SOME NEW ASPECTS OF COMPUTER MODELING IN FIRE SCIENCE

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A.ABSTRACT

In this paper,three kinds of new model are proposed for compartment fire modeling.They are:Field-Zone model(FZ model in short),the main idea of which is to use field model for rooms of fire origin,with strong ventilation,or rooms of complicate geometry,etc;Field-Zone-Network model(FZN model in short),a further development of FZ model,in which the network is applied in rooms faraway from fire origin;Combined modeling of deterministic and probabilistic character(CDP model in short),which provides a framework showing the determinant,probability and their combination of fire rules.
Three simple cases are chosen to demonstrate the applications of these models. The preliminary results are plausible and promising.

B.INTRODUCTION

The continuing growing of fire damage has drawn attention of the human being.In the meanwhile of developing the detector and extinguish equipment,it's necessary to deepen the understanding of fire process;to lay a scientific fundamental for fire protection and control the damage.
"Fire Science",which study the mechanism and rules of occurring,fire growing and fire protection,is a new applied basic science with several branches interrelated.It is not only different from the conventional "disaster science" which is based on the statistical analysis of hazard data,but also different from the "engineering science" whose prime means is modeling research.Fire rules have dual nature:determinant and probability.The prime means of fire science is modeling research and statistical analysis and combination of them.
Computer modeling is an important aspect in the development of fire science.The basis of computer modeling in fire science is to accept that fire process has its laws which could abstracted into experimental formulae from practical fire data or experimental data,or into governing equations(algebraic or differential)describing the fire process.Computer modeling is multifarious.Empiric modeling combines the empirical formulae and the modern computer technology.Semi-physics modeling combines the empirical formulae and basic mathematical equations derived from the fundamental laws.The method and degree of the combination determine the variety of modeling.Physical modeling ,however,is a kind of advanced modeling based on the governing equations of mass,momentum,energy,chemical relation,etc.
The research of physics-mathematical model of fire process(called modeling for short) is bringing up vigorously in the international wide.Taking the building fire modeling as an example,Friedman listed and analyzed the existent 62 kinds of models in 1991.[i] In sum ,there are three kinds of models with regards to the method of modeling:network modeling,zone modeling and field modeling.In network models,the confined space in a building (a room for example)is regarded as an unit.The state parameters(gas temperature,species concentration,etc)are supposed to be uniform in the unit.The fire process is

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then described as the change with time of the parameters of every unit which forms the building.It is usually supposed in zone models that two zones could be formed inside a certain domain:the hot-gas layer above and the ambient-air layer below.The fire processes can be described as the changes of the height of hot layer and the states parameters in the space with time.Field models,however, must give the distribution of the state parameters and their changes with time in the studied domain of fire.The network model is only suitable for those zones far from fire origin.The zone models,to some extent,combines economy and reliability,but in some cases,for example,in a domain with complicated geometry and strong fire origin and strong ventilation,the two layers are not divided so clearly in fire. Large error would be produced in zone models because their presuppositions is no longer adaptable.Field model can provide with details of fire processes,but the capacity of computer required limits its use .Using field model for a high building fire is not practicable in the foreseeable future.

Is it possible to form new models? In this paper,the proposal of the Field-Zone modeling(FZ),the Field-Zone-Network model(FZN) and the Combined Modeling of Deterministic and Probabilistic Character(CDP) is just a kind of such attempts.The main idea of FZ modeling is to use field model in the domains with strong fire origin and strong ventilation,complicated geometry or those fire processes which need to be understood in details,and to use zone models in other domains.The difficulty in FZ modeling is the to deal with the interface of this two models.The FZN model,in which the network applied in the zones faraway from fire field,is a further development of FZ model.The application of FZN model makes it possible to simulate the fire processes within the whole building.The CDP model,however, is to provided a kind of framework or method which could show the determinant,probability and their combination of fire rules.Moreover,a software is produced to incarnate these characters in CDP model.The FZ,FZN and CDP model will be introduced respectively below as well as their practical applications.

C.FIELD-ZONE MODEL

Figure 1 shows the typical fire processes in two contiguous rooms:

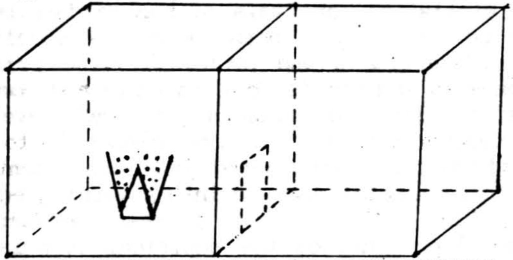

Fig.1 GEOMETRY OF THE 2-ROOMS BUILDING

The fire origin is inside the left room which is connected with the right room by a vent.A narrow fissure for pressure discharge is locate at the right side of the right room.

