A model of backdraft phenomenon in building fires*

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Abstract In order to further investigate the physical mechanism of the backdraft phenomenon in building fires, a simplified mathematical model is established based on energy balance equation, and its catastrophe mechanism is analyzed based on catastrophe theory, and the relationship between system control variables and fire conditions is studied. It is indicated that the backdraft phenomenon is a kind of typical catastrophe behavior, and of the common characteristics of catastrophe.

Keywords: **building fires, backdraft, flashover, nonlinear dynamics, catastrophe.**

In vitiated buildings, a fire will gradually come into a combustion state with lack of oxygen because fresh air cannot be supplied enough to meet the need of accelerating combustion. The hot smoke in such a building fills with a great mass of combustible gas. If the fresh air is allowed to flow into this building by some reasons, such as through an opening door or a broken window, etc, the gas will combust acutely, the temperature will rise rapidly, and the initial fire stage will develop into flashover or deflagration. This phenomenon is termed backdraft. Apparently, because of its abruptness and powerful destruction, the backdraft phenomenon is hazardous to the safety of people, especially firefighters[1,2]. This phenomenon is related to hot smoke components, temperature and environmental conditions. At present, as there is no sound mathematical model to describe it, the backdraft phenomenon is deemed as one of the difficult subjects in fire science[3].

In recent years, the development of nonlinear dynamics has also stimulated the development of fire science. Bishop et al. explained successfully the flashover phenomenon in building fires based on catastrophe theory[4~6]. Xie et al. studied the self-ignition behavior of Semenov system and firebox combustion system with nonlinear dynamics[7,8]. Malamud et al. discovered that a real forest fire shows the self-organized critical behavior[9].

So far, the studies on backdraft phenomenon have been restricted to experiments, but due to its suddenness, it is difficult to understand its physical mechanism under the present experimental conditions. In this paper, a simplified mathematical model of backdraft phenomenon in building fires is established based on energy balance equation, its catastrophe mechanism is analyzed based on catastrophe theory, and the relationship between system control variables and fire conditions is studied. The results indicate that the backdraft phenomenon is a kind of typical catastrophe behavior with common characteristics such as having two steady states and one unsteady state , an S-shaped operating characteristic curve, and hysteretic transformation between the steady states of the system.

1 Mathematical model of backdraft phenomenon

The backdraft phenomenon can be divided into six stages: ignition, free combustion, combustion with lack of oxygen or smoldering, deflagration, developed combustion and decay. Fig. 1 shows a schematic outline of such a development. There are three key time-variables to differentiate these stages: t_c is the transform time from combustion to combustion with lack of oxygen or smoldering; t_o the time of supplying oxygen, and t_d the transform time from developed combustion to decay.

In order to concentrate on studying backdraft phenomenon, only the latter five stages are analyzed. A mathematical model of the backdraft phenomenon is established based on zone model. The assumptions of zone model are that there are upper and lower lay-

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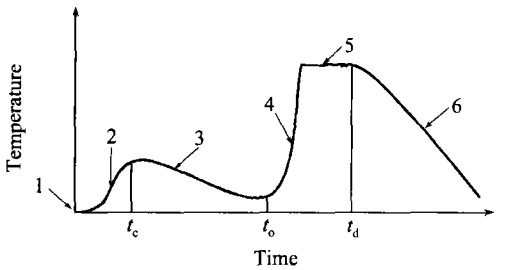

Fig. 1. Schematic outline of six stages of backdraft phenomenon. 1, ignition; 2, free combustion; 3, smoldering; 4, deflagration; 5, developed combustion; 6, decay.

ers in building fires, i.e. hot smoke layer and cold air layer, and that the inner thermal properties are uniform in each layer. Therefore, the temperature of the hot smoke layer can be defined as

$$\frac{dT}{dt} = F_1(T, l) = \frac{G - L - \dot{H}}{c_p m}, \qquad (1)$$

where T is the temperature of hot smoke layer, t the time, l the flame spread distance, G the energy gain rate of hot smoke layer, L the energy loss rate of hot smoke layer, $\dot{H}$ the enthalpy increase rate of hot smoke layer (via mass increase alone), c_p the specific heat at constant pressure of hot smoke layer, and $m = \rho V$ the mass of hot smoke layer, where ρ is the density of hot smoke layer, V the volume of hot smoke layer.

