The Use of Double Fire Shutter System in a Fire Safety Engineering Design

K K YUEN and **S M LO**
Department of Building & Construction
City University of Hong Kong

G H YEOH
CSIRO, Australia

ABSTRACT

Protected lobbies may be stipulated by fire codes to protect openings in compartment walls. Such lobbies will in some cases impair the communication between different parts in a building. In the circumstances, the use of fire shutters may be considered. However, fire shutters available in Hong Kong's market can only provide resistance to fire in terms of integrity. As heat flux can be transmitted by radiation, such fire shutters cannot be regarded as a like-to-like substitution to protected lobbies. This paper is to demonstrate that a double fire shutter system can be an appropriate alternative means of protection to the openings against the spread of flame and heat in stead of using lobby. The effectiveness of the double shutter system will depend on the separation between the shutters and the emissivity of the shutters. Computational Fluid Dynamics (CFD) technique is adopted to analyse the influences of the two parameters.

INTRODUCTION

It is recognized that openings at compartment walls will defeat the fire resisting properties of the walls. However, in order to maintain good communication between different spaces in a building, provision of openings at compartment walls becomes indispensable.

In accordance with paragraph 10.1 of the Code of Practice on Fire Resisting Construction, 1996, Hong Kong (FRC Code, 1996) [1], openings in compartment walls for communication of adjoining compartments should be protected by a lobby with fire resisting doors. Except for places of public entertainment or carparks, any such opening may alternatively be protected by a fire shutter with the same Fire Resistance Period as the compartment wall with regard to the criterion of integrity.

Hong Kong is a densely populated city, the land supply is scare. Multi-storey high-rise buildings are therefore constructed everywhere to satisfy the demand for various purposes. Manufacturing factories are also accommodated in multi-storey factory buildings as if they were apartments. These multi-storey factory buildings are termed as flatted factory buildings. Raw materials, parts and goods are loaded or unloaded at the loading and unloading space situated at ground floor of the building. These goods are then conveyed to the factories at upper floors by elevators. The loading and unloading space which is part of the carparking space and the landing areas of the elevators are different compartments and should be separated by walls with adequate fire resistance. Any openings in such walls should be protected by lobbies. However, lobbies will obstruct the smoothness of the conveyance of the materials and goods.

The FRC Code (Hong Kong) does not allow the use of a single leaf fire shutter to substitute the protected lobby. One of the reasons is that such fire shutter cannot effectively resist heat transmission. The objective of this article is to demonstrate an alternative approach by using a double fire shutter system and illustrate such double shutter arrangement can effectively resist heat transmission. It also indicates that the effectiveness of the system will be governed by the separation and emissivity of the shutters.

THE PERFORMANCE REQUIREMENTS

Openings in compartment walls should be protected in that flame and smoke are resisted to an acceptable standard. A protected lobby is considered to have adequate protection in that:

a) it resists the spread of flame by doors with adequate fire resistance in terms of integrity; and
b) it resists the spread of flame and smoke by offering a buffer zone (reservoir) for smoke and radiant heat transmission.

Therefore, an alternative means of protection should also have similar resistance to spread of flame and smoke.

The alternative approach by double fire shutters system is designed in which the shutters have equivalent Fire Resistance Period [FRP] as the compartment walls in terms of integrity. The arrangement is shown at Figure 1. The shutters will be operated upon actuation of smoke detectors installed immediately adjacent to the openings.

If the fire shutters can function properly, the resistance of spread of flame can be regarded as adequate as the fire shutters are to provide with equal FRP as to the compartment walls in terms of integrity. The question now is whether the fire shutters can also effectively retard the smoke spread and radiant heat transmission.

The control of the operation of the shutters is carried out by smoke detectors installed adjacent to the openings. This indicates that the shutters will be closed once significant amount of smoke has been detected. Once the shutters have been operated, the effectiveness of smoke sealing property will depend on the width of the gaps between the shutters and the frame of the opening. In practice, if a leakage rate of not exceeding $3m^3/m/hour$ when tested at 25 Pa under BS476 is maintained [2], the smoke checking property of the shutters can be considered as acceptable.

If the arrangement of the shutters can be made as described, the system can effectively resists the spread of fire in terms of integrity and smoke. The question then is whether such system can effectively resist radiant heat transmission. Fire shutters with adequate fire resistance in terms of insulation can resist radiant heat transmission. However, in Hong Kong, fire shutters (roller shutter) with adequate insulation property are not available in the market.

