Flashover Fires in Small Residential Units with an Open Kitchen

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ABSTRACT

The open kitchen design in small residential units where fire load density and occupant load are very high introduces additional fire risk. One big concern is that whether flash-over can occur which may trigger a big post flashover fire, resulting in severe casualties and big property damage. It is important to understand and predict the critical conditions for flashover in this kind of units. Based on a two-layer zone model, the probability of flashover is investigated by a nonlinear dynamical model. The temperature of the smoke layer is taken as the only state variable and the evolution equation is developed in the form of a simplified energy balance equation for the hot smoke layer. Flashover is considered to occur at bifurcation points. Then the influence of the floor dimensions and the radiation feedback coefficient on flashover conditions is examined. When the dimensions of the floor vary, the resulting changes in internal surface area or size of floor area both have effect on the flashover conditions. When the radiation feedback coefficient is of small value, there is no possibility of flashover. With the increase of the radiation feedback coefficient, at first it significantly affects the conditions for flashover and then moderately when it reaches a larger value. It is proved that the flashover phenomenon can be demonstrated well by nonlinear dynamical system and it helps to understand the effect of various control parameters.

NOMENCLATURE

c_p specific heat at constant pressure (J/kg.K)
C_d flow coefficient
g acceleration due to gravity (m/s^2)
G_E heat gain rate of the hot smoke layer (W)
h_c convective heat transfer coefficient (W/m^{2}K)
H height of the apartment (m)
H_{com} heat of combustion (J/kg)
H_d height of the opening (m)
H_{vap} heat of evaporation (J/kg)
L length of the apartment (m)
L_E heat loss rate of the hot smoke layer (W)

$\dot{m}_a$ mass inflow rate of ambient air (kg/s)
$\dot{m}_{out}$ mass flow rate of hot smoke out of the opening (kg/s)
$\dot{Q}$ heat release rate of the fire (W)
$\dot{Q}_0$ free burning heat release rate (W)
r stoichiometric ratio
$\dot{R}_{in}$ incident radiant heat from smoke layer to fire base (W)
t time(s)
T temperature of the hot smoke layer (K)
T_{equ} equilibrium temperature (K)
T_0 ambient temperature (K)
T_w temperature of the wall surface contact with the hot smoke (K)
U_c wall temperature parameter
W width of the apartment (m)
W_d width of the opening (m)
Z smoke layer interface height above the floor (m)
z_N neutral plane height (m)

Greek symbols

χ combustion efficiency
χ_R radiation factor
μ radiation feedback coefficient
ρ_0 density of the ambient air (kg/m^3)
λ eigenvalue
σ Stefan-Boltzmann constant (W/m^{2}K^4)

INTRODUCTION

Due to limited land resources, more and more high-rise residential buildings have sprung up, especially in densely populated areas (Chow 2005). Over the years, due to the unique challenges in fire safety, high-rise buildings have attracted people's attention. There are various fire hazards in these tall residential buildings. With the adoption of some design features, like green building (Chow 2003) and open kitchen (Chow 2011a), new fire risks may be posed. Open kitchen design has been adopted for many small units with floor area less than 30 m^2 in tall residential buildings in places like Hong Kong (Chow 2011a, 2011b). This is because open kitchen design in small residential units can give a better space utilization.

Kitchen is an area with special fire hazards. Traditionally, it is required to be enclosed by fire resisting construction. According to the NFPA home fire report (Ahrens 2013), cooking equipment was the leading causes for home fire and injuries. It was also reported that only a small percentage of them (less than 5%) extended beyond the kitchen, but these "escaping" fire accounted for a large proportion of the deaths and damages. Fire load density in some residential buildings was reported to be extremely high, more than 1400 MJm^{-2} (Arup Hong Kong 2010). If fires originating from the open kitchen find their way to other parts of the unit a big fire will be resulted. Once flashover occurs, with the aid of wind effect, the fire may spread to the upper floors or even the adjacent buildings, making the fire damage more catastrophic. Therefore, flashover must be investigated in such types of units and precautions must be provided to prevent it from happening.

