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Estimation of Optimal Water Flow Rate of a Steel Roller Shutter with Water Film Cooling System

Lee S. K.[1, a], Lo W. H. [2,b], Ho M. C. [3,c] and Lin T. H.[2,d]

[1]Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan, 701, Taiwan

[2] Department of Mechanical engineering, National Cheng Kung University, Tainan, 701,Taiwan

[3] Architecture and Building Research Institute Ministry Interior, Taiwan, New Taipei City, 231, Taiwan

[a] sklee1015@gmail.com, [b] qp702@yahoo.com.tw, [c] ho@abri.gov.tw, [d] thlin@mail.ncku.edu.tw

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Abstract. The hybrid inverse method to estimate the optimal water flow rate and surface temperature on the hot surface of the steel roller shutter with water film cooling system subjected to a fire environment is presented in this paper. The results show that the effect of the down-flowing water film flow rate on the present estimates cannot be negligible. The water-film system combined with the steel roller shutter can effectively improve the heat resistance and the temperature of the shutter slat surface can be controlled to around 100 °C. The optimal water flow rate is 110 L/min for a typical 3m x 3m steel roller shutter with water film cooling system.

Introduction

Buildings with ever increasing floor areas are being constructed. If the building floor area is over 1500 m^2, in accordance with the Building Technical Rules of Taiwan [1], the building should be separated into isolated fire compartments by fireproof walls, doors, or windows that have a fire resistance rating of at least one hour. However, solid walls are often undesirable. In order to maintain the original function of buildings, many designers prefer fireproof roller shutters to fixed walls. Fireproof roller shutters prevent fire or smoke from propagating to neighboring areas.

However, most fireproof roller shutters are made of steel, which provides flame resistance (integrity rating) rather than heat resistance (insulation rating). Although a fireproof roller shutter can prevent the spread of fire, it can heat up to high temperatures and produce a great amount of thermal radiation, which may ignite nearby combustibles due to prolonged heating in a later stage of a fire. For fireproof roller shutters to become true fire-protection equipment, their heat resistance capability must be improved. Commonly used heat resistance techniques for fireproof roller shutters on the market can be divided into three types, namely (1) the coating of heat-resistant paint on the shutter slats, (2) the usage of shutter curtains which are made of multi-layer non-combustible fiber cloth, and (3) the application of a water cooling system (such as water mist or film) to the fireproof roller shutter . The cost of a fireproof roller shutter with a coating of heat-resistant paint is five times higher than that of a roller shutter with a 60B rating, which means a 60-minute fire integrity rating without heat resistance. The average strength of shutter curtains is below that of steel shutter slats.

Wu and Lin [3] conducted a series of experimental studies to investigate the heat resistance and fire protection of a glass pane by utilizing a downward-flowing water film. Wu and Lin [3] examined the fire insulation and fire integrity properties of glass panes covered with a down-flowing water film in a standard full-scale 3 m × 3 m door/wall refractory furnace, based on ISO 834-1. Wu et al. [4]designed a small-scale experimental apparatus to investigate the effect of a water spray on the heat-resistance property of a glass pane. Their experimental results showed that the period of fire insulation and fire integrity for a non-heat-resistant fireproof glass and a common tempered glass can be extended from 6 minutes to 100 minutes and that the surface temperature of the glass panes can be kept to below 210 °C with a water film of adequate thickness (~1.5 mm) and flow speed (~0.7 m/s).

These results proved the feasibility of replacing a fireproof glass by common tempered glass with a water film. Although the characteristics of a water film on a roller shutter are different from those on a glass pane, the experimental and design experience of the glass pane with a water film can be transferred to a roller shutter with a water film because the basic mechanism of heat removal is the same. Lee et al. [5] futher conducted the full-scale fire evaluations with a large-scale door/wall refractory furnace to investigate the fire protection performance of a non-heat-resistant fireproof steel roller shutter with a water film cooling system. There are two methods in the water film design, one is formed on “unexposed surface” and another is formed on “exposed surface” of the shutter slat. The main findings in their work indicated that the water-film system combined with the steel roller shutter can effectively improve the heat resistance and the temperature of the shutter slat surface can be controlled to around 100 °C. It not only fulfills to resist the intensive radiation in a fire but also extends the heat resistance period beyond 120 minutes. Furthermore, no matter which side of the roller shutter is exposed to fire, a good fire resistance rating can be achieved by the proposed water film system in their study