The following sections will discuss the possibility of using double fire shutters which are commonly available in the market (i.e. without fire insulation property) to resist radiant heat transmission.

COMPUTATIONAL TOOLS OF THE HEAT CONVEYANCE

The double fire shutters assembly consists basically of two panes of fire shutters. This arrangement can effectively be considered as an assembly of insulation so as to avoid excessive rise of temperature due to heat penetration from the fire side to the unexposed side provided that the separation and the emissivity of the shutters are adequate.

To evaluate the temperature rise at the unexposed side of the arrangement due to conduction, convection and radiation through the air-cavity formed between the two fire shutters, the computational fluid dynamics (CFD) technique has been employed. This involves the setting up of the essential conservation equations (i.e. Navier-Stokes equations) for the mass, momentum and energy. The radiative transfer is handled by modified discrete ordinates method with participating gas absorption. The equations had been solved with appropriate boundary and initial conditions using the FIRE3D computer software package developed jointly by CSIRO, Australia and Department of Building and Construction, City University of Hong Kong based on Finite Volume Technique. The mathematical formulation and computational results are discussed in next section.

DESCRIPTION OF MATHEMATICAL FORMULATION

The mathematical model for the flame spread consists of the three-dimensional. Favre-averaged equations of transport for mass, momentum and enthalpy. Turbulence is modelled using the two-equation κ-ε model, with the turbulent viscosity given by $\mu_t = c_\mu \rho \kappa^2/\varepsilon$ where ρ is the gas density. The effective viscosity is obtained as the sum of the molecular and turbulent viscosities. In the κ and ε equations, production of turbulence due to buoyancy and the effect of thermal stratification of the turbulence dissipation rate are included by the G terms (the production of turbulence due to buoyancy).

An efficient and accurate method of radiative transfer - the discrete ordinates method - is employed in the present study. The finite volume method is employed to discretise the radiative transfer equation and to ensure positive intensities throughout the solution domain, the positive scheme is applied [3].

For the cavity boundary walls, the no-slip condition on the velocity components has been applied. The temperature at the concrete surfaces was calculated using an energy balance of the incoming and outgoing heat fluxes at the boundaries by assuming adiabatic condition. For the fire shutter surfaces, the net heat fluxes are balanced by the convective and radiative heat gains or losses. The conventional logarithmic wall functions are applied all the solid boundaries for the momentum equation.

The conservation equations were discretised using the finite volume method. Hybrid differencing scheme was employed for the convection terms. The velocity and pressure linkage was achieved by the SIMPLEC algorithm. The discretised equations were solved using the Stone's procedure. However, the Preconditioned Conjugate Gradient method was employed for the pressure correction to accelerate convergence.

The non-uniform Cartesian grid is employed for all simulations with the grid concentrated in the vicinity of the solid boundary walls. A two-dimensional grid consisting of 40 cells across the width and 200 cells along the height, a total of 8000 cells is adopted. Although the FIRE3D is actually fully-featured for 3-D fire and flame spread simulations over a range of solid combustible materials, a 2-D approach is adopted as it is considered that the critical conditions can be ascertained for design purpose.

RESULTS AND DISCUSSIONS

Computations for various combination of the emissivities and width of the gap between the fire shutters had been carried out using the FIRE3D package with the above mentioned parameters. It is found that for all the cases of simulations, the steady states are reached at a time around 1000 seconds which is far less than the stipulated heat isolation time in the BS 476: Part 20. Therefore, in this paper, the steady state results which correspond to the highest temperature rise at the unexposed side are presented, although transient temperature and velocity fields were recorded for monitoring purposes during the processes of the simulations.

Figure 2 shows the temperature distribution at the surface of the fire shutter at the unexposed side with an emissivity of 0.02 and the width of the gap of 200, 276, 350, 400 and 500 mm. The curves indicates that in all cases the temperature increase with the height. This is due to the buoyancy driven re-circulating flows which contribute to the heat transfer across the air-cavity. It is worth to note that the curves for different widths are almost overlapping with one another. It could be inferred that the effects on the temperature rise and hence the heat transfer from the exposed to unexposed side due to the variation of the width are insignificant. Table 1 gives the average and maximum temperature and the rise at the unexposed face. With the increase in width of the gap from 200 to 500 mm, the average temperature increases extremely slowly from 135.42 to 137.56 °C, while the maximum temperature is found to decrease moderately from 220.35 to 194.88 °C. These observations will be explained later with the use of the velocity field plots in Figures 4.

