NUMERICAL SIMULATION OF A 3-D ROOM FIRE

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ABSTRACT

A three-dimensional room fire has been simulated with numerical method in this paper. In the numerical simulation process, some theories of field modeling of fire have been used, such as the k-ε turbulence model with the modifications of buoyancy effects, the k-ε-g turbulent combustion model, the soot model, the six-flux radiation model, etc., the interactions of all these processes have been studied here. The results of computations of the room fire have been analyzed and discussed. Comparing with some experiments, these predictions are believable.

Keyword: three-dimensional, fire, simulation

INTRODUCTION

Room fire is a common phenomenon in our life. In previous decades, there were a lot of room fires, these fires have made a great lose to human lives and properties. With the developing of city building, room fires will be more than before, so it is necessary to study the mechanism of the room fire process, including ignition, growth and extinguish.

There are many papers to simulate a room fire with numerical method, but most of them are two dimensional models. Thus, there are some differences between these predictions and a real room fire. In order to understand the rules of a room fire, the fluid flow, heat and mass transfer, chemical reaction, radiation and the interaction of them involved in the fire processes must be studied. The governing equations of such processes are a set of second-order, non-linear partial differential equations which is too complicated to be solved analytically and can only be solved numerically. In recent years, with the rapid developments of computer science, it is possible to simulate a 3-D room fire with numerical method. Through the calculation results, we can get general aspects of a room fire and it is proved that the numerical simulation is reasonable and economical to solve some fire problems.

MATHEMATICAL AND PHYSICAL BASES

Fig.1 shows the studied zone for the 3-D room fire, including pieces of furniture. In order to simplify the problem, we suppose the bed is a fuel-bed, which the fuel is Heptane (C_7H_{16}) and the air is at rest before ignition. We use a line heat source to ignite several grids on the surface of the bed. Fig.2 shows the calculation meshes.

1. Governing Equation

The room fire follows some physical laws, including mass, momentum, energy and species conservation laws, etc.. All these governing equations can be written into a general form for three dimensional fire processes:

$$\frac{\partial(\beta\Phi)}{\partial t}+\mathrm{div}(\beta\vec{V}\Phi-\Gamma_{\phi}\,\mathrm{grad}\Phi)=S_{\phi}$$

where Φ stands for dependent variables, $\Gamma\phi$ for the exchange coefficient and $S\phi$ the source term for the appropriate variable Φ. Table 1 shows the meaning for every term in the equation.

Table 1 Variables in General Equation

Equation	Φ	β	Γ_{ϕ}	S_{ϕ}
Density	1	ρ	0	0
X-momentum	u	ρ	μ	$-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x_i}(\mu\frac{\partial u_i}{\partial x})+(\rho_0-\rho_{eff}g_r)$
Y-momentum	v	ρ	μ	$-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x_i}(\mu\frac{\partial u_i}{\partial y})$
Z-momentum	w	ρ	μ	$-\frac{\partial P}{\partial z}+\frac{\partial}{\partial x_i}(\mu\frac{\partial u_i}{\partial z})$
k	k	ρ	Γ_k	$G_k-\rho\varepsilon$
ε	ε	ρ	Γ_{ε}	$(C_1G_k-C_2\rho\varepsilon)\frac{\varepsilon}{k}$
Enthalpy	h	ρ	Γ_h	0 or $2a(Rx+Ry+Rz-3E)$
Mixture Fraction	f	ρ	Γ_f	0
g	g	ρ	Γ_g	$C_{g1}G_g-C_{g2}\rho g\frac{\varepsilon}{k}$
Soot	m_s	ρ	Γ_s	S_f-S_d
Rx	Rx	0	$\frac{1}{a+s}$	$-a(Rx-E)-\frac{s}{3}(2Rx-Ry-Rz)$
Ry	Ry	0	$\frac{1}{a+s}$	$-a(Ry-E)-\frac{s}{3}(2Ry-Rx-Rz)$
Rz	Rz	0	$\frac{1}{a+s}$	$-a(Rz-E)-\frac{s}{3}(2Rz-Rx-Ry)$

