J. APPLIED FIRE SCIENCE, Vol. 11(2) 195-208, 2003

SAFETY CONSIDERATION OF FIRE SHUTTERS IN LARGE BUILDING SPACE

L. T. WONG
The Hong Kong Polytechnic University

W. W. YUEN
University of California at Santa Barbara

ABSTRACT

The effectiveness of fire shutters as a component in the fire safety design of a large building is examined from the perspective of a "minimum escaped velocity (MEV)" by the occupant in order not to experience pain from the exposure to the shutter's thermal radiation. Using typical fire shutter's geometry determined from a survey of 14 large shopping malls in Hong Kong and the shutter's temperature reported in the literature, the range of MEV and its dependence on shutter's parameters are determined. Shutter's geometry and the occupant's initial location relative to the shutter are shown to be important factors affecting the required MEV for safety. For a particular compartment's geometry, a "safe escape (SE)" region can be identified as a function of the fire shutter size, escape door's location, and the expected walking speed of an occupant. The size of the SE region can be used as a quantitative design criterion for the design of a fire safety system involving the fire shutter.

INTRODUCTION

The size of modern buildings is increasing rapidly to satisfy the urban growth and population demands. From the perspective of fire safety, buildings are often required to be divided into smaller compartments to inhibit the spread of fire. Openings between compartments are generally needed as a provision to maintain good communication between different spaces in a building [1, 2]. Too many openings, however, can potentially increase the possibility of fire spread. The development of an appropriate design which can provide a balance between fire safety and efficient communication is an importance aspect in the design of modern large buildings.

One approach to provide this balance is to connect the different compartments of a large building with a lobby equipped with a fire shutter. A lobby with sufficient openings connected to the different compartments would meet the need for communication. As part of a fire safety design, a fire shutter can be installed such that it closes off the access to some compartments when a fire occurs. To be effective, a fire shutter must resist the passage of flame and smoke up to an acceptable standard [3]. For example, for a given fire resisting period (FPR), the fire shutter needs to be equivalent to the compartment walls in terms of integrity [1]. The operation of a fire shutter is usually linked to smoke detectors installed adjacent to the openings so that it is activated when significant amounts of smoke is detected. Once the shutter is closed, the effectiveness of smoke sealing capabilities depends on the width of gaps at the shutter. According to the UK standard (which is also utilized in Hong Kong), the smoke checking property of the shutters would be acceptable if the leakage rate does not exceed 3 $m^3m^{-1}hr^{-1}$ [4].

Another design issue related to the fire shutter is how much it can retard the radiant heat transmission. Since the maximum temperature of the unexposed surface of fire shutters depends upon the thermal conductivity of the constitutive materials, tests were conducted to determine the radiative heat transfer from typical fire shutters currently used by the building industries in Hong Kong. Temperature-time curves used for testing these fire shutters showed that the shutter would be subject to a temperature of over 1000°C (1273 K) after 2 hours of test [5-7]. The unexposed surface of a fire shutter specimen would be heated up to 650°C when exposed to the standard temperature-time curve for 30 minutes [8]. The high surface temperature of the unexposed side of the fire shutter can cause fire spread by radiant heat transfer. A safe storage distance from a fire shutter is therefore proposed in the current code of practice [6].

Since the escape path provided by normal openings in a building might be blocked by the activation of a fire shutter, an escape door in an area near the fire shutter is generally included as part of the building design. Indeed, a survey of 47 fire shutter installations in 14 local shopping malls showed that the arrangement of escape doors adjacent to a fire shutter is a common practice [9]. The presence of the escape door is clearly an important component for fire safety, particularly in buildings with a high occupant load such as high-rise office buildings, shopping malls, and public transportation centers, in which a longer evacuation time might be required [10-12]. The determination of a "safe" distance between the fire shutter and escape door, however, has not been considered carefully in the existing design considerations [7-9].

The objective of the present work is to provide a quantitative approach in the determination of a "safe" distance between the fire shutter and the escape door.