$$G = \begin{cases} \dot{m}_{in} H_c \\ \chi \dot{m}_{in} H_c \\ \mu \dot{m}_f H_c \\ 0 \end{cases}, \quad L = \begin{cases} \dot{Q}_w \\ \dot{Q}_w \\ \dot{Q}_w + \dot{H}_o, \\ \dot{Q}_w + \dot{H}_o \end{cases}$$

$$\dot{H} = \begin{cases} \dot{m}_{in} c_{gp}(T - T_a) & 0 < t \leqslant t_c \\ \dot{m}_{in} c_{gp}(T - T_a), & t_c < t \leqslant t_o \\ 0 & t_o < t \leqslant t_d, \\ 0 & t > t_d \end{cases} \qquad (2)$$

where $\dot{m}_{in}$ is the determinate mass flow rate of combustible gas in the free combustion and smoldering stages flowing into the room whose length, width, height are L_R, W_R and H_R, respectively, and the height and width of the door of the room are H_D, W_D. c_{gp} is the specific heat at constant pressure of combustible gas, H_c the heat of combustion, χ the combustion efficiency of smoldering. $\dot{m}_f = k(nC)^s l W_R h Q_c / H_c$ is the combustion mass rate of combustible gas in the deflagration and developed combustion stages, where $k = k_0 \exp[-E/(RT)]$ is the chemical reaction rate, k_0 the pre-exponential factor, E the activation energy, R the gas constant, n the total mole number in the room, C the volume concentration of combustible gas in the hot smoke layer, s the reaction order, Q_c the heat of combustion per mole. $h = NH_D$ is the height of mixture layer, $N = D + (1 - D)^2/2$[4] the dimensionless neutral height, $D = Z_D/H_D$ the dimensionless height of the discontinuity plane, Z_D the discontinuity height. μ is the fuel/ventilation control function, defined as

$$\mu = \begin{cases} 1 & \dot{m}_a/\dot{m}_f \geqslant Sr, \\ \dot{m}_a/(\dot{m}_f Sr) & \dot{m}_a/\dot{m}_f < Sr, \end{cases} \qquad (3)$$

where Sr is stoichiometric ratio, and $\dot{m}_a$ the mass flow rate of air, defined as[10]

$$\dot{m}_a = 2/3 C_D \rho_0 W_D H_D^{3/2} \sqrt{2g(1 - T_a/T)(N - D)}(N + D/2), \qquad (4)$$

where C_D is the vent flow coefficient, ρ_0 the air density, g the gravitational constant, and T_a the air temperature.

$$\dot{Q}_w = A_w(\varepsilon\sigma(T^4 - T_w^4) + h_t(T - T_w))$$[4]

is the energy transform rate out through the walls, where ε is the hot smoke layer emissivity, σ the Stefan-Boltzmann constant, h_t the heat transfer coefficient, A_w the area of room exposed to hot smoke layer, $T_w = U_c(T - T_a) + T_a$ the wall temperature. $U_c = e^{-\beta(K_w \rho_w C_w)^B}$[11] is the wall temperature factor, where $\beta = 5.395$, $B = 0.338$ are constants, K_w, ρ_w, C_w are the conduction coefficient, density and specific heat under constant pressure of the wall, respectively. $\dot{H}_o = \dot{m}_o c_p(T - T_a)$ is the enthalpy flow rate out of door (via mass flow alone), where $\dot{m}_o = \dot{m}_a$ is the mass flow rate of smoke out of door (conservation of mass).

The flame spread equation is introduced considering the flame spread characteristics in the deflagration and developed combustion stages[4]:

$$\frac{dl}{dt} = F_2(T, l) = (aV_d + bV_p)\left[1 - \exp\left(\frac{l - l_{max}}{l_{max}}\right)\right], \qquad (5)$$

where $V_d = \dfrac{K_d \dot{m}_a}{\rho_0 W_D N H_D}$[4] is the diffusion flame combustion rate, D_d is a diffusion flame combustion coefficient. $V_p = K_p V_{max}$ is the premixed flame spread

rate, where $K_p = ARe + B$[12] is the premixed flame spread coefficient, A and B are constants. $Re = uh/v$ is the Reynolds number of mixture layer, where $u = \dot{m}_a/(\rho_0 W_R N H_D)$ is the average velocity of mixture layer, v the viscosity, V_{max} the maximum flame spread rate. a and $b = 1 - a$ are proportion factors (the combustion of the gravity current in mixture layer is a combustion between diffusion flame and premixed flame). l_{max} is the maxim flame spread distance. Function $\left[1 - \exp\left(\frac{l - l_{max}}{l_{max}}\right)\right]$ is introduced to limit the flame spreading in the maximum distance, and make $F_2(T, l)$ a smooth function. Eqs. (1) and (5) are the mathematical model of the backdraft phenomenon.