However, above literatures focused primarily on measuring the temperature on the unexposed surface of the glass or steel roller shutter to evaluate the performance of the glazing or steel roller door system with water film. The present study applies the hybrid inverse scheme of the Laplace transform and finite-difference methods in conjunction with the sequential-in-time procedure, least-squares methods and experimental temperature data given by Lee et al. [5] to estimate the surface heat flux and optimal water flow rate on the hot surface of the steel roller shutter with the down-flowing water film in a fire room.

Mathematical Formulation

The IHCP investigated in this study is to estimate the surface heat flux on the fire-exposed side of the steel roller shutter with the down-flowing water film exposed to a fire environment. The schematic of water film system is shown in Fig. 1. Fig. 2 shows the heat transfer mechanism on the steel roller shutter with the down-flowing water film exposed to a fire environment. L_x and L_y respectively denote the length and width of the steel roller shutter. The boundaries of the steel roller shutter are thermally insulated at y = 0 and y = L_y. The initial temperature of the steel roller shutter is T_{in}. The steel roller shutter was exposed to the high and low temperature environments. The experimental data of the absorption of incident solar radiation at y = 0 were not measured by Lee et al. [5]. Lee et al. [5]only measured the surface temperatures on the cold surface of the steel roller shutter, the higher ambient temperature $T_{h\infty}$ and the lower ambient temperature T_∞. Under the condition of the constant thermal properties, the governing differential equation of the two-dimensional transient heat conduction problem in the steel roller shutter can be expressed as [6]

$$\rho c \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad \text{in } 0 < x < L_x,\ 0 < y < L_y \text{ and } t > 0 \tag{1}$$

with boundary conditions

$$-k\frac{\partial T}{\partial x} = h(y,t)(T - T_{h\infty}) \quad \text{at } x = 0 \tag{2}$$

$$-k\frac{\partial T}{\partial x} = h_c(y,t)(T_c - T_\infty) + \sigma\varepsilon(T_c^4 - T_\infty^4) \quad \text{at } x = L_x \tag{3}$$

$$\frac{\partial T}{\partial y} = 0 \quad \text{at } y = 0 \text{ and } y = L_y \tag{4}$$

and the initial condition

$$T = T_{in} \quad \text{for } t = 0 \tag{5}$$

where T is the shutter temperature. x and y are the spatial coordinates. t is the time. k and ρc respectively denotes the thermal conductivity and heat capacity per unit volume of the steel roller shutter. σ and ε are Stefan-Boltzmann constant and the emissivity of the glass, respectively. h(y, t) denotes the unknown overall time- and space-dependent heat transfer coefficient and can be estimated using the additional information of the transient temperature measurements at several selected measurement locations in the steel roller shutter or other approximate conditions.The present study applies the experimental measured temperature data at several selected measurement locations on the cold surface of the steel roller shutter $T_c(y,t)$ given by Lee et al. [5] to estimate h(y, t). Later, the temperature distribution $T_c(y,t_s)$ at a specific time t_s can be obtained from a curve-fitted profile.

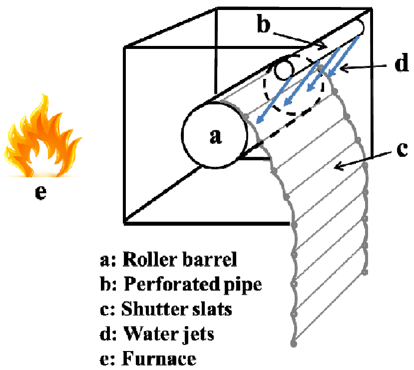


Fig. 1 Schematic of water film system

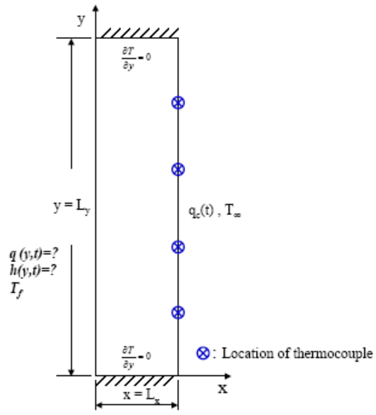


Fig.2 Schematic geometry of the present problem

The natural-convection heat transfer coefficient on the cold surface of the steel roller shutter $h_c(y,t)$ can be obtained from $Nu_y = 0.103 Ra_y^{1/4}$.