While an evacuee can experience some psychological effects of a heated fire shutter in a fire environment (and thus affect his/her decision in choosing an appropriate escape route [10-13]), the possible thermal injury to the skin due to the thermal radiant heat flux is still the primary concern in assessing the safety of an occupant during evacuation [14]. The possible skin damage to a person exposed to the thermal radiation from a heated fire shutter surface during evacuation is thus used as a basis to evaluate the relative safety of the different designs. Specifically, the present work proposes a concept of "minimum escape velocity, MEV." For a compartment with a specific design of fire shutter and escape door, the occupant's MEV is estimated based on first principle and the available data on the critical heat flux which will lead to pain and damage to the human skin. Assuming a typical walking speed for the occupant, a "safe escape (SE)" region is determined for a given compartment's geometry and fire shutter/escape door arrangement. Numerical data for a rectangular compartment are generated to demonstrate the effect of the escape door location on the SE region. These data can serve as effective tools for the fire shutter design.

MATHEMATICAL FORMULATION

Human skin of a person near a fire shutter would experience a net heat gain by thermal radiation if the mean shutter surface temperature T_s (K) is higher than the skin temperature T_b (K). The thermal radiant heat flux q_R ($\mathrm{kWm^{-2}}$) upon exposed human skin is given by [15],

$$q_R = \sigma A_s \zeta T_s^4 \qquad (1)$$

where σ is the Stefan-Boltzmann constant ($5.6696 \times 10^{-8}\ \mathrm{Wm^{-2}K^{-1}}$) and ζ is a dimensionless factor given by [15],

$$\zeta = \left[\left(\frac{1}{\varepsilon_s} - 1\right) + \frac{1}{F_{sb}} + \frac{A_s}{A_b}\left(\frac{1}{\varepsilon_b} - 1\right)\right]^{-1} \qquad (2)$$

A_s ($\mathrm{m^2}$) and A_b ($\mathrm{m^2}$) are the surface area of the fire shutter and human body. The shutter surface area is determined by the height H_s (m) and width W_s (m) of the fire shutter:

$$A_s = W_s \times H_s \qquad (3)$$

Since skin temperature (typical value is about 35°C) is generally much lower than the temperature of the fire shutter, the radiative heat loss from the skin surface is neglected in Eq. (1) [16].

In Equation (2), A_b ($\mathrm{m^2}$) is the effective skin surface area of a human exposed to the radiation of the fire shutter and F_{sb} is the configuration factor between a person and the fire shutter. In general, A_b and F_{sb} depend on many factors such as the size and weight of the individual, the direction he/she faces, whether he/she is standing, sitting, or lying, the disposition of his/her arms and legs, and his/her distance from the fire shutter. Detailed experiments have been conducted to determine the relation between A_b, F_{sb}, and these parameters for actual humans [17]. An empirical expression was proposed to approximate a standing person as an equivalent sphere with a radius given by

$$R_b^2 = \frac{H_b w^{1/3}}{7.21} R^2 \tag{4}$$

where H_b is height (m) and w is weight (kg) of the individual. R is the radius (m) of a standard subject "Mark I" who was 1.73 m tall and weighted 72.7 kg and it is correlated by the data to be

$$R = 3.66\,[0.65 + \cos\alpha\,(7.15 + 0.52\,|\cos\varphi|)] \tag{5}$$

with α being the vertical angle from horizontal to an emitting point on the fire shutter and φ the azimuthal angle between the person's face and the emitting point. For the present work, the equivalent radius of the standard object ($H_b = 1.73$ m and $w = 72.7$ kg) with an orientation of $\alpha = \varphi = 0$ is utilized. Effect of the variation of α and φ will be evaluated in future works.

Based on the equivalent sphere approximation, the view factor F_{sb} is given by [18, 19]:

$$F_{sb} = F_{bs}\frac{A_b}{A_s} \tag{6}$$

with F_{bs} being the view factor from the equivalent sphere to the fire shutter. For the basic geometry as shown in Figure 1, the view factor between a sphere and a rectangle is given by [20]:

$$F_{12} = \frac{1}{4\pi}\tan^{-1}\left(\frac{1}{D_1^2 + D_2^2 + D_1^2 D_2^2}\right)^{\frac{1}{2}} \tag{7}$$

with $D_1 = d/l_1$ and $D_2 = d/l_2$. The view factor F_{sb} for an equivalent sphere and a fire shutter with arbitrary geometry can be readily generated from Equation (7) by superposition.

ε_s and ε_b are emissivity of the shutter surface and human body respectively. The emissivity of human skin ε_b in the long infrared range would be generally of the order of 0.9 to 0.95 based on studies on occupational hot exposure [15]. Total emissivity of the shutter surface ε_s, would depend on the shutter material, surface conditions, and surface temperature [21].