2. The Turbulence Model

Following the k-ε model developed by Launder and Spalding [1], a turbulence model taking into account of buoyancy has been adopted here for calculating of turbulence viscosity. Because ascending hot gas caused by buoyancy would change the turbulence energy, as a result, the source term G_k of k, ε equations must add an additional source term G_B:

$$G_B=-\beta g_r\Gamma_t\frac{\partial T}{\partial x_i}$$

β is the coefficient of thermo-expansion. The efficient viscous coefficient is $\mu=\mu_1+\mu_t$, where μ_1 is the coefficient for laminar flow and μ_t is for turbulence: $\mu_t=C_u\rho k^2/\varepsilon$.

3. The Turbulent Combustion Model

Chemical reaction are in fact multi-step and reversible. Here we mainly discuss single-step model which suggests that the reaction of fuel and oxygen is non-reversible: 1kg Fuel+Skg Oxygen $\longrightarrow$(1+S)kg Product+Heat, where S is the stoichometric oxygen requirement. The turbulent diffusion combustion model suggests that the instantaneous values of fuel and oxygen are non-coexistent. According to this assumption, we can get the equation of "f" as in Table 1.

The bed is treated as the parts of the integration domain. The motion and variations of temperature within the bed are neglected. The surface of the bed contents with heat equilibrium of the phase boundary:

$$\begin{cases} \lambda(T_g-T_w)=\dot{m}[L+C_p(T_w-T_o)] \\ \dot{m}=A_s\exp(-\frac{E}{RT})_w \end{cases}$$

where T_g the temperature of the gas adjacent to fuel surface, T_w the temperature of fuel related to vaporization rate. $\dot{m}$ stands for vaporization rate per unit area.

4. The Soot Model

The mass fraction equation of soot can be written into the same form as the other species equations [2]. The S_s term can be express as: $S_s=S_f-S_d$, where S_f is the soot formation rate and S_d is its destruction rate:

$$S_f=C_f P_{fu}\Phi^n\exp(-E/RT)=0.01P_{fu}\Phi^3\exp(-20140/RT)$$

$$S_d=\min[Am_s\frac{\varepsilon}{k},\ A\frac{m_{ox}}{r_s}\frac{\varepsilon}{k}\frac{m_s r_s}{m_s r_s+m_{fu}S_{fu}}]$$

where P_{fu} is the partial pressure of fuel, $\Phi=S_{fu}(\frac{f}{1-f})$, S_{fu} is the fuel stoichometric air requirement, A is a constant assigned the value 4, and r_s is the soot stoichometric air required.

5. The Radiation Heat Transfer Model

Six-Flux model simplifies the radiative heat transfer from all directions to radiation fluxes on six directions [3]. Here three combination fluxes R_x, R_y and R_z are adopted: $R_x=(I+J)/2$, $R_y=(K+L)/2$, $R_z=(M+N)/2$. Then the radiation equations can be simplified:

$$\frac{d}{dx}(\frac{1}{a+s}\frac{dR_x}{dx})=a(R_x-E)+\frac{s}{3}(2R_x-R_y-R_z)$$

$$\frac{d}{dy}(\frac{1}{a+s}\frac{dR_y}{dy})=a(R_y-E)+\frac{s}{3}(2R_y-R_x-R_z)$$

$$\frac{d}{dz}(\frac{1}{a+s}\frac{dR_z}{dz})=a(R_z-E)+\frac{s}{3}(2R_z-R_x-R_y)$$

where a is the absorption coefficient of medium, s is the scatter coefficient of medium, E is the emissive flux of black body. So the source term of Enthalpy equation is: $S_h=2a(R_x+R_y+R_z-3E)$. If we neglect the radiation effect, then $S_h=0$.

