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STUDY ON FLASHOVER IN SMALL RESIDENTIAL UNITS WITH AN OPEN KITCHEN BY NONLINEAR DYNAMICS

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ABSTRACT

Flashover is a dangerous phenomenon in building fires which is characterized by a sharp increase in burning rate and gas temperature. Open kitchens have been designed for many small units in tall residential buildings in densely populated areas, sparking big concerns about fire safety because of its small confined area and high fire load density. Efforts on preventing flashover should be made. In this paper, nonlinear dynamical system was used to study flashover in an example apartment with an open kitchen. A two-layer zone model was used to simulate the apartment fire by a hot upper smoke layer and a cool lower layer. The hot smoke layer temperature was taken as a single state variable in the model. The rates of heat gain from the fire and heat loss from the smoke layer were expressed as functions of temperature. A differential equation was set up to describe the rate of change of the layer temperature based on a simple heat balance of the smoke layer. Evolution of the smoke layer temperature, equilibrium states of the system and their corresponding stabilities were then investigated. The heat release rate was taken to be one of the most important control parameters affecting the evolution of the system state. The impacts of different heat release rates on the system state were studied. Critical conditions for the onset of flashover obtained from this model were compared with data available in the literature.

INTRODUCTION

Open kitchens have become common in many small residential units with a small floor area in tall buildings [1]. Such design of not enclosing the kitchen with fire resisting walls fails to comply with the building fire safety codes in some places such as Hong Kong. Fire load surveys [2,3] indicated that the fire load density in these small residential units is extremely high, reaching over 1400 MJm^{-2}. It is easy for a small open kitchen fire to intensify and spread out to other parts of the apartment where more combustibles are stored. Flashover plays an extremely important role in disastrous fires which result in many casualties and huge damage to properties [4], while the possibility that flashover will occur in such apartment is very high. Once flashover occurs, it will speed up the spread of the fire and even make the whole building involved, causing a big post flashover fire. Therefore, it is very important to study flashover in small residential units with open kitchens.

When a fire occurs in a compartment, the hot gases will accumulate under the ceiling and heat up the surfaces in contact with them. The radiation feedback from the hot smoke layer and the hot surfaces will augment the burning rate of the fuel. Then, more energy will be released into the smoke layer, which will then result in a higher smoke layer temperature and more energy feedback. There is a moment when the smoke layer temperature reaches a certain value that a sudden increase in fire growth rate and intensity can be seen in a relatively small localized fire. This is called flashover in which all the combustible surfaces are involved in the fire. Once flashover occurs, the fire will spread quickly, which can cause great damage.

The flashover phenomenon is very complicated, as it involves interactions between the fuel, environment and the enclosure boundary. A great deal of research [4, 6-11] has been done on flashover in compartment fires, but till now it has not been understood thoroughly. The criteria for flashover commonly accepted are that gas temperature below the ceiling reaches 500°C to 600°C, or the radiation heat flux at floor level is 20 kW/m^2, or flames come out of the openings. Differences in enclosure geometry, fuel properties, and conditions in the upper layer may give rise to different indicators of the onset of flashover [5].

Flashover has been regarded as a thermal instability phenomenon in fires when the energy generation rate is faster than the energy loss rate with the increase of temperature [7]. The thermal instability nature of flashover suggests that it is a nonlinear dynamical process; therefore, nonlinear dynamical system theory can be applied to study flashover. Different dynamical models have been proposed by researchers, such as Bishop [8], Chow and Liang [9,10] and Novozhilov [11].

This study investigates flashover in an example apartment with an open kitchen fire. Nonlinear theory is used through a simplified two-layer zone model [12].