Consider a fire shutter and escape door geometry as shown in Figure 2. For a specific location of a person (x_b, y_b) and the escape door (x_d, y_d) and assuming that during an evacuation, the evacuee will take the shortest route between

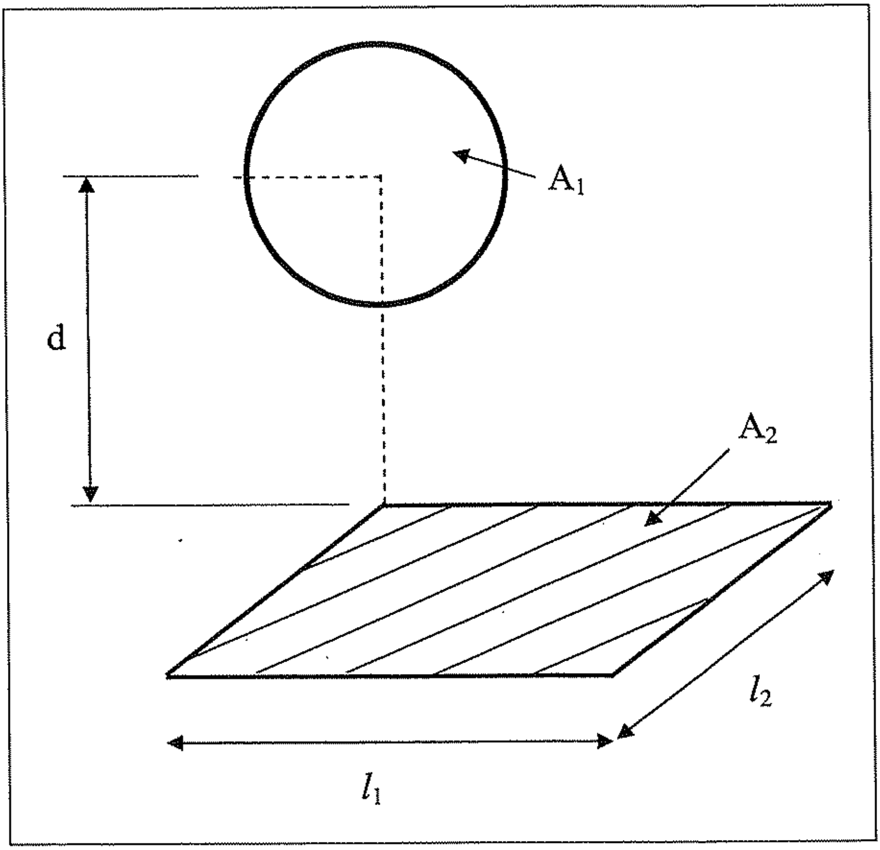

Figure 1. Geometry for the view factor.

his/her initial location and the escape door and walk at a constant speed, the average radiative flux a person is exposed to during the evaluation can be evaluated as

$$q_{R;ave} = \frac{1}{L}\int_{(x_b,\,y_b)}^{(x_d,\,y_d)} q_R \, dl \tag{8}$$

where L (m) is the distance between the person and the escape door given by:

$$L = \sqrt{dx_b^2 + dx_d^2} \tag{9}$$

with dx_b (m) and dy_b (m) being the distance of occupant relative to the center of the escape door in x and y directions as shown in Figure 2,