Table 1: The steady-state average and maximum temperature (rise) at the unexposed face for an emissivity of 0.02 at various widths of gap.

Widths of gap, mm (separation)	Unexposed side temperature, °C	
	Average (rise)	Maximum (rise)
200	135.42 (110.42)	220.35 (195.35)
276	135.90 (110.90)	216.32 (191.32)
350	136.36 (111.36)	206.53 (181.53)
400	136.81 (111.81)	201.25 (176.25)
500	137.67 (112.67)	194.88 (169.88)

Figure 3 shows the temperature distribution at the surface of the fire shutter at the unexposed side with various emissivity from 0.02 to 0.2 with the width of the gap of 276 mm. The temperature distribution curve shifts significantly upwards with the increasing emissivity. This indicates that the heat transfer rate is higher for larger emissivity. Also, the radiation heat transfer pays a predominant role in the overall heat transfer from the exposed to unexposed side fire shutters. It is also observed that the curves becomes "flatter" as the emissivity approaches the value of 0.2. This again confirms that in the case with large emissivity the heat transfer are substantially due to the radiation exchange where the convective heat transfer are relatively less insignificant. Table 2 shows the average and maximum temperature and the rise at the unexposed face for these cases. With the increase in emissivity, the average temperature increase substantially from 135.90 to 417.30 °C and the maximum temperature increases from 216.32 to 448.73 °C.

Table 2: The steady-state average and maximum temperature (rise) at the unexposed face for a width of gap of 276 mm with various emissivities.

Emissivity	Unexposed side temperature (rise), °C	
	Average (rise)	Maximum (rise)
0.02	135.90 (110.90)	216.32 (191.32)
0.06	265.13 (240.13)	351.73 (326.73)
0.10	329.88 (304.88)	390.84 (365.84)
0.20	417.30 (392.30)	448.73 (423.73)

Figures 4 shows the plots of the temperature contours and velocity fields for the cases where the emissivity is 0.02.

From the velocity field plots obtained from the simulation, the velocity are found to increase generally with the increase of the widths of the gap between the fire shutters. In other words, the wider is the air-cavity, the faster is the re-circulation flowrate. This is due to the fact that less wall friction are effectively transmitted to the flow field. The increase in re-circulation flowrate results in a slight increase in the convective heat transfer as the cavity becomes wider. Hence, average temperature rise at the unexposed side is found to increase when the width is increased from 200 to 500 mm, as reported in Table 1 above. From the temperature contour plots in Figures 4 to 8, the increase in re-circulation flowrate also leads to stronger shearing of the temperature contours inside the cavity as the its width increases from 200 to 500 mm. This promotes effectively the mixing of the air inside the cavity and thus lowers the maximum temperature rise at the unexposed side as reported in Table 1 above.

From the above observations and discussions, in the design of double fire shutters assembly for the isolation of heat transfer from a fire compartments, the following essential criteria could be inferred:

1) The most prevailing factor governing the heat transfer is the emissivity of the materials used for the fire shutters. The higher the emissivity the larger is the heat transfer and hence the temperature rise at the unexposed side.
2) The increase in width of the gap of the air-cavity seems to play a relatively minor role in the overall heat transfer and temperature rise at the unexposed side.
3) There is a trend of increase in convective and hence the overall heat transfer as well as the average temperature rise at the unexposed side with the increasing width of the gap due to the strengthening of the re-circulation air flow in the cavity. However, such a portion of heat transfer due to the convection is still far less significant in terms of order of magnitude comparing to the radiation heat transfer even at larger widths of the gap.

4) The maximum temperature rise at the unexposed side decreases with the increase in width. This is because the air mixing is more efficient as the width increases.

To satisfy the requirement of heat isolation equivalent to that of BS476: Part 20, the average temperature rise should not exceed 140 °C from the initial temperature within the stipulated fire resisting period, while the maximum temperature rise must be below 180 °C. From the results presented above, this can only be achieved by having the double fire shutters assembly with an emissivity of less than 0.02. From Table 1, the reasonable range of width satisfying the criteria is 400 to 500 mm which gives an average and maximum temperature rise at the unexposed side of 111.81 to 112.67 °C and 176.25 to 169.88 °C respectively. The practical width will depend on the installation details as well as the thickness of the compartment wall.