NUMERICAL METHOD

The set of governing equations which has been discreted is solved iteratively with the SIMPLE procedure. The effect of the bed and the desk can be solved by the method of porosity [4]. All of models and numerical methods described above have been programed as a FAC3 computer code. All calculations were performed with the VAX8700 computer and the typical computer time for each time-step is around 5 hours.

RESULTS AND DISCUSSIONS

Many results for 3-D unsteady room fire have been obtained. Only a few typical results are presented in this paper.

Fig.3 shows the charts of velocity and isotherms on the plane of z=0.2 (non-dimensional length) considering the radiation effects at four time steps. Form the chart, we can see, at the ignition moment, the value of velocity is small and isotherms are closely concentrate, the value of temperature is low too; as the time goes, shown in Fig.3(b,c,d), fire is more violent, the value of velocity becomes increasing, the maximum value reaches 1.29m/s, the isotherms are becoming looser, but the maximum value of temperature reaches 2050K, the top of temperature chart cracked, because the fire has spread at this time, the top of fire has reached the ceiling, and become to expand. Obviously, after ignition, the fire releases heat and the heat makes the temperature rise to ignite other grids mainly due to radiation heat transfer, thus, the fire spreads. On the other hand, we can find that there are two recirculation flows on each side of the chart of velocity, they become strongly when the fire is in process. It is because the hot gas in middle goes up and forms the plume flow, the cool gas goes down from each side near the wall, so, the gas recirculates. This result is reasonable and has been verified by experiments.

Fig.4 shows the isotherms at 0.57 second neglecting the radiation. The differences of temperature from Fig.3(d) are obvious. The location of the same isotherm are more concentrate than those in Fig.3(d). The basic reason is the neglecting of radiation heat transfer. In Fig.3(d), because of radiation, the gas with high temperature transports energy to that with low temperature which causes high temperature decrease and low temperature increase, and the distribution of temperature becomes more uniform, the maximum value of temperature is 200K lower than the case that the radiation is neglected.

Fig.5 shows the process of fire spread. At the ignition moment, the fire is small, and only several grids have been ignited with the line heat source. With the time going, the flame gives lot of heat energy and the energy heat up the bed surface; at the time of 0.15 second, the flame almost covers the whole bed. From Fig.5, we can see this phenomena clearly and we also can get that flame has a character which trends to wall or corner of room. This is because the back pressure is smaller near the wall or the corner of room than the middle of room. From the calculated data, we can get that the average speed of fuel bed fire spread is about 0.76m/s. This value is agreement with some experiment data in quantitative rank.

Fig.6 shows the temperature changing with the time at a fixed point near the ceiling up above the fire. At the beginning time, the fire is so small that the temperature at the point is about the constant of 300K, when the time is 0.40 second, the temperature rises rapidly, the fire has reached the ceiling making the temperature rise. After 0.5 second, the fire near the ceiling spreads widely, the temperature of the fire center becomes lower as shown in the top of the curve. From the this chart, we can know that if we place a fire alarm, we must put it in the upper place of some combustible objects. Thus, we can get the fire alarm quickly and do something to extinguish it.

CONCLUDING REMARKS

The unsteady fire of a 3-D room has been simulated with the field modeling. The computational results obtained including flow field, isotherms and contours of mass fraction of fuel are plausible and promising. Some useful models, such as the k-ε turbulent model with the modification of buoyancy effects, the k-ε-g turbulent combustion model, the soot model, the six-flux radiation model, etc., have shown their good functions again and some of the predictions are in good agreement with some experiment data or people's experience.

But this subject is still under development and improvement, both models and numerical methods adopted for calculations are needed to be verified by comparison of predictions and experimental data exactly. Therefore, experimental studies on fire are required and appreciated.