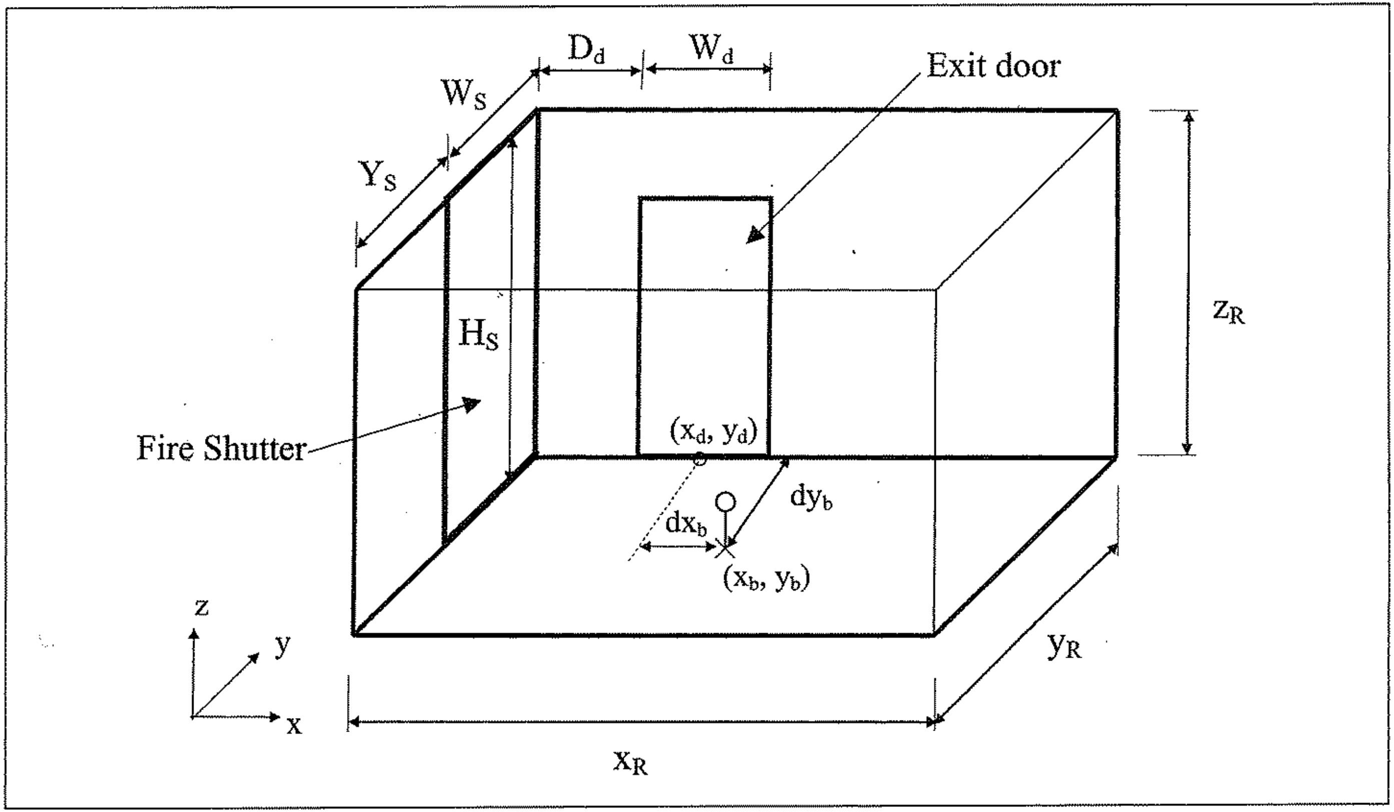

Figure 2. Geometry of the fire shutter installation.

$$dx_b = x_d - x_b \tag{10}$$

$$dy_b = y_d - y_b \tag{11}$$

Apart from the psychological effects, the skin damage to an evacuee caused by the incident thermal radiant heat flux q_R (kWm^{-2}) is the primary safety concern. Skin injury begins when the skin temperature exceeds 44°C [14]. The amount of damage is a function of the skin temperature and the period of time for which the temperature exceeds the limit. Experimentally, it has been determined that below a critical heat flux of 1.7 kWm^{-2}, a person would not experience any pain no matter how long the duration of the exposure. Between 1.7 to 20 kWm^{-2}, the exposure time which will lead to skin pain was determined empirically to be [14]:

$$t_b = \frac{250}{S} q_R^{-1.9} \tag{12}$$

This equation is good for engineering applications and has a safety factor (S) of 2 accounting for human variability [14]. In the present work, the average exposed radiative heat flux, Equation (8), will be used to determine the time of skin pain using Equation (12). Taking the t_b (s) as the available safe egress time for an occupant to leave the space through the escape door, the minimum escape velocity (MEV) V_b (ms^{-1}) of the evacuee to avoid skin pain is given by:

$$V_b = \frac{L}{t_b} \tag{13}$$

For a given compartment geometry, a "safe escape" (SE) region can be determined by identifying area in which MEV is less than the expected average walking speed of evacuees. For simplicity, Equations (12) and (13) are used for all values of q_R. Since low value of q_R (i.e., less than the critical heat flux of 1.7 kWm^{-2} required for experiencing pain) would yield a small MEV, the inclusion of these cases would have no impact in the determination of the SE region.