CONCLUDING REMARKS

The fire engineering study by using CFD techniques have demonstrated that the design of a double fire shutters system for the isolation of heat transfer from fire compartment can be satisfactory. The most predominant factor affecting the heat isolation is the emissivity which is affected by the selection of materials for the fire shutters and their surface finishes. The overall heat transfer and temperature rise at the unexposed side are found notably increased with the increase in the emissivity. However, the width of the gap of the air-cavity between the double fire shutters plays an insignificant role, if any, to the overall heat transfer and temperature at the unexposed side. A clear yet moderate trend of increase of the temperature rise has been observed with the increase in the width of the gap. In conclusion, to isolate efficiently the heat transfer from fire compartment to an acceptable level, it is inevitable that the fire shutters used should be made of highly polished metallic sheet such as stainless steel with mirror-type surface finish. However, this could mean very special manufacturing processes and workmanship resulting in very substantial increase in materials and manufacturing costs for adopting such a design.

Further exploration could be made to look for employment of water spraying actuated automatically by smoke detectors. This may open up the possibility of designing double fire shutters assembly incorporating water spraying to serve the same heat isolation objectives where the ordinary mild sheet fire shutters can be used at a relatively much lower material and manufacturing cost.

REFERENCES

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2. The Approved Document B, Building Regulations, Department of the Environment, HMSO, United Kingdom, 1992.
3. T. K. Kim and H. Lee : Effect of Anisotropic Scaterring on Radiative heat Transfer in Two-Dimensional Rectangular Enclosure. International Journal of Heat and Mass Transfer, Vol. 31. (1988), pp. 1711-1721.