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In Fig.1: 1 — Door (Open)
2 — Desk
3 — Window (Open)
4 — Bed
5 — Line heat source
6 — Fixed point

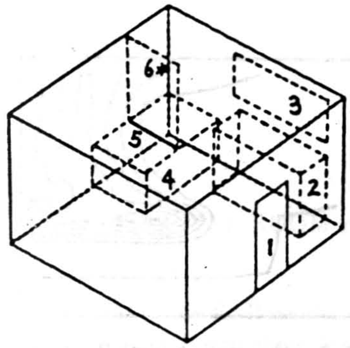
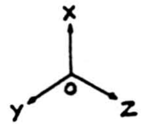


Fig.1 Studied zone



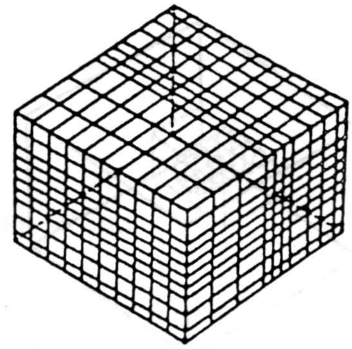


Fig.2 Calculating meshes

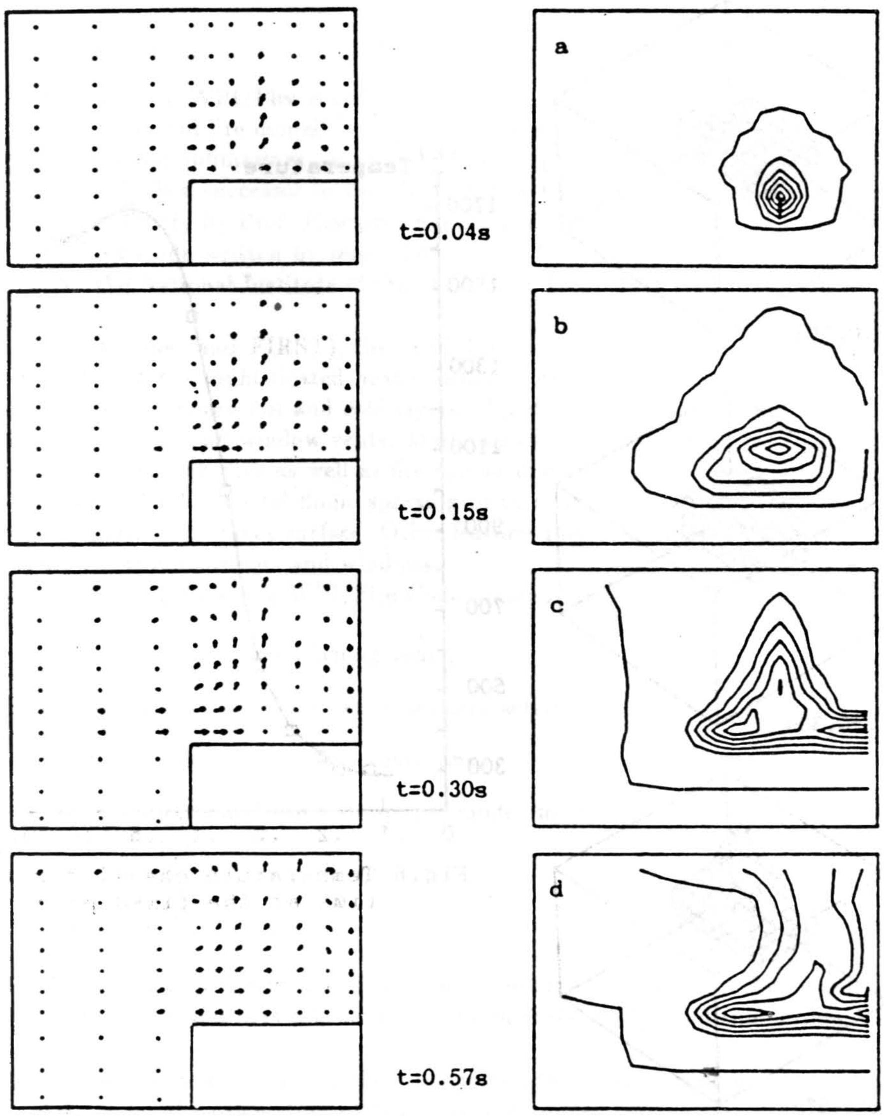


Fig.3 Velocity and isotherms at z=0.2
(Considering radiation)