NUMERICAL EXAMPLES

The geometry and the associated coordinate system for the present study is shown in Figure 2. The room is assumed to be cubical with dimensions x_R, y_R, and z_R. The fire shutter is assumed to be part of the left wall ($x_R = 0$) with dimensions $y_R - y_s$ and z_R. The leading distance, y_s, is used to simulate the possibility that the fire shutter did not extend all the way to the opposite wall. It can also simulate the possibility that a leading section of the fire shutter is designed to be of low emission (due to either low emissivity or low temperature). The escape door is assumed to be at right angle to the fire shutter in the plane $y = y_R$.

A survey of 14 local shopping malls [9] shows that the typical shutter height is in the range from 2.2 to 5.5 m with a large fraction (79%) of which in the range of 2.5 to 3.5 m. The shutter width ranges from 1.6 to 8.6 m. A small fraction (16%) of the surveyed shutter has width less than 2 m while a majority (79%) of the shutter has width ranging from 2 to 8 m. All escape doors are closed to the fire shutter and, in general, is perpendicular to the fire shutter. The separation from the fire shutter, D_d, is less than 1 m for all cases and in about half (45%) of the surveyed cases, D_d is less than 0.2 m.

Based on the surveyed data, the present work generates numerical data for a room with $x_R = 5$ m, $y_R = 9$ m, and $z_R = 3$ m. The shutter is assumed to extend all the way to the top of room and two leading distances ($y_s = 0$ and $y_s = 3$ m) are considered. The width of the escape door is assumed to be 1 m and results for different separation ($D_d = 0, 1, 2, 3, 4$ m) are generated to show the effect of the location of the escape door on MEV and the SE region. In all cases, the fire shutter is assumed to be made of polished steel with an emissivity (ε_s) of 0.36. The temperature of the fire shutter is assumed to be at 900 K.

RESULTS AND DISCUSSIONS

The minimum escape velocities (MEV) for the two cases with different separation of the escape door are shown in Figures 3 and 4. As expected, MEV increases with increasing distance from the escape door and decreasing distance from the fire shutter. Evacuees who are closer to the fire shutter and further from the escape door thus have a higher risk of getting injured. It is interesting to note that for the case of a fire shutter with a "cool" leading edge ($y_s = 3$ m), evacuees who are near the shutter ($dx_d = 1$ m), the MEV for $dy_d = 8$ m (behind the hot section of the fire shutter) is larger than that for evacuees with $dy_d = 6$ m (right at the beginning of the hot section of the fire shutter). Physically, an evacuee is always running away from the fire shutter toward the escape door. The evacuee who starts at a location behind the start of the hot section will experience a lower average radiative heat flux than an evacuee who starts from a position nearer to the hot section. This result suggests an interesting possibility of increasing the safety of evacuees by reducing the radiation from the leading section of the fire shutter (for example, with materials or paint with lower emissivity).

The "Safe Escape" (SE) region for the different D_d and y_s is shown in Figure 5. It is interesting to note the SE region increases with increasing distance between the escape door and the fire shutter. Physically, the larger separation between the escape door and the fire shutter causes the evacuee to run away from the fire shutter, thus reducing the average radiative heat flux received by the evacuee. The design of placing the escape door near the fire shutter, utilized by most facilities in the survey, is thus not optimal from the perspective of safety. The reduction of radiation from the leading edge of the fire shutter also increases the SE region. The reduction is quite significant particular for cases in which the escape door is away from the fire shutter.