For convenience of the present hybrid inverse scheme, the Newton's law of cooling is introduced into the present study. Thus, Eq. (2) is written as

$$-k\frac{\partial T}{\partial x} = q_h(y,t) \qquad \text{at } x = 0 \tag{6}$$

where the unknown surface heat flux $q_h(y,t)$ is defined as $h(y,t)[T(0,y,t)-T_{h\infty}]$. On the other hand, this unknown surface heat flux $q_h(y,t)$ on the hot surface of the steel roller shutter with the down-flowing water film can be regarded as the sum of the absorptive and direct evaporative heat fluxes, convective heat flux and radiative heat flux. Thus, h(y, t) can be regarded as the convection and radiation heat transfer coefficients and that due to mass transfer. h(y, t) was not predicted in the works of Lee et al. [5].

Due to the introduction of the surface heat flux on the cold surface of the steel roller shutter $q_c(y,t)$, the boundary condition (3) can be written as

$$-k\frac{\partial T}{\partial x} = q_c(y,t) \qquad \text{at } x = L_x \tag{7}$$

where $q_c(y,t)$ is defined as $q_c(y,t) = h_c(y,t)(T_c - T_\infty) + \sigma\varepsilon(T_c^4 - T_\infty^4)$ and is a given function of y and t.

Numerical analysis

In order to remove the time-dependent terms from the governing differential and boundary conditions, the method of the Laplace transform is employed. Then the discretized forms of G.E. using the central-difference approximation can be arranged to yield the following matrix equation

$$[A][\tilde{T}] = [F] \tag{8}$$

where [A] is a coefficient matrix, $[\tilde{T}]$ is a matrix representing the nodal temperatures in the s domain and [F] is a matrix representing the forcing term. The Gaussian elimination algorithm and the numerical inversion of the Laplace transform are applied to solve Eq. (8) in order to determine the temperature distribution in the steel roller shutter at a specific time.

Once the unknown surface heat flux $q_h(y,t_s)$ at a specific time t_s can be determined, the overall heat-transfer coefficient $h(y,t_s)$ can also be obtained from the Newton's law of cooling. However, it can be difficult to obtain an approximate function that can completely fit the distribution of the unknown surface heat flux $q_h(y,t)$ at a specific time. Under this circumstance, $q_h(y,t)$ can be approximated using a cubic polynomial function at a specific time. Thus $q_h(y,t)$ can be assumed to be a cubic polynomial function in space and a linear function in time during a specific time interval. On the other hand, the surface heat flux $q_h(y,t)$ can be expressed as

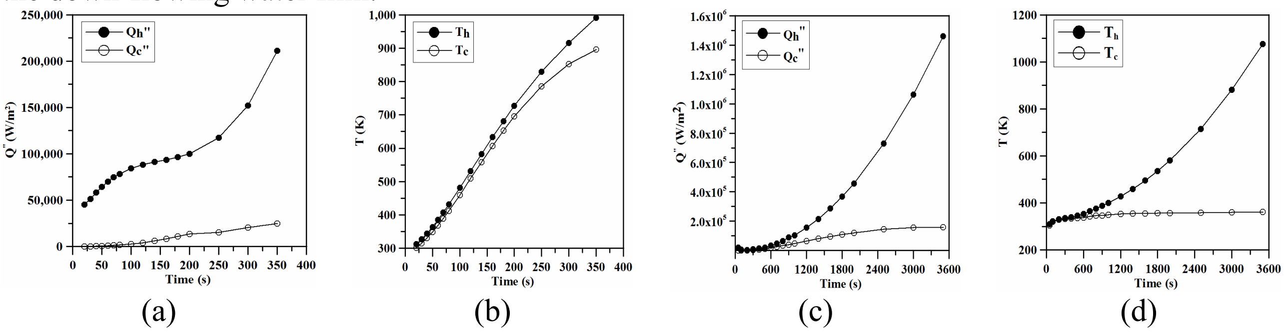
$$q_h(y,t) = \sum_{j=1}^{4}(C_{2j-1} + C_{2j}t)y^{j-1} \quad \text{for } t_s \le t \le t_s + \Delta t \tag{9}$$

