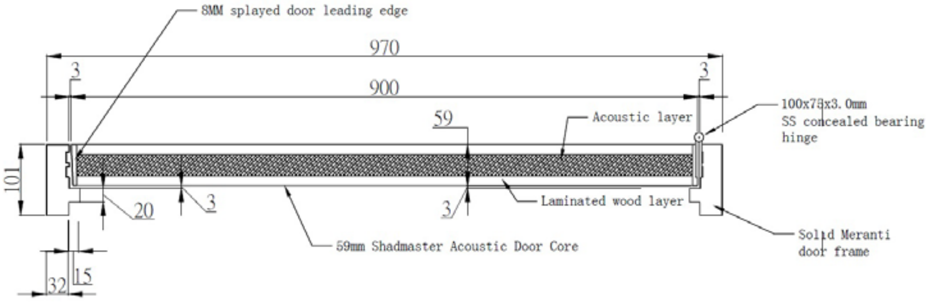


Figure 3. Cross-section of the tested door

COMSOL Multiphysics®, which is an engineering computation software in finite element analysis, has also been used to analyze the thermal behavior of the construction materials [6-9]. Therefore, the COMSOL Multiphysics® was used in this study to design and develop a three-dimensional simulation model to analyze the thermal behavior of the fire door under the fire resistance experiments. Figure 4 represents the three-dimensional model simulated in by Multiphysics. As shown in the figure, the model mainly includes a steel frame, a concrete, and a wooden door. Below lists the setting of those components:

1. Steel frame and concrete – The stainless steel frame is used in the model. The thickness of the concrete is 101 mm, which is the same as the door frame.
2. Door frame – The door frame is an inverted U-shape frame (Figure 5a). The material used for a frame is Meranti wood. The thickness of the door frame is 101 mm.
3. Door leaf – A 53-mm hardboard is sandwiched in two pieces of 3-mm thickness plywood boards. The thickness of the total door leaf is 59 mm.
4. Steel Hinge – Four steel plates are used as the hinges and installed between the door frame and the door leaf (Figure 5b).

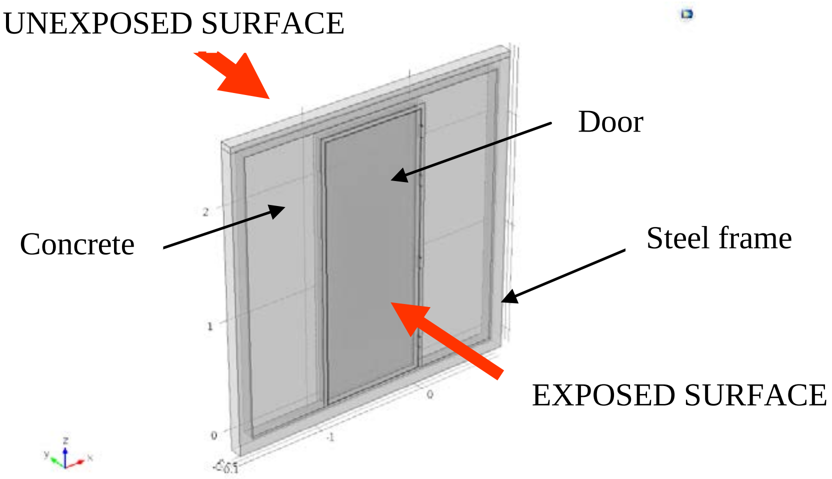
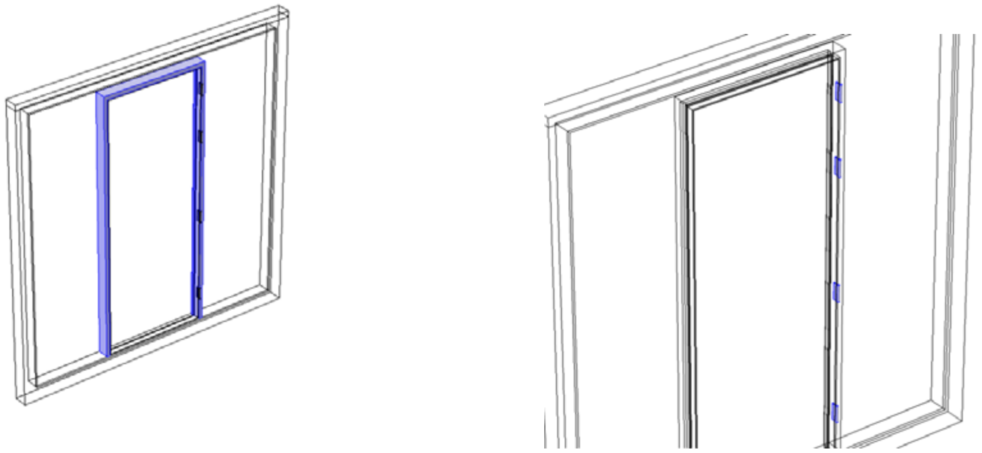