Flashover is often defined as a very rapid and sudden transition from a growing fire to a fully developed fire (Karlsson and Quintiere 2000). Because it has contributed a lot to many disastrous fires (Rasbash 1991), numerous researches have been conducted to understand and predict this dangerous phenomenon, experimentally or numerically. Thermal instability is considered to be one of the mechanisms of flashover (Thomas et al. 1980). During the process of a compartment fire, heat radiation from hot smoke and heated surfaces intensifies the burning rate of the fuel causing more energy to be released. Consequently, the smoke layer temperature becomes higher and then energy feedback is also augmented. A positive feedback loop is formed. There may be a moment that a relatively small, localized fire suddenly jumps to a big ventilation controlled fire with all the exposed combustible surfaces involved in the fire. This jump is called flashover. Therefore, flashover is considered as a nonlinear dynamical process and nonlinear dynamical theory has been applied to study flashover (Beard et al. 1992). Different dynamical models have been suggested (Beard et al. 1992, 1994; Bishop et al. 1993; Graham et al. 1995; Liang et al., 2002, 2013; Novozhilov 2010; Liu and Chow 2014). These models are based on a zone model (one-zone or two-zone) with an energy balance equation set for the hot smoke layer. The number of system state variables ranges from one to three. Assumptions and simplification are made to obtain algebraic solutions. Critical conditions for flashover derived from most of the models are based on the analysis of heat gain rate and loss rate for the smoke layer. Ignition of virgin fuels is considered as alternative critical condition for flashover in a conjugate thermal model proposed which depends on the thermal and physical property of the fuel (Novozhilov 2010).

Compared with numerical or experimental study, nonlinear dynamical models can offer a better and simple way to understand flashover. In a compartment fire system, the onset of flashover is affected by various parameters. The effect of heat release rate has been described in detail previously (Liu and Chow 2014). The effect of dimensions of the apartment and radiation feedback on the critical condition of flashover is examined here.

THE ROOM FIRE MODEL

Flashover in an example apartment with an open kitchen was examined by nonlinear dynamics. The example apartment as shown in Figure 1 has a length of L, width of W and height of H. A single rectangular vent of width W_d and height H_d is located at the center of one wall. A fire source is centered at the floor level. The process of the apartment fire is considered as a dynamical system. The state of the system is controlled by a set of parameters. Based on a two-layer zone model, the evolution equation is developed for the upper hot smoke layer. Temperature is often used to describe the development process of a compartment fire and it is an important indicator of the advent of an untenable condition. Therefore, temperature of the smoke layer T is chosen as the single state variable. Parameters such as heat release rate, dimensions of the enclosure, geometry of the opening, and height of the smoke layer serve as control parameters. When change is made to one or more control parameters, the system state responds accordingly and normally a small perturbation only causes a relatively slight variation in the state of the system. Notably, the system can experience violent change with its structure becoming qualitatively different at critical parameter values. These qualitative changes in system state are called bifurcations (Thompson and Stewart 2002). A local bifurcation occurs when parameter changes cause an equilibrium point to lose its stability. The local stability of an equilibrium point can be determined by its eigenvalues of the constant Jacobian matrix. If all eigenvalues are negative, the equilibrium point is stable. Conversely, it is unstable. When the eigenvalue is equal to zero, bifurcation occurs. In this application, when bifurcation occurs, the system jumps from the current equilibrium state to a new remote one and flashover is deemed to happen. More information about nonlinear dynamical theory can be found in references, such as Thompson and Stewart (2002).