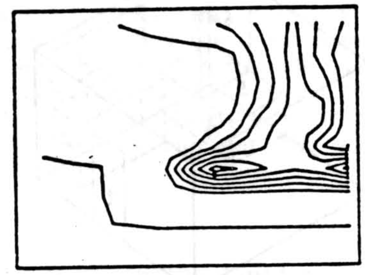
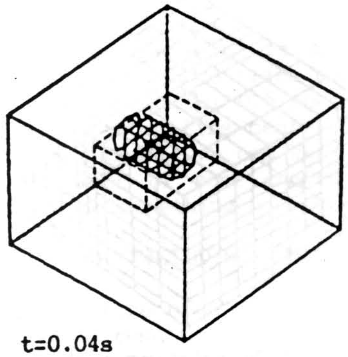
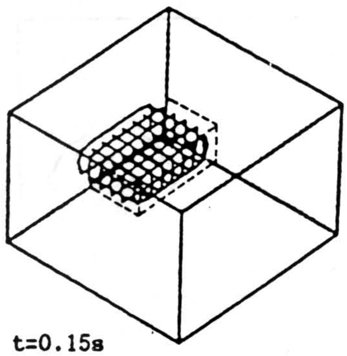


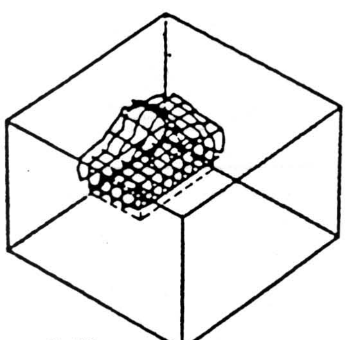
Fig.4 Isotherms at z=0.2, t=0.57s
(Neglecting radiation)



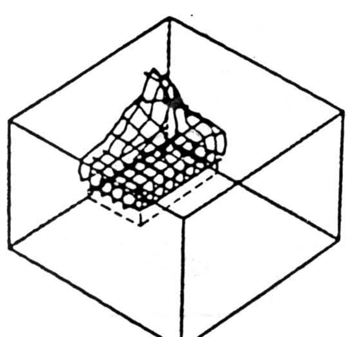
t=0.04s



t=0.15s



t=0.30s



t=0.57s

Fig.5 Process of fire spread

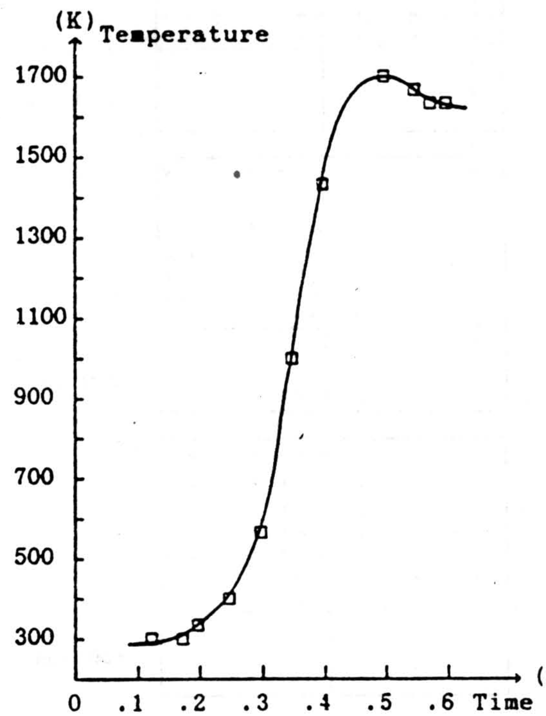


Fig.6 Temperature changing with
time at the fixed point