Figure 4. Overview of model



(a) (b)

Figure 5. (a) Wooden Door frame, (b) Steel hinges

In this study, the governing equation used in the simulation is expressed as:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q + Q_{ted} \tag{1}$$

where Q_{ted} is the thermoelastic damping heat source, since it is not a loadbearing system, so Q_{ted} is equal to zero.

In the current simulation, four boundary conditions are assigned in the heat transfer model:

(1) A uniform initial temperature was applied to all domains of the model at the initial time $t = 0$;

(2) As shown in Figure 6, the temperature boundary condition of the exposed surface and the door crevice is expressed as [5]

$$T = 345 \cdot \log(8t + 1) + 20 \tag{2}$$

(3) As shown in Figure 7, the radiation boundary condition is applied to unexposed surface of the door, the concrete and the whole steel frame. The radiation equation used is written as

$$-\vec{n} \cdot (-k\nabla T) = \varepsilon\sigma(T_{amb}^4 - T^4) \tag{3}$$

where the surface emissivity of wood with concrete and steel are 0.25 and 0.83, respectively [7].

(4) As shown in Figure 8, the natural convection boundary condition is also applied to unexposed surface of the door, the concrete, and the steel frame. The natural convection equation used is written as

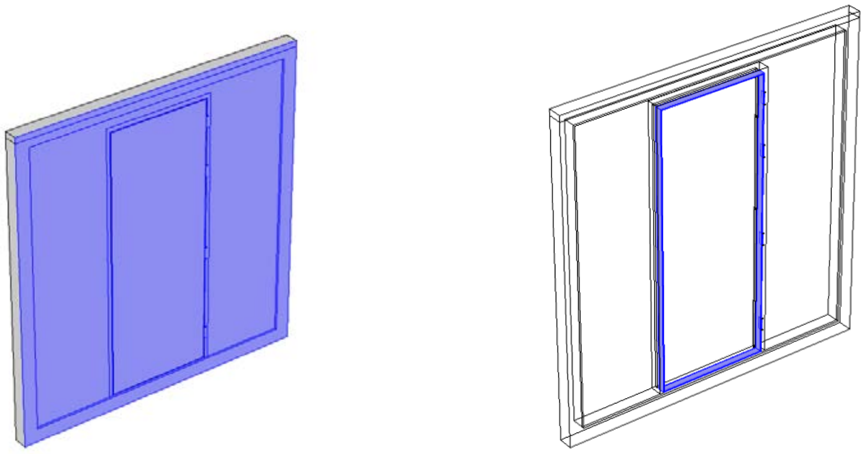
$$-\vec{\mathrm{n}} \cdot (-k\nabla T) = h(T_{ext} - T) \tag{4}$$

where is restricted by the following condition:

$$\mathrm{T} = T_0,\ \text{if } \vec{n} \cdot \vec{u} < 0 \tag{5}$$

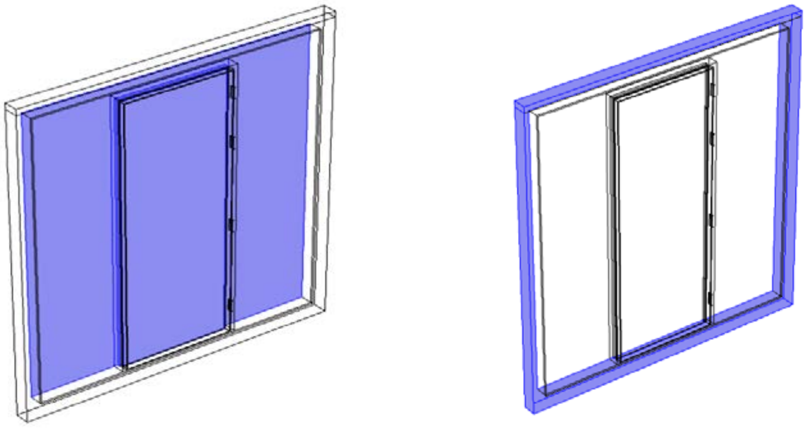
$$-\nabla T \cdot \vec{n} = 0,\ \text{if } \vec{n} \cdot \vec{u} \geq 0$$