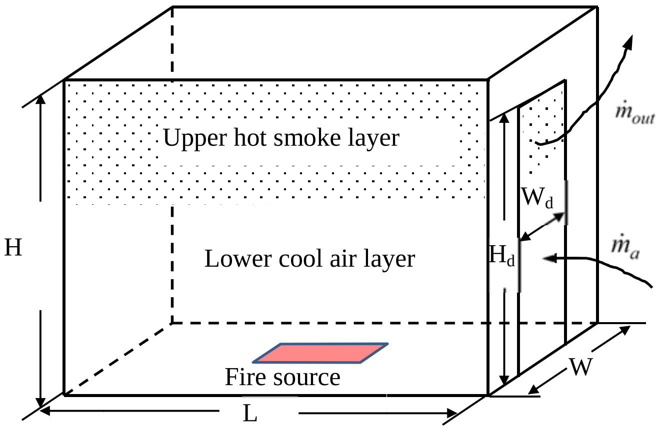


Figure 1. Schematic of the example apartment

Some assumptions are made in this nonlinear dynamical model as listed below:

- The density of the smoke layer is assumed to be constant, i.e. a value of ambient density ρ_0.
- The temperature of the lower air layer and its bounding surfaces are assumed to be kept at the initial temperature T_0.
- The fire source temperature is assumed to be the ambient value T_0 and its emissivity is taken to be 1.
- Before flashover, the fire is assumed to be quasi-steady and the height of the smoke layer interface is constant and kept at 0.5 H (Thomas et al. 1980).

- The height of the neutral plane coincides with the height of the smoke layer interface.
- In ventilation-controlled stage, the air entering into the apartment is assumed to be completely consumed.
- The surface of the wall is assumed to be black body and the emissivity of the smoke layer is assumed to be 1.

The evolution equation for this fire dynamical system is developed based on the energy conservation for the upper hot smoke layer. It takes a similar form as described in (Bishop et al. 1993; Graham et al. 1995; Liang et al., 2002, 2013; Novozhilov 2010; Liu and Chow 2014).

$$m \cdot c_p \cdot \frac{dT}{dt} = G_E - L_E \tag{1}$$

The left hand side of Equation (1) is the energy change rate of the smoke layer. m is the mass of the smoke layer; c_p is the specific heat capacity (at constant pressure); T is the average temperature of the hot smoke layer and t is time. On the right hand side, G_E and L_E are net heat gain rate and net loss rate of the hot smoke layer respectively. Both are functions of smoke layer temperature. Since time is not explicitly included in the right side of the equation, this fire compartment dynamical system is a continuous autonomous system.

$$G_E = (1 - \chi_R) \cdot \dot{Q} \tag{2}$$

The heat gain rate of the smoke layer G_E is determined by the fraction of the heat release rate of the fire $\dot{Q}$ that goes into the upper smoke layer. Part of the energy released by a fire is emitted by radiation and does not enter the smoke layer. In real fire plumes, for many common fuels, the radiant part χ_R typically accounts for 20 to 40% of the total energy released (Karlsson and Quintiere 2000).

The calculation of heat release rate is based on the availability of air supply. There are two cases: fuel-controlled fire and ventilation-controlled fire. For a fuel-controlled fire, there is enough air for combustion and the heat release rate depends on the mass of combustible gas released:

$$\dot{Q} = \dot{Q}_0 + \chi \cdot \dot{m}_f \cdot H_{com} \tag{3}$$

For a ventilation-controlled fire, excess of fuel is released and the heat release rate depends on the mass flow rate of air into the compartment:

$$\dot{Q} = \chi \cdot \frac{\dot{m}_a}{r} \cdot H_{com} \tag{4}$$

Where $\dot{Q}_0$ is the free burning heat release rate of the fire, without feedback from enclosure and smoke layer; χ is the efficiency of the combustion ; $\dot{m}_f$ is the additional rate of fuel burned due to thermal feedback from the enclosure and hot smoke; H_{com} is the heat of combustion of the fuel, $\dot{m}_a$ is the mass flow rate of ambient air into the compartment; r is the stoichiometric air to fuel mass ratio. $\dot{m}_f$ can be determined through the net incident radiant heat on the fuel surface $\dot{R}_{in}$ and the heat of evaporation or gasification of the fuel H_{vap}.

$$\dot{m}_f = \frac{\dot{R}_{in}}{H_{vap}} \tag{5}$$

In a compartment fire, the hot smoke layer and heated boundary surfaces radiate heat back to the fuel surfaces, which accelerate the gasification rate of the fuel. This radiant feedback has been recognized as playing an important role in the onset of flashover (Yuen and Chow 2004). It is affected by both the emissivity and temperature of the smoke layer and the wall surfaces, and their view factors to the fuel surface. In this model, calculation is based on a considerably simplified formulation.

$$\dot{R}_{in} = \mu \cdot \sigma \cdot (T^4 - T_0^4) L \cdot W \tag{6}$$

Where $L \cdot W$ is the area of the smoke interface; σ is the Stefan-Boltzmann constant; μ is the radiant feedback coefficient; and T_0 is the ambient temperature.