NOMENCLATURE

c_p	[J/kg.K]	Specific heat at constant pressure
G_E	[W]	Heat gain rate of the hot smoke layer
g	[m/s^2]	Acceleration due to gravity
H	[m]	Height of the apartment
H_{com}	[J/kg]	Heat of combustion
H_{vap}	[J/kg]	Heat of evaporation
h_c	[W/m^{2}K]	Convective heat transfer coefficient
L	[m]	Length of the apartment
L_E	[W]	Heat loss rate of the hot smoke layer
$\dot{m}_a$	[kg/s]	Mass flow rate of ambient air
$\dot{m}_f$	[kg/s]	Fuel mass loss rate due to incident radiation from smoke layer
$\dot{m}_{out}$	[kg/s]	Mass flow rate of hot smoke out of the opening
$\dot{Q}$	[W]	Rate of heat release of the fire
$\dot{Q}_0$	[W]	Free burning heat release rate
$\dot{R}_{in}$	[W]	Incident radiant heat from smoke layer to firebase
T	[K]	Temperature of the hot smoke layer
T_{equ}	[K]	Equilibrium temperature
T_0	[K]	Ambient temperature
T_w	[K]	Temperature of the wall surface contact with the hot smoke Layer
t	[s]	Time
U_c	[-]	Wall temperature parameter
W	[m]	Width of the opening
W_0	[m]	Width of the apartment
z_d	[m]	Smoke layer interface height above the floor
z_N	[m]	Neutral plane height
σ	[W/m^{2}K^4]	Stefan-Boltzmann constant
χ	[-]	Combustion efficiency
S_r	[-]	Stoichiometric ratio
μ	[-]	Configuration factor
χ_R	[-]	Radiation factor
ρ_0	[kg/m^3]	Density of the ambient air
C_d	[-]	Flow coefficient
λ	[-]	Eigenvalue

NONLINEAR DYNAMICS

Nonlinear systems are often used to deal with nonlinear problems in science and engineering. By establishing nonlinear equations for the system of interest, the dynamics of a model can be presented in a phase space. Dynamical systems can be classified into different categories. In this study, the fire system model developed is a continuous autonomous dynamical system.

The state of a dynamical system is controlled by a set of parameters. If there is a change in one or more parameters, the state of the system will vary accordingly. Generally, a slight change in parameters will only cause a small variation in the state of the system and qualitative change in the structure of the system will not happen. However, the state of a system may change violently and its structure will become qualitatively different (such as the number and type of solutions) at certain critical parameter values. These qualitative changes in system state are termed catastrophes or bifurcations [13].

Equilibrium solution is important to dynamical systems. The equilibrium points or fixed points are points at which the rates of change of the state variables become zero. At the same time, the local stability of an equilibrium solution of a dynamical system is also of great importance too. When an equilibrium point loses its stability, new stable states that are qualitatively different might emerge, i.e., bifurcation occurs. Eigenvalues of the constant Jacobian matrix at an equilibrium point can help to determine the local stability of it. The fixed point is stable if all eigenvalues are negative. Conversely, it is called an unstable equilibrium point if at least one eigenvalue is positive. When eigenvalues become zero, bifurcation might take place.

In this paper, as the temperature of the upper smoke layer T is of considerable importance for predicting hazardous conditions in a compartment fire, it was chosen as the single state variable. Parameters that control the change of the system state were also selected. Flashover is deemed to happen when eigenvalues become zero.

EVOLUTION EQUATION OF THE FIRE SYSTEM BASED ON TWO-LAYER ZONE MODEL

Many zone models have been described in the literature. In two-layer zone models, the compartment is divided into a hot upper smoke layer and a cool lower layer. In this paper, a simplified two-layer zone model based on the work by Chow and Liang [9,10] was used.

A compartment of length L, width W_0 and height H was used as an example. There was a single rectangular vent of width W and height H (i.e., the vent extended from floor to ceiling) at the center of one wall. A fire source was centered at the floor. Temperature of the upper hot smoke layer T was taken as the single state variable. Assumptions were made that the lower layer was consisted of air of ambient temperature and the thickness of the smoke layer was constant. A quasi-steady process was also assumed before flashover.

Based on energy conservation in the upper hot smoke layer, the evolution equation of the open kitchen fire dynamical system is expressed as:

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

m is the smoke layer mass; c_p is the specific heat at constant pressure of the gas; T is the temperature of the hot smoke layer; G_E and L_E are energy gain rate and loss rate of the upper hot smoke layer respectively, which are functions of smoke layer temperature.