2 Nonlinear dynamics analysis

2.1 Qualitative analysis

Fig. 2 shows the schematic outline of the energy gain and loss rates of system versus temperature, where G_1 and L_1 are the energy gain and loss rates under vitiated conditions, G_2 and L_2 are the energy gain and loss rates after the door opens. From Fig. 2, it is evident that the energy gain rate increases exponentially with temperature; that is, $G \propto \exp[-E/(RT)]$, because the chemical reaction rate rises due to energy feedback in the deflagration stage (fuel controlled combustion). However, The relation between energy loss rate of system and temperature is close to direct proportion. In the development of building fires, the curves of the energy gain and loss rate may be tangential. Any slight positive perturbation in temperature will result in a jump from unsteady state A_1 to steady state A_2 in the developed combustion stage (ventilation controlled combustion), as well as an abrupt rise in temperature. This is deemed the sign and characteristic of the backdraft phenomenon.

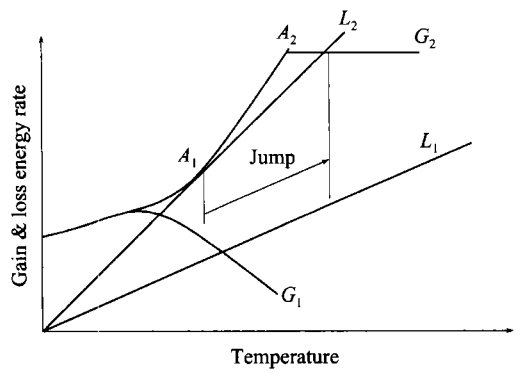

Fig. 2. Schematic outline of the energy gain and loss of system versus temperature.

The catastrophe behavior of the backdraft phenomenon occurs in the deflagration stage, on which the emphasis of this study is laid.

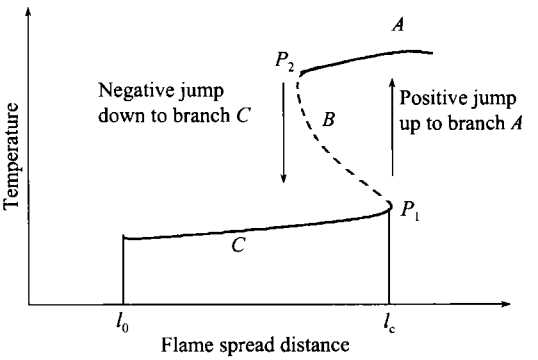

Fig. 3. Schematic outline of catastrophe behavior of the backdraft phenomenon.

Fig. 3 shows schematically the catastrophe behavior of the backdraft phenomenon, in which the flame spread distance l is a system control variable. The fire with the initial flame spread distance l_0 spreads along branch C. Eventually it intersects the unstable branch B at point P_1 with flame spread distance l_c, and a positive jump occurs up to branch A. When the fire spreads along branch A, its spread distance will reduce, and eventually intersects the unstable branch B at point P_2 and a negative jump occurs down to branch C. It is evident that this system has two steady states and one unsteady state, and an S-shaped operating characteristic curve, which is well known in thermal explosion theory[13].

Usually the eigenvalue of dynamical system can be used to determine whether the system is steady in nonlinear dynamics[14]:

$$\lambda_1 = \frac{F_1(T + \delta, l) - F_1(T, l)}{\delta}, \qquad (6)$$

where δ is small perturbation. When the eigenvalue of a point is negative, the system is steady; otherwise, it is unsteady. So the deflagration stage of the backdraft phenomenon occurs at $\lambda_1 \geqslant 0$. Therefore, whether the deflagration stage of backdraft phenomenon occurs can be determined by using the evolution of the eigenvalue versus time.