In a ventilation-controlled fire, the gas temperature is most often very high and the smoke gas is roughly mixed evenly. A simplified expression can be used to obtain the mass flow rate of air into the compartment through openings (Karlsson and Quintiere 2000):

$$\dot{m}_a = 0.5 \cdot W_d \cdot H_d^{1.5} \tag{7}$$

Where W_d and H_d are the width and height of the opening respectively. The product of W_d and $H_d^{1.5}$ is the well-known ventilation factor.

The total energy lost from the hot smoke layer L_E is caused by mass flow through the opening, conduction loss to the compartment boundary and radiation loss to the opening.

$$\begin{aligned} L_E = {} & \sigma(T^4 - T_0^4)[LW + W_d (H_d - Z)] \\ & + \sigma(T^4 - T_w^4)[LW + (2L + 2W)(H - Z) - (H_d - Z)W_d] \\ & + h_c (T - T_w)[LW + (2L + 2W)(H - Z) - (H_d - Z)W_d] \\ & + \mathrm{c}_p \dot{m}_{out} (T - T_0) \end{aligned}$$

(8)

Here, T_w is the surface temperature of the upper parts of the walls bounding the hot smoke gas; Z is the height of the smoke layer interface from the floor level; and h_c is a convective heat transfer coefficient. In Equation (8), there are four items on the right hand side. The first item is the radiative heat loss from the smoke layer to the lower part of the compartment and vent; the second item and the third item are the radiative and convective heat loss to ceilings and the upper part of the walls, respectively; the forth item is the enthalpy flowing out through the vent.

For simplicity, the surface temperature of the heated walls T_w is approximated as a fraction of the smoke layer temperature (Bishop et al. 1993):

$$T_w = U_c(T - T_0) + T_0 \quad (9)$$

Where U_c is a wall temperature parameter ranging from 0 to 1, which depends on the thermal inertia properties of wall materials.

In compartment fires, the hot smoke flows out through the portion of openings above the neutral plane and fresh air enters the compartment from below. The outflow driven by buoyancy through the vent can be estimated (Rockett 1976):

$$\dot{m}_{out} = \frac{2}{3} C_d \cdot \rho_0 \cdot W_d \cdot H_d^{\frac{3}{2}} \sqrt{2 \cdot g(1 - \frac{Z_N}{H_d}) \frac{T_0}{T}(1 - \frac{T_0}{T})}(1 - \frac{Z_N}{H_d}) \quad (10)$$

C_d is the flow coefficient; Z_N denotes the height of neutral plane from floor; g is the acceleration due to gravity; Z is the height of smoke layer interface from floor. For simplicity, Z_N was assumed to be coincided with Z, then Equation (10) can be rewritten as

$$\dot{m}_{out} = \frac{2}{3} C_d \cdot \rho_0 \cdot W_d \cdot (H_d - Z)^{\frac{3}{2}} \sqrt{2 \cdot g \frac{T_0}{T}(1 - \frac{T_0}{T})} \quad (11)$$

According to the dynamical theory, the critical conditions for flashover are:

$$\frac{dT}{dt} = 0 \quad (12)$$

$$\lambda = \frac{\partial}{\partial T}\frac{dT}{dt}\bigg|_{T=T_{equ}} = 0 \tag{13}$$

T_{equ} represents the equilibrium points of the system and λ denotes the eigenvalues.

Based on the model developed above, the effect of varying floor dimensions and different radiation feedback coefficient on the critical condition for flashover was examined.