The energy gain rate of the hot smoke layer is determined by the heat release rate of the fire, which depends on whether the fire is fuel-controlled or ventilation controlled.

For a fuel-controlled fire:

$$\dot{Q} = \dot{Q}_0 + \chi \cdot \dot{m}_f \cdot H_{com} \tag{2}$$

For a ventilation-controlled fire, the heat release rate is usually estimated by the mass flow rate of air through the opening into the compartment [8]:

$$\dot{Q} = \chi \cdot \frac{\dot{m}_a}{Sr} \cdot H_{com} \tag{3}$$

$\dot{Q}$ is the heat release rate of the fire; $\dot{Q}_0$ is the free burning heat release rate of the fire (free burn is that the fire burns in the open, without enclosure effects and no radiation feedback from the smoke layer); χ is the combustion efficiency; $\dot{m}_f$ is the 'extra' mass flow rate of fuel volatilized due to the incident heat radiation from the upper hot smoke layer (radiation from hot surfaces is neglected here). H_{com} is the heat of combustion of the fuel, $\dot{m}_a$ is the mass flow rate of ambient air into the compartment, and S_r is the stoichiometric ratio.

$$\dot{m}_f = \frac{\dot{R}_{in}}{H_{vap}} \tag{4}$$

$\dot{R}_{in}$ is the net incident radiant heat on the fuel surface from the hot smoke layer and H_{vap} is the heat of evaporation or gasification of the fuel. It was assumed that the firebase and the smoke layer have an emissivity of 1 and the temperature of the firebase was taken to be the ambient temperature T_0. Therefore, the formula for $\dot{R}_{in}$ is

$$\dot{R}_{in} = \sigma(T^4 - T_0^4) LW_0 \mu \tag{5}$$

LW_0 is the area of the smoke interface; σ is the Stefan-Boltzmann constant; and μ is the radiant configuration factor from the smoke layer to the firebase, which is related with the geometry of the smoke layer and the firebase area and the relative position of the two.

The inflow of air into the compartment in a fully developed fire (ventilation-controlled) is derived by the formula below [5]:

$$\dot{m}_a = 0.5W \times H^{1.5} \tag{6}$$

When heat is released from the fire source, part of it is emitted from the fire in radiation form and a large part goes into the hot smoke layer in convective form. In real fire plumes, for many common fuels, the radiant part χ_R typically accounts for 20 to 40% of the total energy released [5]. G_E is given in terms of the fraction of the heat generated by the fire source that would go into the upper smoke layer:

$$G_E = (1 - \chi_R) \cdot \dot{Q} \tag{7}$$

The total energy lost from the hot smoke layer L_E is assumed to be composed of three items. The formula is written as

$$\begin{aligned} L_E &= \sigma(T^4 - T_0^4)[LW_0 + W(H - Z_d)] \\ &+ [LW_0 + (2L + 2W_0 - W)(H - Z_d)][\sigma(T^4 - T_w^4) + h_c(T - T_w)] \\ &+ \mathrm{c}_p \, \dot{m}_{out}(T - T_0) \end{aligned} \tag{8}$$

T_w is the surface temperature of the upper parts of the walls which are in contact with the hot smoke layer and T_0 is the ambient temperature. In equation (8), the first item represents the radiant heat loss rate from the smoke layer to the outside through the vent and to the lower part of the compartment. The second item denotes the heat loss to ceilings and walls that bounded the hot smoke layer through radiation and convection. The third item is the energy loss due to enthalpy flow through the vent.

The surface temperature of the upper part of the compartment walls T_w is approximated as a fraction of the gas layer temperature [8]:

$$T_w = U_c(T - T_0) + T_0 \tag{9}$$

U_c is a wall temperature parameter which ranges from 0 to 1, depending on the properties of the wall materials.