where C_j are the unknown coefficients and can be determined using the least-squares method in conjunction with experimental measured temperatures. Δt denotes the measured time-step.

The least-squares minimization technique is applied to minimize the sum of the squares of the deviations between the calculated and experimental measured temperatures at several selected measurement locations and two specific times t_s and $t_s + \Delta t$. In order to avoid repetition, the computational procedures for determining the unknown coefficient C_j are not shown in this paper. Its detailed computational procedures can be found in Ref. [6]. Finally, the above numerical procedures are repeated until the values of residualsat any specific time are all less than 10^{-6} through all the inverse calculations.

Results and discussion

It can be observed from Fig. 3 that the steel roller shutter without the water film is destroyed about at 350 second due to the flame impingement on the steel roller shutter. The results shows that the temperature for the fire test without a water film reached about 900 °C, which is well over 210 °C, the highest regulated temperature in CNS 14803. On the other hand, the effect of the water film along the hot surface of the steel roller shutter on the histories of its surface temperatures is shown in Figs. 3(c) and 3(d). The steel roller shutter with the water film can endure such a high temperature environment until the test is finished. It can also be found from Fig. 3 that the heat on the hot surface of the steel roller shutter can be taken away rapidly through heat transfer and evaporation of the water film. Thus the average heat flux on the fire-exposed surface of the steel roller shutter without down-flowing water film can be several times than that with the down-flowing water film. This result displays that the existence of the water film on the fire-exposed surface of the steel roller shutter has a significant effect on the total incident heat flux of the steel roller shutter. It is also found that the average temperature on the cold surface of the steel roller shutter with and without the down-flowing water films also increase from 300 K to 370K for 0 s ≤ t ≤ 3600 s and from 370 K to 900 K for 50 s ≤ t ≤ 350 s, respectively. It is obvious that the difference between the average temperature on the hot and cold surface of the steel roller shutter with the down-flowing water film is much higher than that without the down-flowing water film.



(a) (b) (c) (d)

Fig.3 History of the temperature on the hot surface of the steel door without or with the water film

Table 1 shows some estimated temperature on hot surface of the glass pane or the steel roller shutter with the down-flowing water film by using hybrid inverse method with experimental data given by Wu et al. [4] and Lee et al. [5]. The predicted results shows that the temperature for the unexposed surface fire test with a water film for 110 L/min reached about 210 °C. Therefore, the optimal water flow rate is designed as 110 L/min in order to extend the heat resistant period to at least

120 minutes. The temperature of the exterior shutter slat surface was held under 210 °C in a 120-minute fire test.

Table 1 Estimation of averaged temperature on hot surface of the glass pane and steel roller shutter

Type of speciman	Size (m×m)	Water flow rate (L/min)	Position of water film	Hot surface temperature at 1hour	Hot surface temperature at 2 hour
steel roller shutter	3×3	111	Unexposed surface	187℃	193℃
steel roller shutter	3×3	120	exposed surface	98℃	100℃
glass pane	1.2×1	52.2	exposed surface	185℃	-
glass pane	1.2×1	59.4	exposed surface	121℃	-

Conclusions

The present study proposes a hybrid inverse method with experimental temperature data on the cold surface of the steel roller shutter to determine the unknown total incident heat flux and surface temperature on the hot surface of the steel roller shutter subjected to a fire environment. The results show that the effect of the water flow rate on the total incident heat flux and heat-transfer coefficient is of importance. If the down-flowing water film can uniformly cover on the hot surface of the steel roller shutter with an appropriate thickness, it can effectively absorb the high heat rate and resist the radiation of the fire. Consequently, the optimal water flow rate can be estimated by the hybrid inverse method.

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