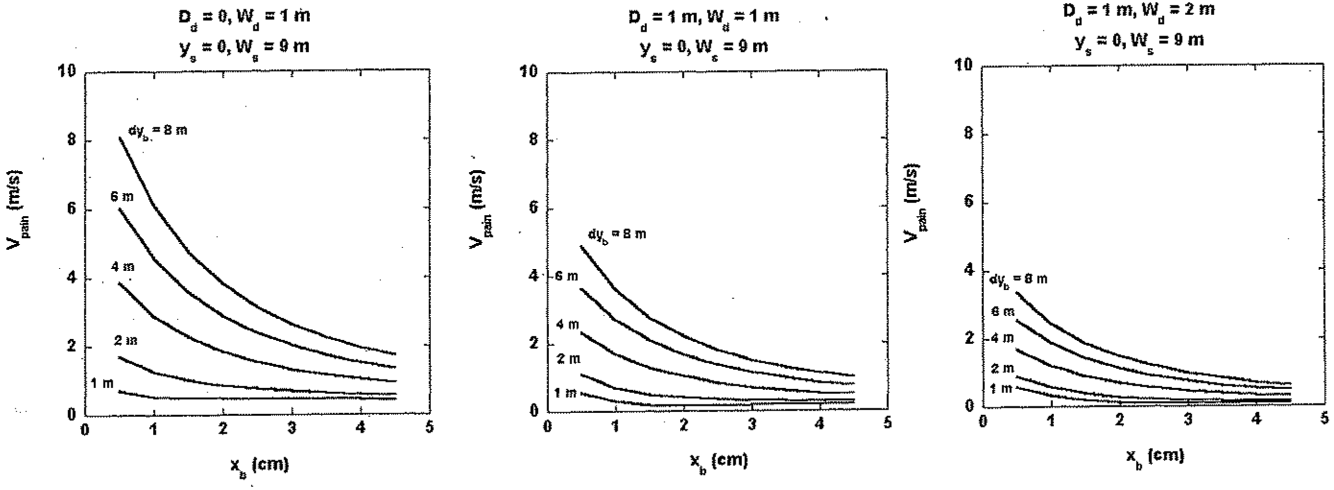

Figure 3. MEV for the case with $y_s = 0$ and various separation distance of the escape door.

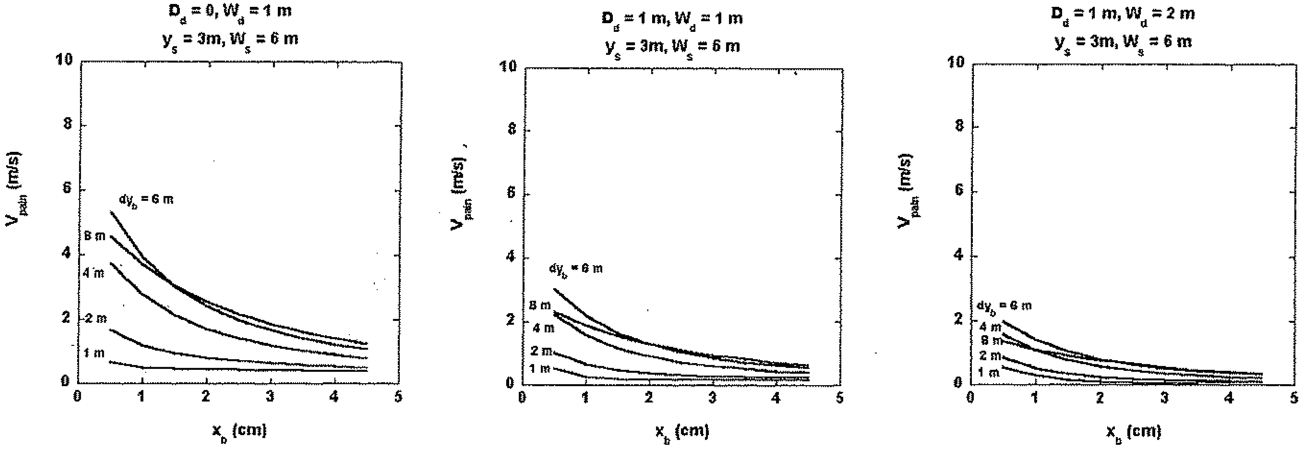

Figure 4. MEV for the case with $y_s = 3$ m and various separation distance of the escape door.