In a compartment fire, hot smoke flows out from the top part of the opening and fresh air enters through the lower part of the opening. The inflow and outflow through the vent are considered to be driven by buoyancy [14]:

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

C_d is the flow coefficient; Z_N is the height of the neutral plane from the floor at which the pressure difference is zero; g is the acceleration due to gravity;

and W is the width of the opening. For simplicity, Z_N was assumed to be the height of the smoke layer interface Z_d.

The evolution equation is developed as described above based on a two-layer zone model which can be used to determine the equilibrium states and their stabilities by the parameters concerned. The likelihood of flashover in an example apartment with an open kitchen can be examined.

FIRE IN AN EXAMPLE APARTMENT WITH AN OPEN KITCHEN

An example small apartment of dimensions 6 m × 3.5 m × 3 m with an open kitchen was considered. According to the nonlinear theory, the equilibrium points T_{equ} of the open kitchen fire nonlinear system are characterized by

$$\frac{dT}{dt} = 0 \tag{11}$$

Eigenvalues of the equilibrium states can be determined by:

$$\lambda = \frac{\partial}{\partial T} \frac{dT}{dt}\bigg|_{T=T_{equ}} \tag{12}$$

The values of selected control parameters and constants used are listed below. The influence of Q_0 on the state of the system is discussed here.

$\sigma = 5.67 \times 10^{-8}\ W \cdot m^{-2} K^{-4}$ $\quad T_0 = 300K$

$C_p = 1003.2\ J \cdot kg^{-1} K^{-1}$ $\quad C_d = 0.7$

$g = 9.81\ m \cdot s^{-2}$ $\quad \rho_0 = 1.18\ kg \cdot m^{-3}$

$H_{comb} = 4.2 \times 10^7\ J \cdot kg^{-1}$ $\quad H_{vap} = 1.008 \times 10^6\ J \cdot kg^{-1}$

$S_r = 30$ $\quad h_t = 7\ W \cdot m^{-2} K^{-1}$

$U_c = 0.7$ $\quad \mu = 0.15$

$\chi_R = \frac{1}{3}$ $\quad \chi = 1$

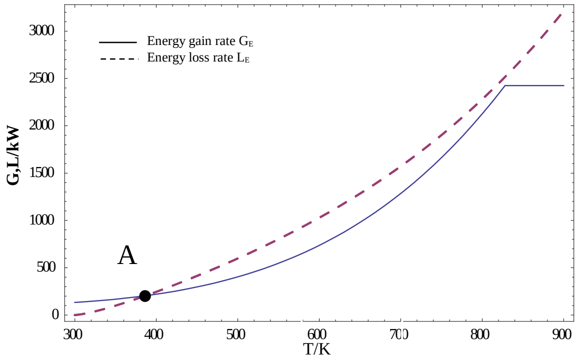
$W = 1\text{m}$

The value of Z_d was assumed to be constant and kept at 0.5H.

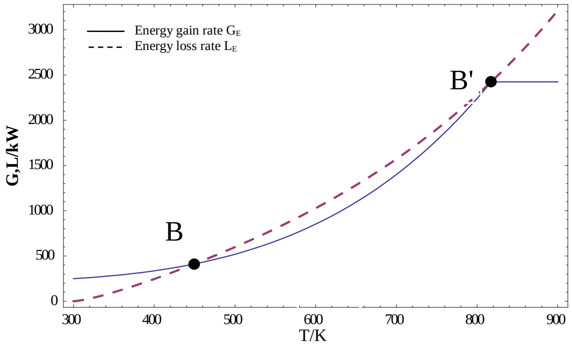
The parameters described above have effect on the equilibrium states of the model system T_{equ}. In this paper, parameter Q_0 was chosen as the single parameter to control the state of the system with the other control parameters kept at the values listed above.