Figure 9 shows the unstructured tetrahedral meshes used in COMSOL. In the figure, there are 897,469 domain elements, 207,354 boundary elements, and 6,977 edge elements used in the model. The finer mesh is suitable for simulating the model, especially, the door hinge.



(a) (b)

Figure 6. Temperature boundary of (a) exposed surface and (b) door crevice



(a) (b)

Figure 7. Radiation boundary of (a) the door and the concrete wall and (b) steel frame

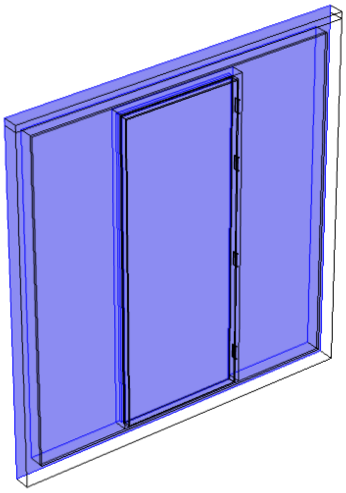


Figure 8. Natural convection boundary

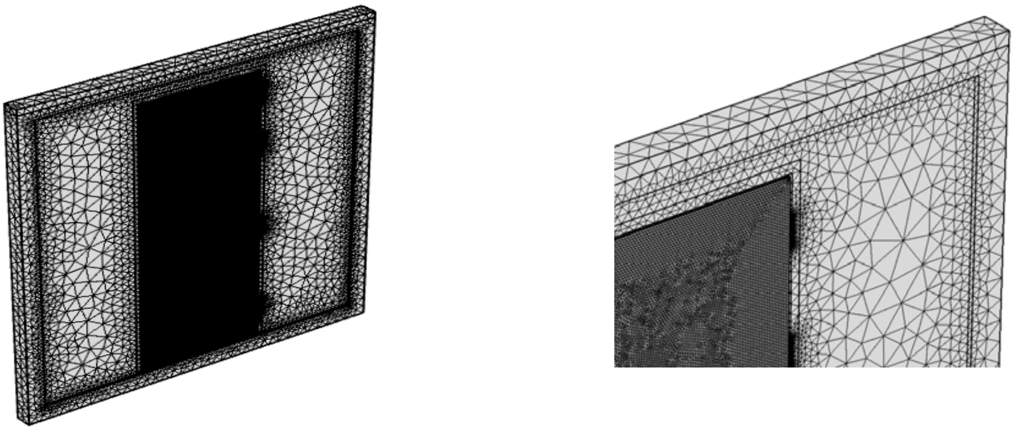


Figure 9. Tetrahedral mesh for the COMSOL model.

Table 1 shows the major properties of the materials used in the simulation. The properties of stainless steel and concrete are obtained from COMSOL library and the others are obtained from the book [10, 11].

Table 1. Material Properties used in this study

Material	Density (kg/m^3)	Thermal conductivity (W/m·k)	Specific heat capacity (J/kg·k)
Hardboard	330	0.15	1500 to 2000
Laminated wood (or plywood)	545	0.12	1210
Meranti wood (or softwood)	513	0.1 to 0.2	950 to 1600
Stainless steel	7194 to 7861	14.7 to 40.7	332 to 476
Concrete	2300	1.8	800

Numerical results and discussion

Figure 10 shows the temperature distribution of the unexposed surface at 1 hour. It is obvious that the temperature of the door is lower than the temperature of the concrete wall and steel frame. Moreover, the door crevice suffers a higher temperature than the wooden door and frame. This observation was also found in the experiment. Figure 11 shows the picture taken at the 1 hour of the experiment. It shows the location near the crevice was scorched and the smoke was released from the crevice so that the temperature of the location near the crevice was higher than the door core.