2.2 Quantitative computation

In this subsection, the mathematical model of the backdraft phenomenon introduced in this paper is integrated using adaptive step size Runge-Kutta. The

initial conditions, boundary conditions and various computational parameters are listed as follows.

The given combustible gas: methane.

Room parameters: $L_R = 4.8$ m, $W_R = 3$ m, $H_R = 3$ m, $H_D = 2$ m, $W_D = 1$ m.

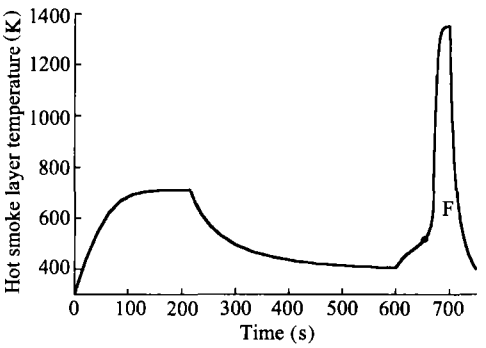

Fig. 4. Hot smoke layer temperature-time history. Point F corresponds to the gain and loss energy rate shown in Fig. 6.

Fuel parameters: $\dot{m}_{in} = 0.0075$ kg/s, $c_{gp} = 2482.6$ J/(kgK), $H_c = 50$ MJ/kg, $\chi = 0.1$ (assumption), $Q_c = 800$ kJ/mol, $Sr = 17.25$, $l_{max} = L_R$, $K_p = 0.01$ (assumption), $A = 0.000125$[13], $B = 1.3$[13], $V_{max} = 0.3731$ m/s[13], $a = 0.8$ (assumption).

Fluid parameters: $c_p = 1003.2$ J/(kgK), $\rho = \rho_0 = 1.25$ kg/m^3(assumption), $D_D = 0$ m (assume that the total room is filled with the hot smoke layer), $C_D = 0.7$[4], $T_a = 300$ K, $\nu = 0.017$(m^2/s).

Heat transfer parameters: $\varepsilon = 0.4$[4], $h_t = 7$W/(m^{2}K)[4], $K_w = 0.69$ W/(mK), $\rho_w = 1600$ kg/m^3, $C_w = 840$ J/(kgK).

Chemical reaction parameters: $k_0 = 200$ s^{-1}(estimated), $E = 50$ kJ/mol (estimated), $s = 1$ (assumption), $C = 0.2$.

Time parameters: assume that oxygen concentration at t_c is 10%, $t_o = 600$ s, $t_c = 700$ s.

The typical evolutions of the hot smoke layer temperature and eigenvalues with time are given in Figs. 4 and 5. The energy gain and loss rate curves corresponding to the point F shown in Figs. 4 and 5 are given in Fig. 6. In Fig. 4, the temperature rises in the free combustion stage, and falls down in the smoldering stage because the energy loss rate exceeds the energy gain rate. In the deflagration stage, the temperature rises sharply because the chemical reaction rate accelerates due to energy feedback. Finally the fire comes into the decay stage due to exhausted fuel after the developed combustion stage. In Fig. 5,

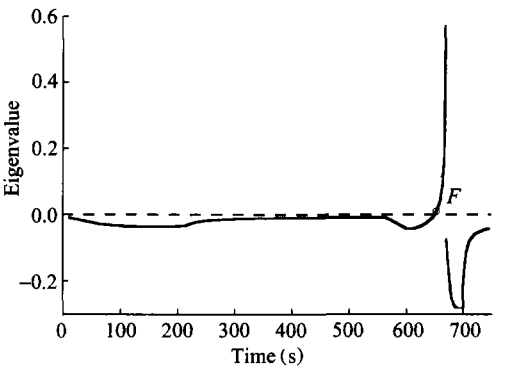

Fig. 5. Eigenvalue-time history corresponding to the curve in Fig. 4.