The selected values of control parameters and constants used are listed below. Referring to DiNenno (2008), the combustion heat of food oils are about 40 MJ/kg, so a value of 42 MJ/kg is given to H_{com}, but the vaporization heat for miscellaneous materials is difficult to determine. Some of the values in Table 1 refer to (Quintiere et al. 1979).

Table 1. Selected values for parameters

Parameters	Values	Parameters	Values
σ	$5.67{\cdot}10^{-8}$ $Wm^{-2}K^{-4}$	r	30
c_p	1003.2 J/kg K	T_0	300K
C_d	0.7	U_c	0.7
g	9.81 m s^{-2}	W_d	1 m
h_c	7 W m^{-2} K^{-1}W/m^2K	Z	1.5 m
H	3 m	χ	1
H_{com}	$4.2{\cdot}10^7$ J /kg	χ_R	1/3
H_{vap}	$1.008{\cdot}10^6$J/kg	ρ_0	1.18 kg·m^{-3}

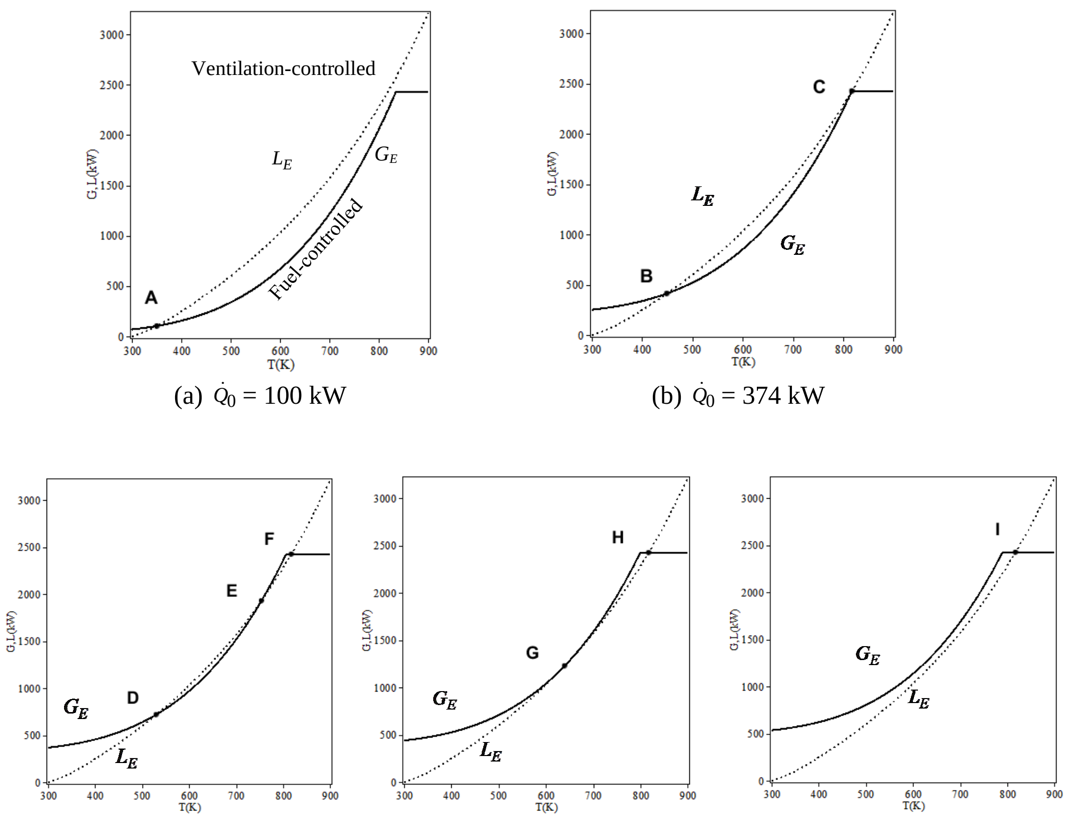
EFFECT OF THE APARTMENT GEOMETRY

Many of the small units with open kitchens are less than 30 m^2 in area in tall residential buildings in Southeast Asia including Hong Kong (DiNenno 2008). Units with floor dimensions of 6 m × 3.5 m, 7 m × 3 m, 5 m × 6 m, 5 m × 5 m, 7.5 m × 4 m are chosen to study the effect of floor dimensions on the critical condition for flashover. In these scenarios, the radiation feedback coefficient μ keeps a constant value of 0.15 and the other parameters are set as listed in Table 1.