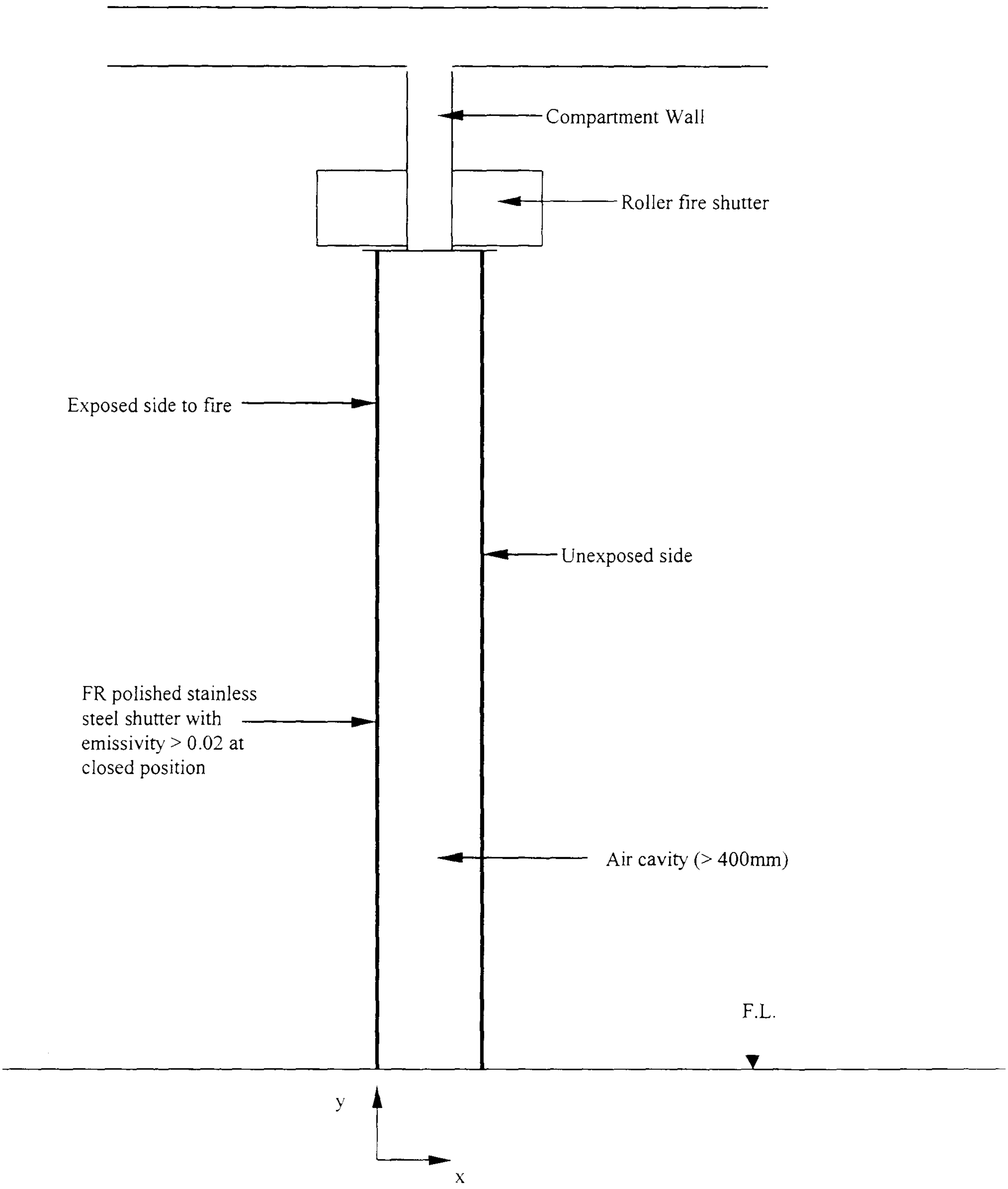

Figure 1. Schematic diagram of the double fire shutter assembly

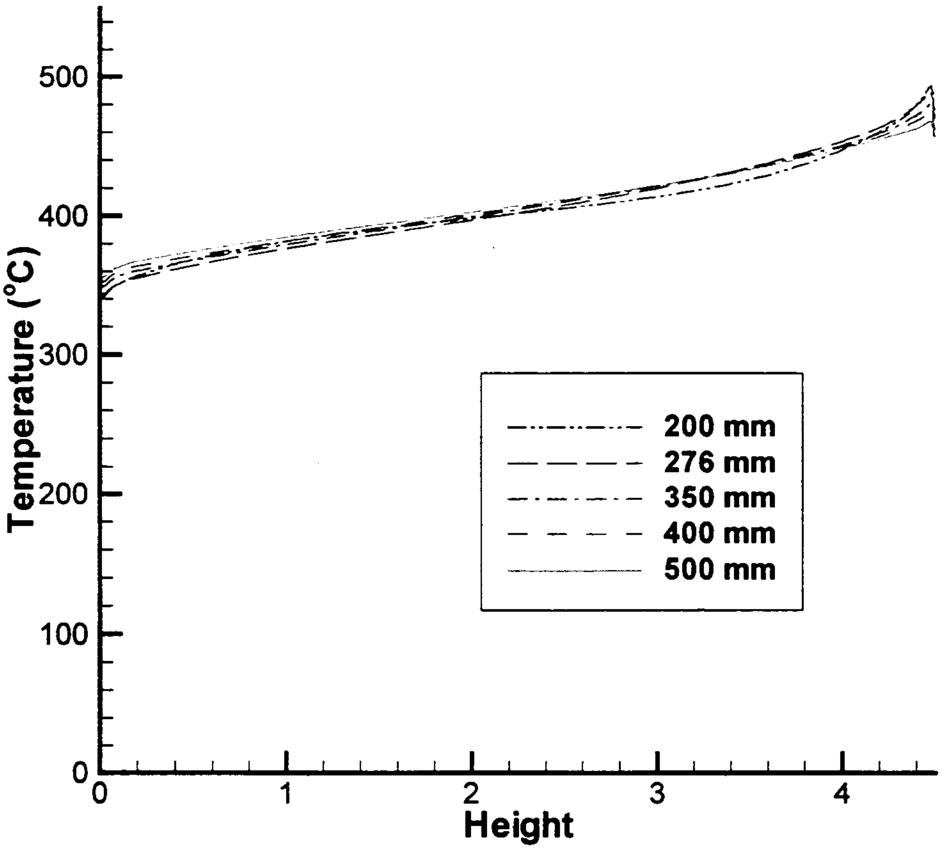

Figure 2. Steady-state temperature distribution on the fire shutter at the unexposed side with an emissivity of 0.02 and the air-cavity widths of 200, 276, 350, 400 and 500 mm.