RESULTS AND DISCUSSIONS

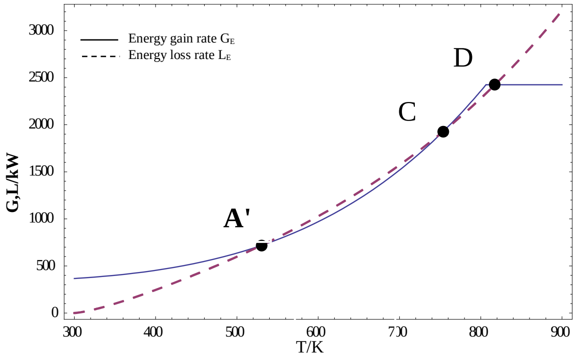
In Figure 1, curves of G_E and L_E for five different values of $\dot{Q}_0$ are presented as functions of the upper smoke layer temperature, showing the influence of varying $\dot{Q}_0$ on an open kitchen fire. There are two parts in the G_E curves. One part represents a fuel-controlled fire and the other part where the energy gain rate becomes constant represents a ventilation-controlled fire. When the value of parameter $\dot{Q}_0$ increases, the relative positions of the two curves also change. One, two, three, two and one intersections were observed respectively. These points represent different equilibrium states of the fire system.



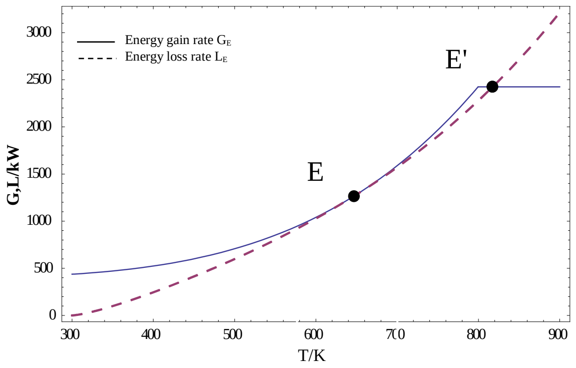
(a) Q_0 = 200 kW



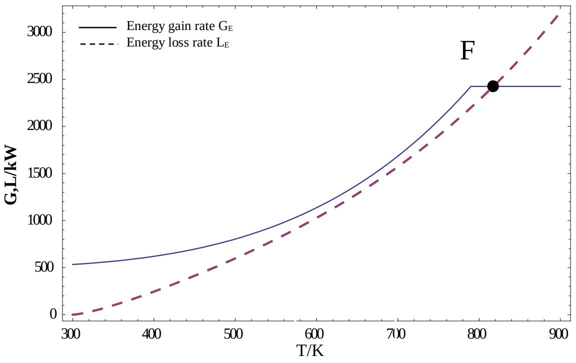
(b) Q_0 = 373.6 kW



(c) Q_0 = 550 kW



(d) $Q_0 = 656$ kW



(e) $Q_0 = 800$ kW

Figure 1 Heat gain and loss curves under different Q_0

The equilibrium point *A* in Figure 1(a) is stable. When there is a minor perturbation in temperature near point A, the system can regain stability. Similarly, equilibrium points B and A' are also stable. However, the equilibrium state at B' in Figure 1(b) is unstable. When there is a small decrease in temperature, a fire represented by B' will go down the gain curve until it encounters point B. Similarly, the equilibrium state at point C is unstable too. Additional attention should be paid to the equilibrium state at point E in Figure 1(d). When the temperature slightly rises, the temperature of the upper smoke layer will increase rapidly and a fold catastrophe bifurcation appears. The temperature of the smoke layer will suddenly jump to a higher value represented by state E'. After that, the fire enters a ventilation-controlled stage. This jump in smoke temperature can be identified with flashover.