First, the critical condition for flashover in an apartment with a floor area of 6 m × 3.5 m was examined. The curves of energy gain rate G_E and energy loss rate L_E were plotted respectively as a function of temperature under different $\dot{Q}_0$ value to find their intersections (equilibrium points), as shown in Figure 2. The G_E curves consist of a fuel-controlled stage and a ventilation-controlled stage. The heat release rate in the latter stage is constant and thus corresponds to a horizontal line. Figure 2 shows there may be one, two or three possible intersections of the G_E and L_E curves. From a temperature perturbation analysis, it is easy to find that equilibrium points A, B and D are stable, which can be also seen from Figure 3. When a fire progresses to equilibrium points like A, B or D, the temperature of the smoke layer will stabilize at a relatively low temperature.

The equilibrium state at points C, E and G are unstable. At point C (ventilation-controlled equilibrium point), if there is a small decrease in temperature, the fire would drop sharply to point B and stabilize there. The more dangerous situation is point G which we have interest in. If there is a small increase in temperature at point G, the fire will jump rapidly from an equilibrium state to a new stable state.

Figure 3 demonstrates how a bifurcation occurs in the fire system. From Figure 4, it can be observed that the corresponding eigenvalues of branch ABDG are negative, so they are stable. Branch GEC are unstable because their eigenvalues are positive. Point G is the critical point whose eigenvalue is zero.



(a) $\dot{Q}_0$ = 100 kW (b) $\dot{Q}_0$ = 374 kW

(c) $\dot{Q}_0$ = 550 kW (d) $\dot{Q}_0$ = 656 kW (e) $\dot{Q}_0$ = 800 kW

Figure 2. Curves of heat gain and loss rate for the smoke layer

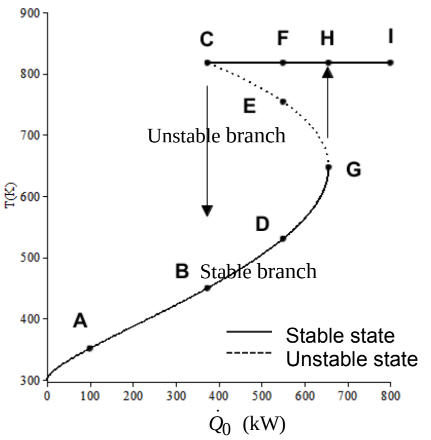


Figure 3. Schematic of bifurcation

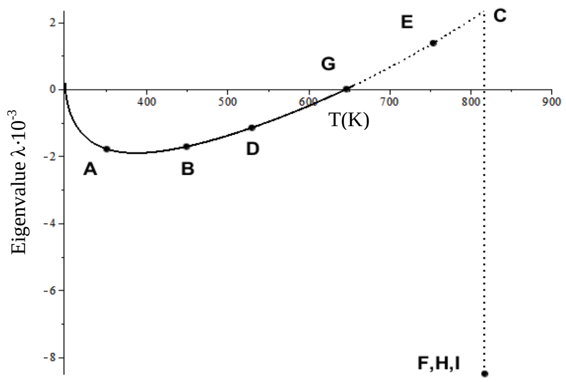


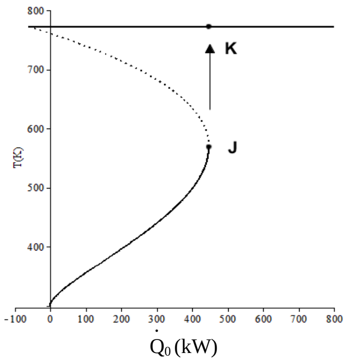
Figure 4. Eigenvalues for equilibria

When a small fire starts on branch ABDG, as the free burning heat release rate of the fire increases, the fire will eventually reach G, the intersection of stable branch with unstable branch, a fold catastrophe occurs. At point G, the system state rapidly jumps from a fuel-controlled equilibrium point to a new remote ventilation-controlled equilibrium state denoted by point H with a sharp increase in temperature. Flashover occurs at the bifurcation point. At point G, the heat release rate is about 1270 kW and the smoke layer temperature is 646 K. The new state H has a temperature of 818 K.

