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C. L. Chow
University of Cambridge

W. K. Chow
The Hong Kong Polytechnic University

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Fire Safety Concern on Well-sealed Green Buildings with Low OTTVs

Cheuk Lun CHOW¹, Wan Ki CHOW²*

¹Department of Architecture, The Martin Centre for Architectural and Urban Studies, University of Cambridge, UK
(E-mail: nadiaclc@yahoo.com.hk)

²Research Centre for Fire Engineering, Department of Building Services Engineering, Area of Strength: Fire Safety Engineering, The Hong Kong Polytechnic University, Hong Kong, China
(Phone: 852 2766 5843, Fax: 852 2765 7198, E-mail: bewkchow@polyu.edu.hk)

* Corresponding Author

ABSTRACT

The Overall Thermal Transfer Value (OTTV) of building façade is controlled in many big cities in East Asia such as Hong Kong and Singapore for building energy conservation. For example, the OTTV is limited to 20 Wm⁻² in Hong Kong to reduce solar heat gain. Buildings are also sealed up to reduce cooling load of the mechanical heating and cooling systems. Therefore, heat generated in an accidental fire in well-sealed buildings with low OTTVs would be trapped indoor. The time to flashover would then be shortened. In this paper, fire safety of concealed green buildings with low OTTVs will be discussed. A heat balance equation in a compartment fire was set up. Common buildings materials including brick, concrete, gypsum plaster, glass panels, fibre glass composites and timber were then evaluated. Façade materials are proposed to be tested under flashover conditions.

1. INTRODUCTION

Sustainable buildings are the design target all over the world (Chow and Chow, 2003). Constructing energy efficient buildings is a key point in reducing the amount of carbon emission. In places including Singapore, Malaysia and Hong Kong, the heat transferred through the building envelope is controlled by using Overall Thermal Transfer Value (OTTV) (Buildings Department, 1995; Chow and Chow, 2004). OTTV has to be kept at a very low value to reduce solar heat gain through the building envelop. For example, the OTTV is up to 20 kWm⁻² in the suggested guide in Hong Kong. This can be achieved either by reducing the window-to-wall area ratio or by using materials with higher thermal insulation. However, there are potential fire risks in thermally insulated buildings with low OTTV. Providing better thermal insulation of the envelopes with appropriate building materials would reduce the heat lost from the compartment when there is a fire. The heat emitted from a fire is trapped in the compartment, giving higher chance to flashover (Thomas and Bullen, 1979). There were many fires on air-conditioned buses in the Far East cities including Hong Kong and Shanghai (e.g. Chow, 2000; Chow, 2001) reported in the past few years. The bus envelopes were made of good thermal insulation materials such as sandwich panels. Only the engine chassis was left in less than 15 minutes after the ignition. But comparing with the poor thermally insulated metal sheet bus in 1980s, flashover was difficult to onset. The same concern was raised in buildings with better thermal insulation. The associated fire safety aspects for well-lagged buildings with low OTTV thermal insulating materials should be investigated and will be discussed in this paper.
Three parts should be considered in fire hazard assessment for façades with better thermal insulation:

- Estimating the ratio of heat lost through the wall to the heat release rate of a fire.
- Plotting heat lost rate through wall and heat release rate of a fire against gas temperature rise in the compartment (similar to Semenov’s diagram in classical explosion studies) for studying the possibility of transition to flashover.
- Studying the fire growth time for walls of different thermal inertia with empirical relations.

### 2. MATERIALS WITH BETTER THERMAL INSULATION

A heat balance equation (e.g. Chow, 2000; Chow, 2001) in a compartment inside a building can be set up by considering the heat gain due to the fire \( \dot{Q}_f \) (in W); heat lost through the wall \( \dot{Q}_L \) (in W); and the heat carried out of the enclosure by smoke determined by the outflowing rate \( \dot{m}_g \) (in \( \text{kgs}^{-1} \)) in terms of the temperature rise \( \Delta T \) (in °C) in the compartment and the specific heat capacity \( C_p \) of air (say of value 1100 Jkg\(^{-1}\)K\(^{-1}\)):

\[
\dot{m}_g \cdot C_p \cdot \Delta T = \dot{Q}_f - \dot{Q}_L \tag{1}
\]