Figure 12 shows the comparison of the temperature results of the simulation with the experimental results measured at different locations of the tested door. In the figure, the experimental data points are shown in circular symbols and the simulation results based on the standard time-temperature curve and the actual mean furnace temperature measured in the experiment (see Figure 12) are shown in triangular symbols and square symbols, respectively. The difference between the simulations based on different furnace temperatures is nearly the same (within ± 2% error). For the curve trend, all the the simulated results show an agreement with the experiment. However, there is still a deviation between the experiment and the simulation. For the door leaf, the maximum temperature error between the experimental data and the simulated data is calculated within ± 25%. For the door frame, the maximum temperature error between the experimental data and the simulated data is calculated within ± 35%. The larger difference on the door frame is calculated because the practical smoke passing through the door crevice between the leaf and frame, due to the door sealant failure, was not simulated in this model.

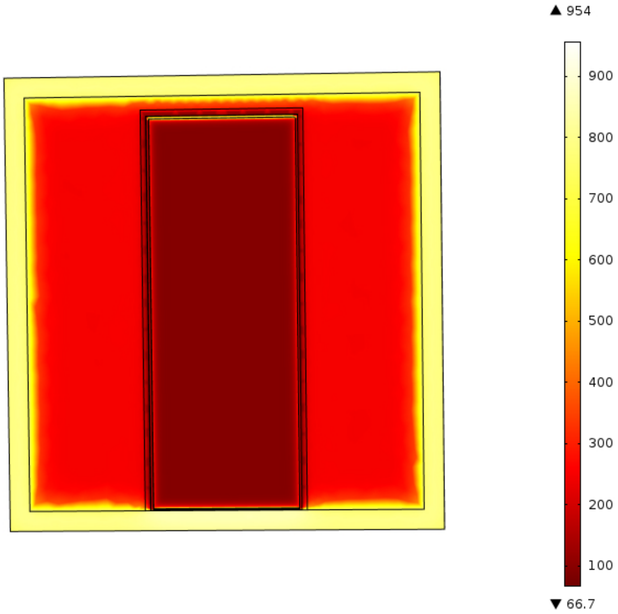


Figure 10. Unexposed surface temperature of model at the time of 60 minutes

Figure 11. Unexposed surface condition of experiment at the time of 60 minutes

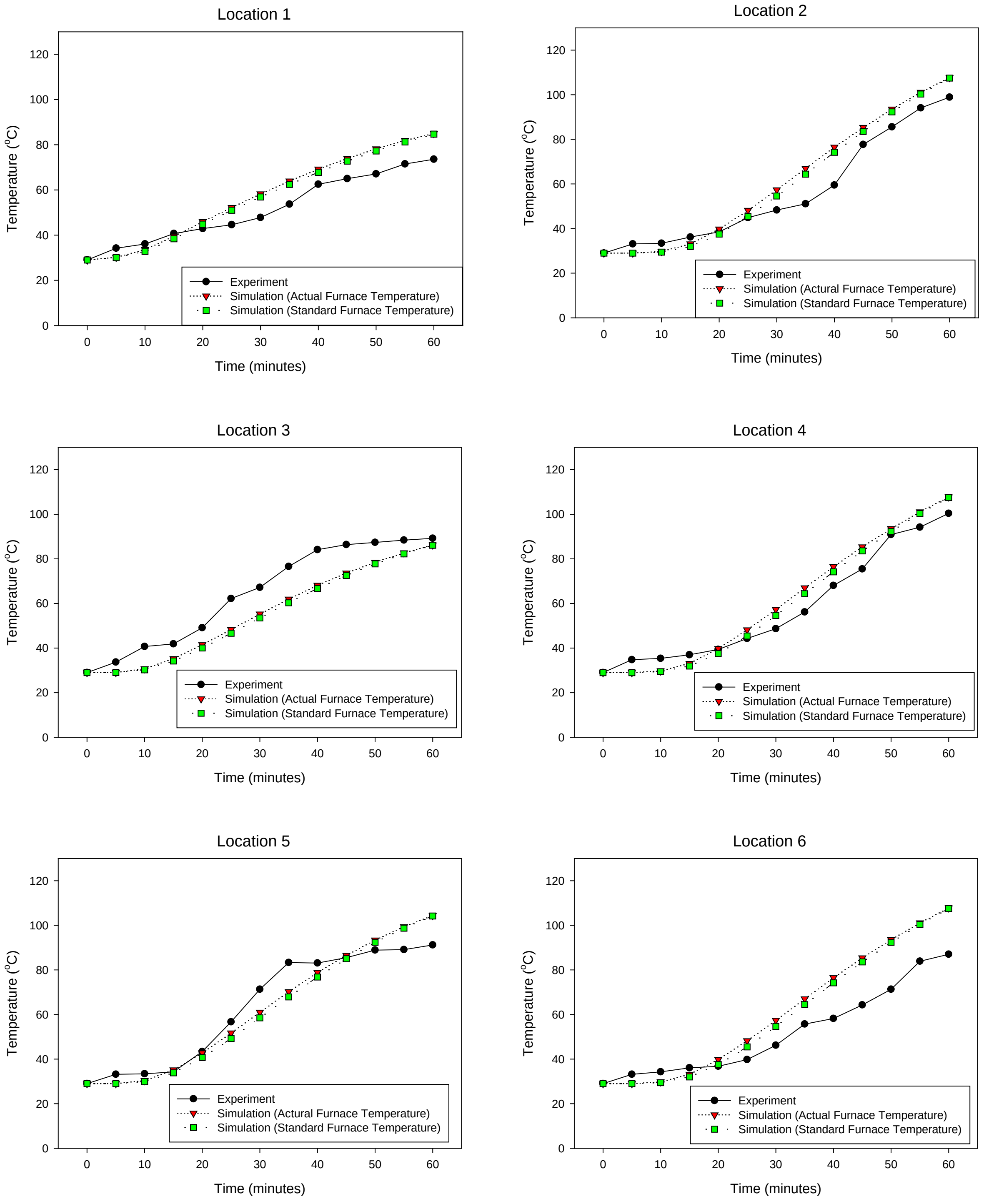