Figure 2 shows the schematic of the fold catastrophe with Q_0 as the only varying control parameter. The eigenvalues of the corresponding equilibrium states are shown in Fig. 3. The branch BE is stable as the corresponding eigenvalues $\lambda < 0$, whereas, branch B'E is unstable due to $\lambda > 0$. The eigenvalue λ for point E (Q_0 of 656 kW, T of 646 K) is equal to zero, which means the structure of the dynamical system may possess a qualitative change. New state(s) may emerge and dangerous bifurcation may occur in the fire system. When a fire with a small Q_0 begins on branch BE, the smoke temperature will be relatively low. When free burning heat release rate of the fire grows, the smoke layer temperature will climb along branch BE until it reaches the unstable branch EB' at critical value Q_0 (656 kW). A fold catastrophe will occur at point E, resulting in a sudden jump of smoke temperature to branch B'E'. It is assumed that flashover will happen. If Q_0 of a fire on branch B'E' decreases, when it arrives at the point of B' , it will undergo a decay drop to point B. Critical value of parameter Q_0 at point B is 0.656 MW; the corresponding total heat release rate $\dot{Q}$ at this point is 1.265 MW. The temperature of the upper smoke layer just before the catastrophic jump is 639.6 K. The temperature at which flashover occurs in this study is similar to that in the literature [9].

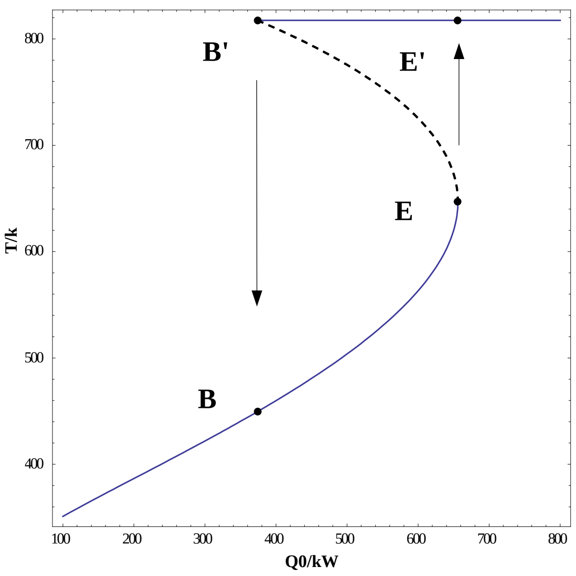


Figure 2 Schematic of the catastrophe

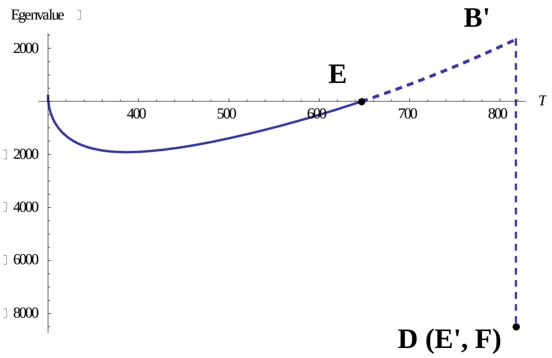


Figure 3 Eigenvalues of equilibrium states

Many control parameters will affect the evolution of the system state, such as the heat release rate, air supply and thermal properties of the boundary materials. Undoubtedly, heat release rate is one of the most important one. The nonlinear dynamical model used in this paper was very sensitive to the variations of the parameters. The state of the system will exhibit different characteristics under different sets of control parameters. The simulation results shown here were just made with selective control parameters.

CONCLUSIONS

Kitchens are reported to be the leading area of origin for home fires [15]. The open kitchen design in small units with a high fire load density in tall residential buildings is more challenging in the aspect of fire safety. With the aid of flashover, a small kitchen fire might cause big casualties and large damage to the building. Protective measures must be taken to prevent flashover from happening.

One-state variable nonlinear dynamical model of the fire system based on a two-layer zone model has been developed. The evolution equation is set up based on the heat balance equation, therefore, the accuracy of the heat balance model [16] used in the two-layer zone model is extremely important. Due to the complexity of compartment fire, simplifications such as of the wall temperature, emissivity, and height of neutral plane are made. Assumptions are also made such as on the height of the smoke (or hot air) layer interface Z_d (assumed to be 0.5H) and the stoichiometric ratio (assumed to be 30). These assumptions and simplifications can lead to errors, which may not be known.

Though improvement work should be done, the results showed that flashover can be well modeled by using nonlinear dynamical theory, which can give a better understanding of this special phenomenon in an apartment with an open kitchen fire. However, there might be other mechanisms for flashover.

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