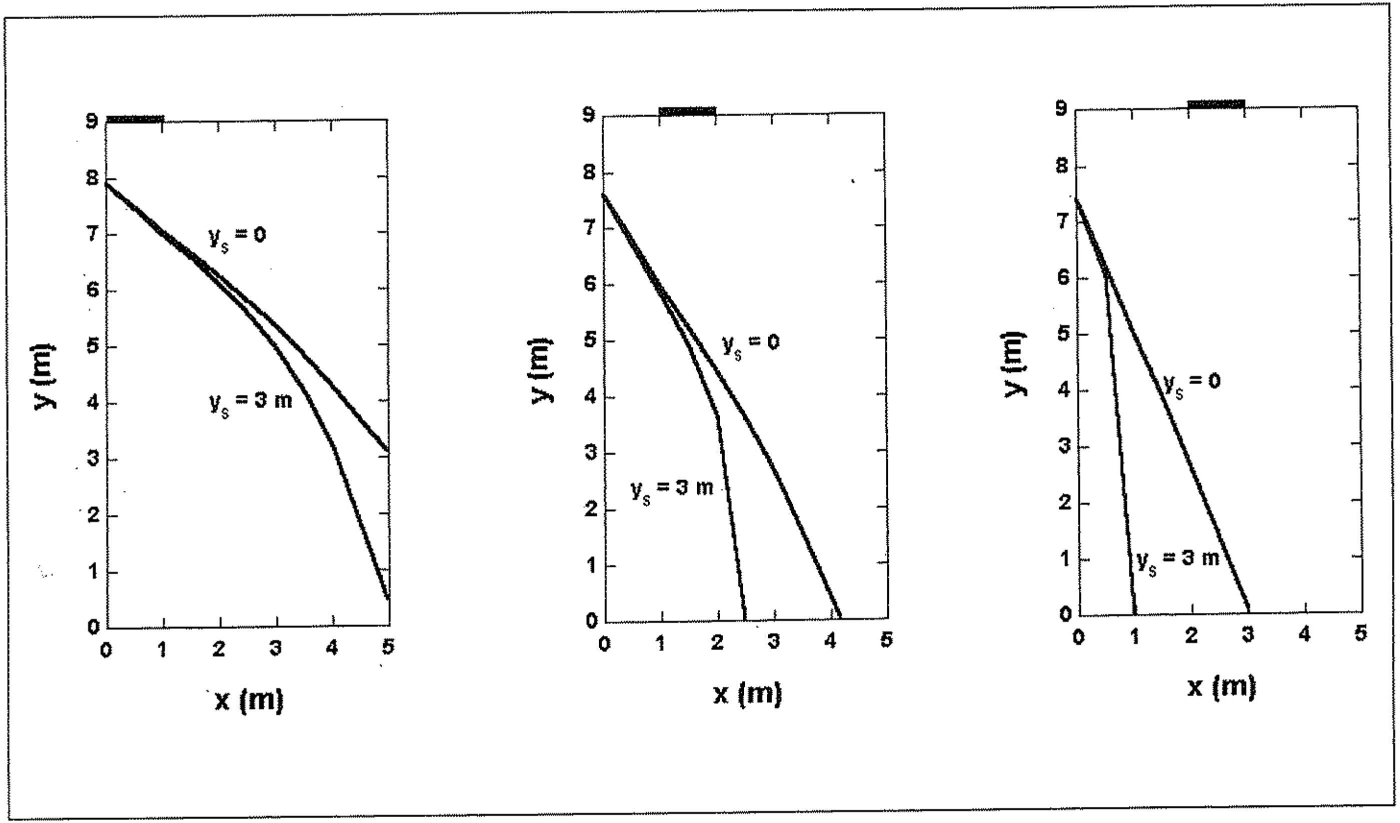

Figure 5. The "Safe Escape" (SE) region (area above the line) for the two considered fire shutter design. The darkened area on top represents the escape door.

CONCLUSION

The fire shutter installation used in Hong Kong shopping malls is generally designed to conform with the statutory requirement of compartmentation in terms of integrity. Until now, fire safety from the perspective of the thermal radiation emitted by the fire shutter and its effect on the evacuee has not been considered. In this work, the exposure to radiant heat from the heated fire shutter to an evacuee running toward an escape door was determined from first principle. An empirical expression for the time of exposure to thermal radiation leading to skin pain is used to determine the minimum escape velocity (MEV) required for an evacuee to avoid skin pain. Using a typical walking speed, a safe escape (SE) region can be identified for a room with a particular fire shutter and escape door design. Numerical data are generated for a room with typical dimensions. Results show that the escape door location relative to the fire shutter has an important effect in reducing the risk of skin pain experienced by evacuees. An unheated section of the fire shutter can also be helpful in reducing the MEV and increasing the size of the SE region.

ACKNOWLEDGMENT

The second author wishes to thank The Hong Kong Polytechnic University for offering the visiting professorship from 2001 to 2003.