\( \dot{Q}_L \) includes the heat transfer through the wall surfaces and then lost to outside. This term is roughly proportional to \( \Delta T \) and can be expressed in terms of the heat transfer coefficient \( h_w \) (in Wm\(^{-2}\)K\(^{-1}\)) at exposure time \( t \) which depends on the thermal conductivity \( k_w \) (in Wm\(^{-1}\)K\(^{-1}\)), density \( \rho_w \) (in kgm\(^{-3}\)), specific heat capacity \( C_w \) (in Jkg\(^{-1}\)K\(^{-1}\)), surface area \( A_w \) (in m\(^2\)) and thickness \( d_w \) (in m) of the compartment walls:

\[
\dot{Q}_L = h_w \cdot A_w \cdot \Delta T \tag{2}
\]

and \( h_w \) is:

\[
h_w = C_1 \cdot \text{Max} \left\{ \left( \frac{k_w \rho_w C_w}{t} \right)^{0.5}, \frac{k_w}{d_w} \right\} \tag{3}
\]

Note that \( k_w \rho_w C_w \) is also known as the thermal inertia of the materials \( I_w \) (in (Wm\(^{-2}\)K\(^{-1}\))^2s\(^{-1}\)). The time to ignition of materials depends on \( I_w \). Value of \( C_1 \) becomes a constant and was measured by Deal and Beyler (1990) to be 0.4 for compartment fires when the exposure time becomes longer than the thermal penetration time \( t_p \) (in s):

\[
t_p = \left( \frac{\rho_w C_w}{k_w} \right) \left( \frac{d_w}{2} \right)^2 \tag{4}
\]

The outflowing rate of smoke \( \dot{m}_g \) is the sum of the inflow rate of air and the burning rate of the fuel. For a near flashover or post-flashover fire in a room with small openings and burning rate appeared to be stoichiometric, the mass flow rate of air entrainment was analyzed by Kawagoe (1958) to be proportional to the ventilation factor \( A_o \sqrt{H_o} \) of the opening, with \( A_o \) (in m\(^2\)) and \( H_o \) (in m) being the area and height respectively of the opening. This was further discussed by Chow (2009) on studying thermal induced air flow through doorways with Computational Fluid Dynamics.

For a ventilation-controlled fire, the burning rate of the fuel, though much smaller than the mass flow rate of air entrainment, depends also on the ventilation factor. All these suggested that \( \dot{m}_g \) (in \( \text{kgs}^{-1} \)) is related to the ventilation factor (e.g. Chow, 2009; Babrauskas, 1980) as:
The heat lost through the envelope $Q_L$ is given by equation (2), and the ratio $\gamma$ of heat lost through the compartment wall to the heat flowing out with hot gas is:

$$\gamma = \frac{h_w A_w}{0.5 C_p A_o \sqrt{H_o}}$$  \hspace{1cm} (6)

The percentage $\beta$ of heat lost through wall with respect to the rate of heat generated by the fire is then given by the following expression from equation (1):

$$\beta = \frac{Q_L}{Q_f} = \frac{\gamma}{1 + \gamma}$$  \hspace{1cm} (7)

3. ONSETTING FLASHOVER

To study the effect of wall materials on the possibility of having flashover, heat lost through walls is being assessed. A typical building of 10 m long, 6 m wide and 3 m high with an open window of width 3 m and height 1 m is considered and, giving $A_w$ of 96 m$^2$ and $A_o \sqrt{H_o}$ of 3 m$^{5/2}$. Key thermal data on materials including brick, concrete, gypsum plaster, glass panels, fibre glass composites, and timber tested in a project funded on studying double-deck bust fires (Chow, 2000; Chow, 2001) are useful in studying onsetting flashover in a building fire. Values of $t_p$, $\gamma$ and $\beta$ were calculated for wall thickness $d_w$ varying from 1 cm to 15 cm. Results were reported (Chow, 2000; Chow, 2001; Chow and Chow, 2004) together with physical properties $\rho_w$, $C_w$ and $k_w$.

Variation of $\gamma$ and $\beta$ against $h_w$ are plotted in Figures 1 and 2. In view of equation (7), $\gamma$ is proportional to $h_w$. Materials with higher $h_w$ would give higher ratio of heat lost through wall, reducing the heat left to raise the air temperature.

As reported before (Chow, 2000; Chow, 2001), $\beta$ for poor thermal insulation such as steel sheet would have high value of 1. The heat lost rate through wall is much bigger and so it takes a longer time to heat up the compartment air. Materials with good thermal insulation such as fibre glass composites and timber would have very low heat lost through wall, having $\beta$ less than 0.2. Therefore, there will be a higher chance to have flashover as the indoor air will be heated up.