It is indicated by lots of experiments and fire field observation that the gas layering are unclear in the fire origin room,but in the connected rooms, the gas forms layer clearly.The FZ model is applicable for this character of fire with use of field model in fire origin room and zone model in the connected rooms.The fire processes in the origin room is usually a three-dimensional,unsteady,turbulent combustion influenced and activated by buoyancy.In order to describe this process quantitatively the parameters of the indoor fire such as the temperature of gas and solid,the gas velocity and the concentrations of species, etc. and their changes with time must be predicted.Therefore,the equations governing the fire process must be constructed.They include the basic equations of mass,momentum,energy and chemical reactions, the physical models for turbulence transportation, turbulent combustion, the production and destruction of soot, radiation and the interactions of these processes. The heat and thermophysical properties of the object inside the room such as the combustion heat of object, the specific heat and thermal conductivity of gas and solids, etc are needed. The initial conditions and boundary conditions must be specified. This kind of work has been referred to computational combustions[2] and the method of field modeling. The governing equations can be generally written as:

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i\phi)=\frac{\partial}{\partial x_i}(\Gamma_\phi\frac{\partial\phi}{\partial x_i})+S_\phi$$

To use zone models in the connected room is to construct the governing equations for the status and height of the hot lay and their changes with time taking account of the influences the fire origin, plume flow, ceiling jet flow and the mass and heat transfer, etc. The details of the zone modeling could be referred in the predecessor's work relating to zone modeling[3].

The difficulty of FZ model is to correctly deal with the interface between the zones of field modeling and zone modeling. That is, to give the status parameter of the gases flowing through the interface properly. The parameters are usually change with time and is not uniform along the interface. They influence not only the boundary conditions of field modeling equations, but also the source term of the governing equations of zone modeling. Therefore, there are two parts in dealing with the interface: the boundary conditions of governing equations in field modeling and the influences on the source of the governing equations for zone modeling. In general, the boundaries are composed of vents and solid walls. The effects of the wall is negligible. Only the boundary conditions of vents are discussed below.

1. The boundary conditions on the vents

Consider a control volume on the vent boundary, as shown in figure 2 The gratitude of variables u, w, k, ε are supposed to be zero across the boundary. The velocity component v can be calculated from mass continuity.

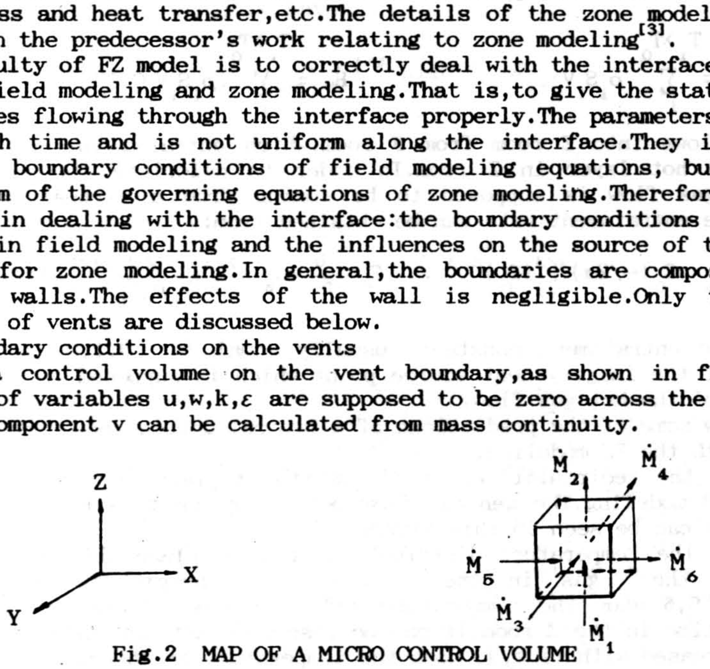

Fig.2 MAP OF A MICRO CONTROL VOLUME

$$\dot M_6=\dot M_1-\dot M_2+\dot M_5+\dot M_3-\dot M_4-\frac{\partial\rho}{\partial t}\cdot vol$$

Thus $v=\frac{\dot M_6}{\rho S_6}$, where S_6 is the surface of the control volume along the vent

The temperature T and other variables are determined by the V vector:

if V>0, the gratitude of the variables are zero.

if V<0, the variables remain the corresponding values inside the Z room.