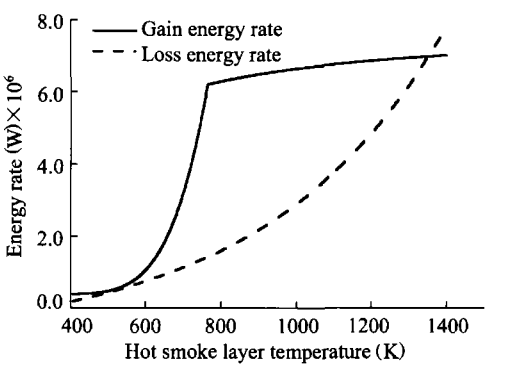

Fig. 6. Evolution of the energy gain and loss rate of point F versus hot smoke layer temperature.

the deflagration stage begins with point $F(\lambda_1 = 0)$, and the system is unsteady. But in other stages the system is steady owing to negative eigenvalues. The energy gain and loss rate curves of point F are tangential in Fig. 6, which indicates point F is a critical point from steady state to unsteady state.

2.3 System control surface

In order to study the catastrophe mechanism of the deflagration stage of the backdraft phenomenon, the flame spread distance l and the volume concentration of combustible gas in hot smoke layer C are used to control the evolution of hot smoke layer temperature. Therefore, the steady state values of hot smoke layer temperature satisfy Eq. (7) to form a system control surface; that is, for each value of l and C, there are one or more corresponding T values.

$$F_1(T, l, C) = 0. \tag{7}$$

Since the hot smoke layer temperature quickly moves onto this control surface, the value of T evolves on this surface most of the time, making sudden jumps at certain critical points from one part of the surface to another. Thus the system control surface effectively describes the possible behavior of the backdraft phenomenon. Fig. 7 shows numerically the system control surface represented by an envelope and upper and lower fold lines. This system control surface indicates that the deflagration stage of the backdraft phenomenon occurs only at a high volume concentration of the combustible gas in hot smoke layer C, and the flame spread distance l corresponding to transient jump line is slightly above that corresponding to lower fold line, which shows that the transformation between the steady states of the system is hysteretic.

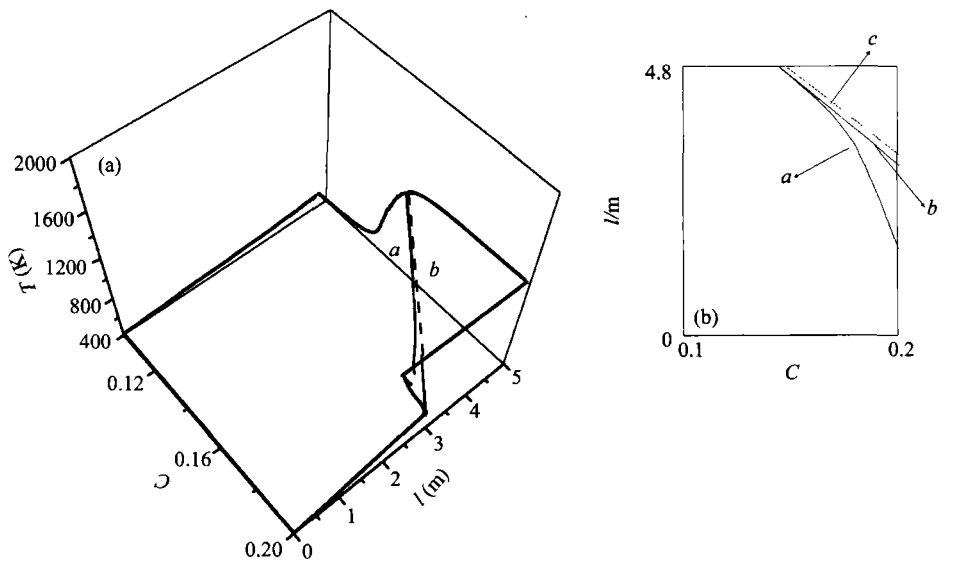

Fig. 7. Numerical system control surface. (a) 3-D side view, (b) 2-D plan view (from above).

3 Future work

Future work should focus on the study of other parameters as system control variables, such as room size, wall temperature factor, flame spread rate proportion factor, etc. These parameters may have similar effects on the system to those of the flame spread distance and the volume concentration of combustible gas in hot smoke layer on the control surface and need to be explored. The hot smoke layer height has been assumed to be invariable after the door is opened. However, if the evolving model of the hot smoke layer height is introduced, it may have important effects on the dynamical evolution of fire and the characteristics of the system control surface, which is also needed to be studied further.

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