Figure 12. Comparison of the simulation temperatures with the experiments at different measuring locations.

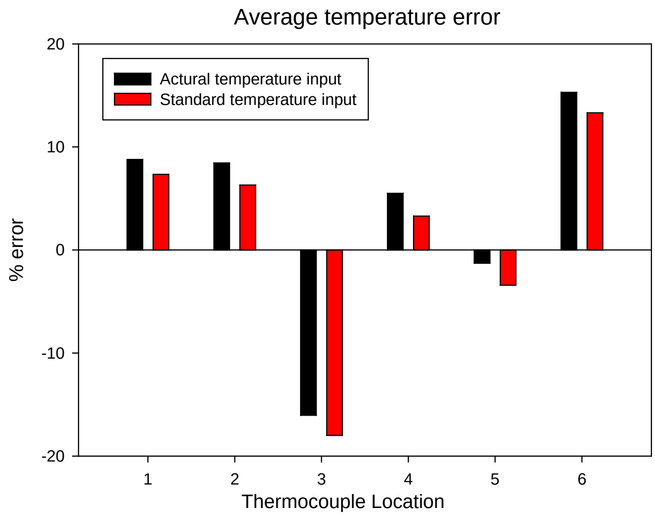


Figure 13. Average temperature error with the experiments at different measuring locations.

Conclusions

In this study, the CFD method is used to simulate the heat transfer through the tested door installed on a fire testing furnace with the standard furnace temperature rise. After comparing the simulation results with the experimental data, it can be concluded that the heat transfer model developed in this study can reasonably predict the unexposed temperature of the door leaf. The insolation of the simulation and experiment result at the unexposed size are consistent. Even the maximum temperature error of door core and door frame were within ± 25% and ± 35%, and the average temperature was within ± 18%. The simulation result of this model, include all the computation error, are capable to adjudge the insolation of this wooden door. In the future, the current heat transfer model can be improved by taking the smoke passing through the crevice, the furnace pressure condition, and the chemical reaction on the wood in the simulation.

Nomenclature

c	specific heat	J/kg·K
T	temperature	ºC or K
k	thermal conductivity	W/m·K
h	convection coefficient	W/ m^2·K
Q	total heat transfer	kJ
t	time	minute

Greek Symbols Letters

ε	surface emissivity (dimensionless)	
ρ	density of material	(kg/m^3)

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