For the pressure, it's suggested that the distribution along the boundary is identical with the pressure inside the Z room.

$$P = P_0\exp(-\frac{\rho_0 T_0}{T_i P_0}gh) \qquad h<h_0$$

$$P = P_0\exp(-\frac{\rho_0 T_0}{T_l P_0}gh_0)\exp(-\frac{\rho_0 T_0}{T_u P_0}g(h-h_0)) \qquad h\geq h_0$$

where h_o is the thickness of the hot gas layer. T_u and T_l are the temperature of upper and lower gas layer. ρ_o, T_o and P_o are the reference density, temperature and pressure respectively.

2.Effect on the source of zone modeling

Because the distributions of velocity component along the vents are determined in the field modeling, the mass and energy transfer through the boundary can be calculated. The mass flow rate and enthalpy flow rate are:

$$\dot{M} = \sum_i \rho_i S_i V_i \qquad \dot{H} = \sum_i \rho_i S_i V_i C_p T_i$$

$$\dot{M}_u = \sum_{i}^{T_i > T_o} \rho_i S_i V_i \qquad \dot{H}_u = \sum_{i}^{T_i > T_o} \rho_i S_i V_i C_p T_i$$

The hot gas flows into Z room from F room, which entrains the surrounding air to form a hot layer in Z room. In order to calculate the entrainment rate the hot-gas flow is supposed to be coming from a virtual heat-point source. Thus the entrainment rate can be obtained from:

$$\dot{M}_{ep} = C_o (\Theta/2\pi)^{2/3} (Z_o)^{5/3} \quad , \quad C_o = \frac{6}{5} \alpha \rho_o \pi^{2/3} \left(\frac{g\dot{Q}}{C_p \rho_o T_o}\right)^{1/3} (9\alpha/10)^{1/3}$$

where α is the entrainment constant, usually equal to 0.1, $\dot{Q}$ is the heat release rate of the imagery heat source point which is supposed to be located at the middle of the hot gas flow.

Figure 3-6 show some of the predictions of a typical double-room fire sketched in figure 1 with the FZ modeling.

Figure 3 shows the recirculations in the middle z plane in the fire origin room with field modeling. The general flow pattern along this plane driven by the heat source can be seen in this figure.

Figure 4 shows the temperature distribution in this plane. All these results indicate that the gas in the room of fire origin is not clearly layered. Figure 5,6 show the temperature and thickness of the hot gas layer changing with time in the Z room. It can be observed that the thickness of the hot gas is increased with time, so does the temperature of the hot gases layer.

D.THE FIELD-ZONE-NETWORK MODEL(FZN)

In the rooms faraway from the fire origin, because the parameters inside them are relatively uniform, the network method is usually adapted. That is to divide these spaces into several different network nodes, and suppose the temperature and other parameters to be uniform in these nodes, and then construct the governing equation for each nodes based on the mass and energy conservation laws, and calculate the status parameter's and their changing with time.

The basic idea of the FZN models is to apply field models to those rooms in which the gases layering is unclear, apply zone models to those rooms nearby, and network models to rooms faraway from fire origin. Thus, a computer code can be written to predict the fire processes in the whole building. Based on the FZ models, the important point in the FZN model is how to combine the network models to FZ models properly and form an unified method, and how to deal with the interface of zone model and network model.

Just as the FZ model, here we lay the emphasis on the flow through the boundary of vents.

The variation of pressure of these two rooms with height are:

$$P_{1y} = P_1 \exp\left(-\frac{\rho_0 T_0}{T_1 P_0} gy\right), \qquad y<h_r-h_0$$

$$P_{1y} = P_1 \exp\left(-\frac{\rho_0 T_0}{T_1 P_0} g(h_r-h_0)\right)\exp\left(-\frac{\rho_0 T_0}{T_h P_0} g(y-(h_r-h_0))\right), \qquad h_r>y\geq h_r-h_0$$

$$P_{2y} = P_2 \exp\left(-\frac{\rho_0 T_0}{T_r P_0} gy\right)$$

where H_r is the height of room ,H_0 is the thickness of hot lay in the Z room;T_h and T_l are,respectively,the temperature of hot gas and cool gas;T_r is the temperature inside the room using network model;P_1,P_2 are,respectively,the pressure of floors of these two rooms.