The wall thickness $d_w$ would play a significant role in thermal insulation. In view of equation (3) on $h_w$ and values on computed $\beta$ and $\gamma$, $h_w$ reduced as $d_w$ increased. It takes a much longer time for heat to conduct through the wall and then be lost by convection and radiation in the exterior side. Taking concrete as an example, values of $t_p$ increased from 0.5 min to 105.5 min by increasing $d_w$ from 1 cm to 15 cm, $h_w$ decreased from 64 Wm$^{-2}$K$^{-1}$ to 4.3 Wm$^{-2}$K$^{-1}$, reducing $\beta$ from 0.79 to 0.20. Thicker materials would have lower heat loss rates, so easier to get flashover. However, the effect of thickness would not be significant when the material is thicker than a certain value as pointed out by Thomas (1979).
Thermal insulation fibre glass materials for energy conservation of thickness 15 cm to 1 cm would have small $\beta$ from 0.01 to 0.08. The heat generated from a fire in a room made of those materials would be trapped, giving shorter time to flashover. Further, the organic bonding materials are easily ignited if fire retardants are not provided. But under high radiation heat fluxes in a big fire, those materials will also be ignited even if they are treated with fire retardants.

Quasi-steady states can be found when $Q_r$ is the same as $Q_L$. Plotting these two terms against $\Delta T$ would give curves similar to Semenov’s diagram in classical thermal explosion theory for determining the criteria for flashover.
Rate of heat lost curves for $Q_L$ expressed in terms of $h_w$, $A_w$ and $\Delta T$ are plotted against the temperature rise $\Delta T$ in Figure 3 for concrete and glass panels. The two-layer zone model HotLayer in FIREWIND 3.3 (1998) was applied to calculate steady value of $\Delta T$ which corresponds to constant $Q_T$. In this way, a curve $Q_T$ can be plotted against $\Delta T$. Note that the minimum heat release rate for flashover is 2.8 MW in this building with the specified ventilation condition.

For thermal insulating materials like concrete or glass panels, wall thickness is important in affecting heat flow through the wall. Glass panel of 4 cm thick would have greater heat lost than the heat generated in a fire as shown in Figure 3. Concrete wall of 4 cm thick might give $Q_L$ less than $Q_T$ for $\Delta T$ up to 1850°C, but for those glass panels of 2 cm thick, $Q_L$ is less than $Q_T$ for $\Delta T$ from 150°C to 1250°C. If $\Delta T$ is slightly below 150°C due to an accidental fire, it is likely to have transition to flashover under some thermal perturbation.

4. THERMAL INERTIA

It was further proposed by Thomas (e.g. Thomas, 1979; Thomas and Bullen, 1979) that the growth time $t_g$ (in s) of a compartment fire for an exponential rise in burning rate depends on $I_w$ as:

$$t_g = A_T + B_T I_w^n$$

In the above equation, $n$ is an exponent of value less than 0.5; $A_T$ and $B_T$ depend on the fire details.

Values of the first term $A_T$ in equation (8) might be much greater than the second term $B_T I_w^n$ (Thomas, 1979) for a fast growing fire. Value of $A_T$ under a slow growing fire might be about 20 $B_T I_w^n$, effect of wall materials on the fire growth is not significant. But when $A_T$ and $B_T I_w^n$ are of similar magnitude, the result will be very different.

Assuming $A_T$ is roughly similar to $B_T$, $t_g$ (expressed in arbitrary unit) is plotted against $I_w$ in Figure 4. The wall materials are also labeled to illustrate the relative values of $t_g$. Note that much longer time to flashover under an accidental fire would be resulted for materials with high values of $I_w$.
5. CONCLUSION

As discussed in the literature, environmental control system in new architectural features for green or sustainable buildings should be operated with less energy (e.g. Cole, 1999) in order to give a healthy environment. The use of good thermal insulation materials for building envelopes might give a higher chance of transition to flashover as pointed out in above.

Using poor thermally insulated materials would give higher heat lost, hence increasing the cooling or heating load of the heating, ventilation and air-conditioning system. New architectural features such as double-skin façade (Chow and Hung, 2006) might give a lower heat lost rate. However, as discussed above, it is much easier to onset flashover for buildings with good thermally insulated façade. Heat generated in a fire would be trapped to give rapid rise of room air temperature. It appears that poor thermally insulated materials like glass with higher heat lost might be safer in a fire. The chance of having flashover is then reduced. Unfortunately, glass panels itself will be cracked at a certain temperature (Skelly et al., 1991), normally around 200°C. Large glass sheets in a big room fire would even fall down. More air will be entrained to burn the high amount of combustibles stored to give a very big fire. Therefore, studying the response of glass façade under a big fire is essential. The related study is in progress and will be reported later.

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