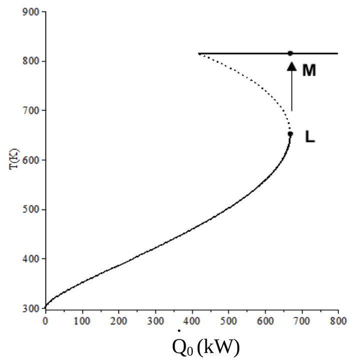
The critical flashover conditions for apartments with floor dimensions of 7.5 m × 4 m, 7 m × 3 m, 5 m × 5 m, 6 m × 5 m were examined similarly. Figures 5(a) to 5(d) show the bifurcation points and the new equilibrium states for each case. The values for critical temperature, critical heat release rate and equilibrium temperature after flashover are presented in Table 2.

Table 2. Summary

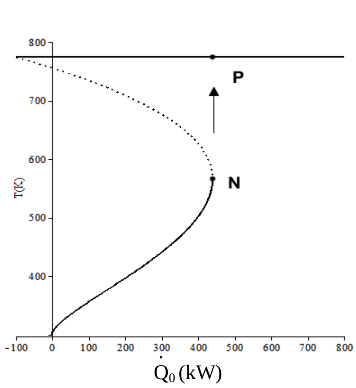
Scenario number	1	2	3	4	5
Floor dimensions (m.m)	6×3.5	7×3	5×5	6×5	7.5×4
Internal surface area (m^2)	57	60	60	66	69
Critical temperature (K)	647	652	604	566	569
Critical $\dot{Q}_0$ (kW)	656	669	542	439	447
Corresponding $\dot{Q}$ (kW)	1898	1953	1694	1444	1475
New stable Temperature (K)	818	814	772	774	772



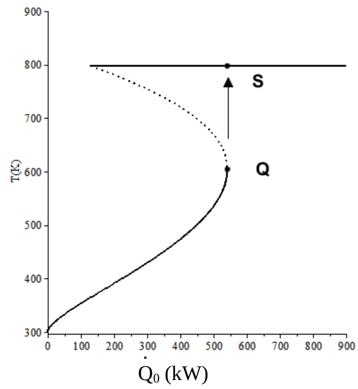
(a) Floor of 7.5 m × 4 m



(b) Floor of 7 m × 3 m



(c) Floor of 6 m × 5 m



(d) Floor of 5 m × 5 m

Figure 5. Critical conditions for flashover with different floor geometry

The flashover criteria (Karlsson and Quintiere 2000) include smoke layer temperature below the ceiling reaching 500 to 600°C, heat flux to the floor more than 20 kW/m^2 or flames coming out the openings. As shown in Table 2, the temperatures after bifurcation in Cases 1 to 5 coincide with the temperature criterion. In Case 1 and Case 2, the floor areas are equal but with different length to width ratio which give rise to difference in the internal surface area. Case 4 and Case 5 hold the same situation. For cases with the same floor area, the values of critical temperature and critical heat release rate for an apartment with a smaller internal surface area are lower when compared with the one with a bigger internal surface area. When the internal surface area of an apartment is small, less heat is conducted away from the enclosure boundary, allowing more energy to be stored in the apartment. Therefore, it requires a smaller heat release rate to initiate flashover and when flashover occurs, a higher compartment temperature appears. Three floor area values 21 m^2, 25 m^2 and 30 m^2 were investigated. It can be summarized that compartments with larger floor area needs a small critical heat release rate for flashover. In the fire dynamical model developed, the thermal radiation feedback is closely related with the smoke layer interface area, i.e. the floor area. If the other conditions are the same, as the floor area increases, the fire base receives more energy feedback from the upper part of the compartment. But for a large compartment, it may take a longer time to reach a higher temperature. When the effect of compartment geometry on flashover condition is examined, the radiation feedback coefficient is kept constant. Actually, it varies with the geometry of the compartment and it varies in the process of the fire even in the same compartment. However, it is difficult to tell how it changes quantitatively. Therefore its effect is specifically studied in the next section.