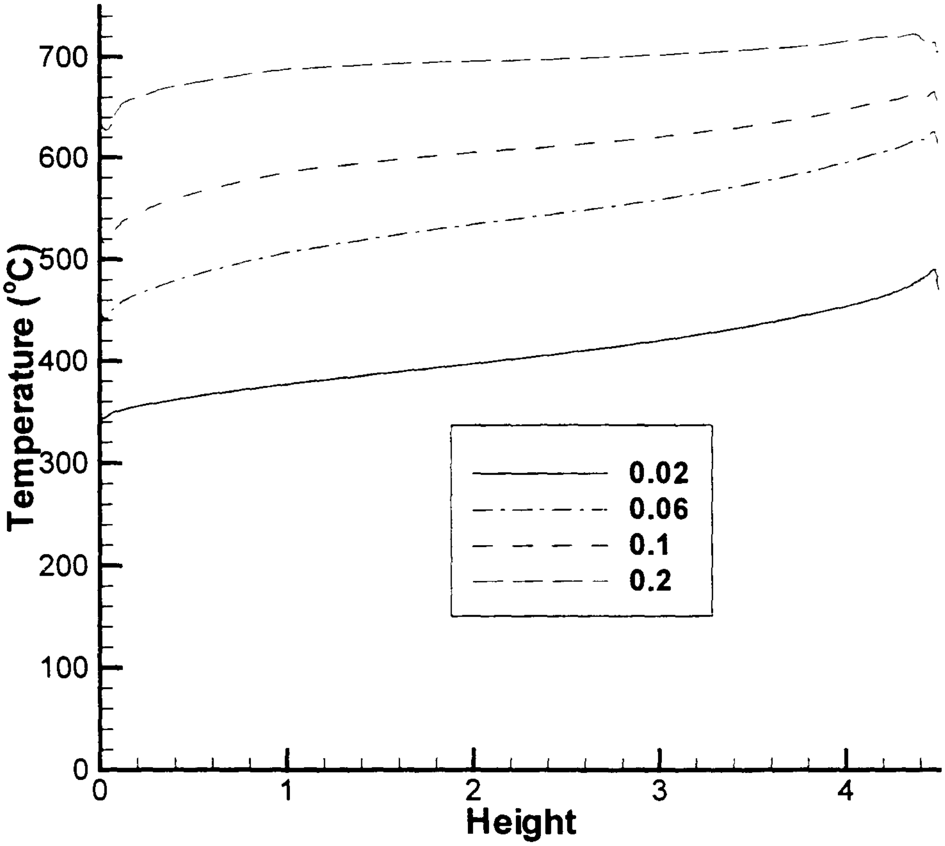

Figure 3. Steady-state temperature distribution on the fire shutter at the unexposed side for the width of gap of the air-cavity of 276 mm and emissivity of 0.02, 0.06, 0.1 and 0.2.

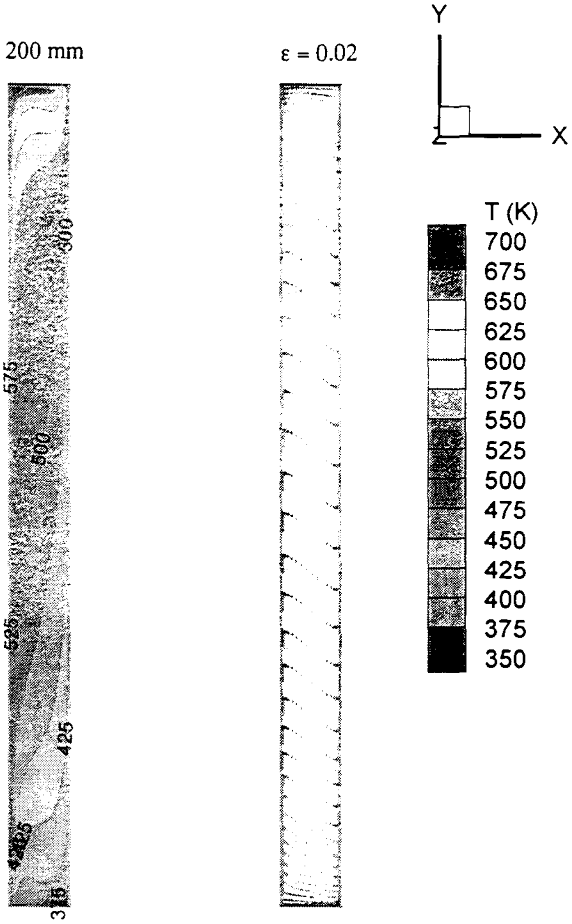

Figure 4. Steady-state temperature contours and velocity field in the air-cavity with a width of 200 mm and emissivity of 0.02 (field plots for other widths not provided).