LIST OF SYMBOLS

A	Area (m^2)
dx_b, dy_b	Distance between the evacuee and the escape door in the x and y direction as defined in equations (10) and (11)
D_1, D_2	Perpendicular distance between the center of a sphere to an offset rectangle normalized by the length and width (dimensionless)
F	View factor, area basis
H	Height (cm)
L	Distance between the person and the escape door (m)
q_R	Thermal radiant heat flux (kWm^{-2})
R	Equivalent sphere radius for man (cm)
S	Safety factor for the time to pain of human skin in equation (12)
T	Temperature (K)
t_b	Time to skin pain (s)
V_{pain}	Minimum escape velocity (MEV) of the evacuee in order not to experience skin pain (cm s^{-1})
W	Width (cm)
w	Weight of a person (kg)
x, y, z	Coordinates (cm)

ε	Emissivity (dimensionless)
σ	Stefan-Boltzmann constant (5.6696×10^{-8} Wm^{-2} K^{-1})
ζ	A dimensionless factor defined in equation (2)

Subscript

ave	of average value
b	of human body skin
d	of escape door
i	of time interval
s	of fire shutter unexposed surface
1, 2	of conditions 1, 2

REFERENCES

1. Buildings Department, *Code of Practice for Fire Resisting Construction* Building Authority, Hong Kong, 1996.
2. Buildings Department, *Code of Practice the Provision of Means of Escape in Case of Fire* Building Authority, Hong Kong, 1996.
3. British Standard Institution, *BS476 part 22: Methods for Determination of the Fire Resistance of Non-Loadbearing Elements of Construction,* BSI, United Kingdom, 1987.
4. Department of the Environment, *The Approved Document B,* HMSO, United Kingdom, 1992.
5. Z. Ma and P. Makelainen, Parametric Temperature-Time Curves of Medium Compartment Fires for Structural Design, *Fire Safety Journal, 34*:4, pp. 361-375, 2000.
6. Fire Protection Association, *The Design for the Fire Protection of Buildings 2000: A Code of Practice for the Protection of Business,* LPC, London, 1999.
7. R. K. K. Yuen, S. M. Lo, and G. H. Yeoh, Heat Isolation Scenario for a Double Fire Shutter System, *Journal of Applied Fire Science, 7*:2, pp. 129-144, 1997-98.
8. L. T. Wong, Hazard of Thermal Radiation from a Heated Fire Shutter Surface to a Standing Person, *Building Services Engineering Research and Technology, 24:1,* pp. 1-8, 2003.
9. L. T. Wong, *Thermal Hazard of a Fire Shutter in Shopping Malls in Hong Kong,* presented in the International Conference on Advances in Building Technology, Faculty of Construction and Land Use, The Hong Kong, Polytechnic University, Hong Kong, December 4-6, 2002.
10. G. Proulx, Movement of People: The Evacuation Timing, *The SFPE Handbook of Fire Protection Engineering* (3nd Edition), SFPE, Massachusetts, 2002.
11. T. J. Shields and K. E. Boyce, A Study of Evacuation from Large Retail Stores, *Fire Safety Journal, 35*:1, pp. 25-49, 2000.
12. CIBSE, *CIBSE Guide E: Fire Engineering,* London, United Kingdom, 1997.
13. S. C. Tsui and W. K. Chow, Review on the Local Code of Practice for the Provision of Means of Escape, *International Journal on Engineering Performance-Based Fire Codes, 4*:3, pp. 35-50, 2002.

14. C. J Wieczorek and N. A. Dembsey, Human Variability Correction Factors for Use with Simplified Engineering Tools for Predicting Pain and Second Degree Skin Burns, *Journal of Fire Production Engineering, 2*:2, pp. 88-111, 2001.
15. G. H. Galbraith, R. C. McLean, and D. Stewart, Occupational Hot Exposures: A Review of Heat and Mass Transfer Theory, *Journal of Engineering in Medicine, 203*:3, pp. 123-131, 1989.
16. P. F. Millington and R. Wilkinson, *Skin,* Cambridge University Press, New York, 1983.
17. R. V. Dunkle, Configuration Factors for Radiant Heat Transfer Calculations Involving People, *Journal of Heat Transfer, 85*:1, pp. 71-76, 1963.
18. R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer* (4th Edition), Taylor and Francis, New York, 2002.
19. M. F. Modest, *Radiative Heat Transfer,* McGraw-Hill, New York, 1993.
20. J. R. Howell, *A Catalog of Radiation Configuration Factors,* McGraw-Hill, New York, 1983.
21. T. J. Love, *Radiative Heat Transfer,* Charles E. Merrill Publishing Company, Ohio, 1968.

Direct reprint requests to:

L. T. Wong
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China
e-mail: beltw@polyu.edu.hk