EFFECT OF RADIATION FEEDBACK

In compartment fires, heat released from the fire is the source term of the energy obtained by the smoke layer. In the thermal instability theory for flashover, the radiation feedback to the fire source is of great importance. The heat feedback process is very complicated with many factors involved. It relates with the geometry of the enclosure, temperature and emissivity of the wall surface, the concentration and distribution of the participating media such as carbon monoxide and soot, the thickness and temperature of the smoke layer, the size, temperature, emissivity of the fire source and its position in the compartment. In the model employed, the heat radiated to the fuel is significantly simplified. The parameter μ, radiation feedback coefficient, implicitly incorporates the effect from emissivity, view factor. And except radiation from smoke layer, there is radiation from the hot surfaces and ceilings which should not be ignored when they are at an elevated temperature. In fact, the parameter μ varies with the change in compartment geometry, smoke layer emissivity, fire area and so on. While, it is taken as a constant when the effect of other parameters is addressed which may result in errors.

The effect of radiation feedback coefficient μ on the onset of flashover was evaluated in an apartment with dimensions of 6 m in length, 3.5 m in width and 3 m in height. The other parameters are set as in Table 1. Figure 6 shows the critical heat release rate and critical temperature for flashover with a varying μ, respectively.

As demonstrated in Figure 6, when the value of μ is small, little thermal energy is radiated back to the fire source, so that flashover does not occur. When the radiation feedback coefficient μ increases gradually, the critical heat release rate drops sharply at first, then more gently. When μ is 0.1, the critical heat release rate and critical temperature are 14.88 MW and 1273 K respectively. By contrast, when μ is 0.25, the minimum energy required for flashover is about 0.8 MW and the corresponding critical temperature is 484 K. This is because due to a strong radiation feedback, the fire grows very quickly, flashover can take place earlier.

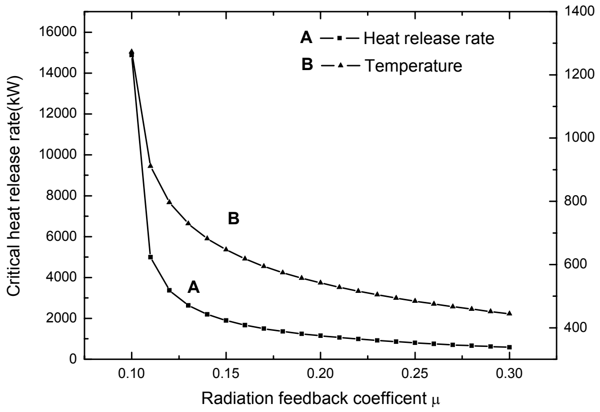


Figure 6. Critical heat release rate and critical temperature against varying radiation feedback coefficient for the case with a floor of 6 m × 3.5 m

CONCLUSIONS

The open kitchen design makes the fire risk increase in these high-rise residential buildings with a high fire load density. The ignition probability and the probability that the fire can spread out from the kitchen are necessary to assess the fire risk, however they are difficult to obtain. The critical flashover conditions were examined by a single variable nonlinear dynamical model. The smoke layer temperature was taken as the single state variable. The effects of apartment dimensions and radiation feedback on flashover conditions were examined with selective parameter values. The internal compartment surface or the floor aspect ratio may change with the variation of the unit floor area. Consequently, they will have effect on the heat transfer process and then affect the critical condition for flashover. The thermal radiation feedback coefficient is an important parameter which is changing in the fire process and it is difficult to determine the exact value for it. It was proved that flashover can be demonstrated by the model developed in terms of thermal instability. The complicated heat transfer process in fire scenario is represented by a simplified model which results in errors. A more accurate model addressing the heat radiation feedback to the fire source is needed to achieve more reasonable prediction.

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