To obtain the mass and energy transfer through the vent,we divide the vent into n strips,For each strip we have

$$\dot{M} = C_d B_v \frac{h_v}{n} \cdot (2\rho\,|P_{2y}-P_{1y}|)^{1/2} \operatorname{sign}(P_{2y}-P_{1y})$$

$$\dot{H} = C_p T\dot{M}$$

where,

$$\operatorname{sign}(P_{2y}-P_{1y})=1 \qquad \text{if } (P_{2y}-P_{1y})>0$$

$$\operatorname{sign}(P_{2y}-P_{1y})=-1 \qquad \text{if } (P_{2y}-P_{1y})<=0$$

$T=\frac{\text{sign}+1}{2}T_2 + \frac{\text{sign}-1}{2}T_1$,The value of T_1 is either T_h or T_l depending whether the point is in the hot layer or not.

In this paper,a fire processes inside a five-storied building shown in figure 7 is simulated with the FZN method.The floor areas of the room and the stairway are all 1.3m × 1.3m.The height of a single floor is 1.3m.The area of each vent is 0.39m(W)×0.78m(H)(except for the vent between the fire origin room and the outside,whose area is 0.39m(W)×0.50m(H)).A heat point source is located in the F room simulating the fire origin.The flow and transport of the hot gas inside the building is predicted with neglecting the radiation.

Some of the results are shown in figure 8-14. The figure 8,9,and 10 show the temperature distributions,recirculations and the flow patterns on the middle z plane of the F room at 0.5s,7.5s and 15.5s after ignition respectively.The temperature distribution contains a series of isotherms,their values can be expressed by $T=288.15+(1050-288.15)\times\alpha$,where α takes the value of 0.0,0.0002,0.002,0.2,0.3,0.4,0.55,0.85 and 1.0 respectively.It can be seen clearly that the hot-gas flow driven upwards by the buoyancy, and forms recirculation on each side of the fire source.A hot-gas layer is formed after hot-gas flow reaches the ceiling and accumulated.The thickness of the hot-gas layer increases with time.After a certain period,the bottom of the hot-gas layer reaches the top of the vent,and flows out from the upper part of the vent to the environment or Z rooms.Meanwhile,the cool air flows into the the room from the lower part of the vent.Figure 11 and 12 show the temperature and thickness of the hot-gas layer of the Z room changing with time.As shown in the figures,the thickness of the hot gas-layer remains zero in the first 2.5 seconds.This is because that the hot gases in the F room has not descended yet to the top of the vent.After 2.5 seconds,the hot gas-layer begins to form in the Z room.During the initial period(2.5s-8.0s),the temperature and thickness of the layer increased slowly and the slope of the contour is small.Afterwards,however,the slope of the contour increased,and temperature and thickness of the layer increased more rapidly,presenting an approximately exponential distribution.

Figure 13 shows the trend of flow on the network nodes at each time steps.Those figures in which no arrows is marked indicate that the flow in this place is not clear enough,and its velocity is almost equal to zero.Figure 13(a) shows the flow pattern inside the building at t=0.5s.Because the the fire source releases heat and gasified mass in the F room,the inside pressure increases,and the gas flows out into the Z room,and upward finally along the stairway and flow into the rooms in each floor through the vents.Figure 13(b) is the flow pattern at 2.5s,the flow rate increases,and gas in the N2 room begins to flow into the environment through the vent.Figure 13(c) shows the flow at 4.5s,the trend of flow remains unchanged,but the flow rates begin to decrease due to the decrease of pressure in Z room caused by the F room's entrainment.With Z room's gas being further entrained,the pressure in Z room becomes lower than in the stairway,and the gas in the stairway flows reversely.However the pressure of N8,N11 rooms increases due to inertia,and gas in these rooms flows out.These phenomena can be seen in figure 13(d).With further heat release of the fire origin,the pressure in the Z room increases again and the flow resumes its former pattern.Figure 13(e) to 13(h) illustrate the gradual process of the flow pattern's changing.

After about 16.25s,the thickness of the hot-gas layer comes to 10.0cm.At this moment,the upper edge of the vent between the Z room and stairway is supposed to move upwards so as to increase the height of the vent to 1.25m.Therefore,the hot gas in the Z room begins to flow out of the room into the stairway and permeates into the whole building.

Figure 14 shows the temperature of each network node related to the zone modeling room at several time step afterward.

E.COMBINED METHOD OF DETERMINISTIC AND PROBABILISTIC CHARACTERS.(CDP)

There are rules for fire occurring,growing and fire protection.These laws,however,are neither totally deterministic nor totally probabilistic.They have both deterministic and probabilistic character.Only if we investigate the determinant and the probability and their combination can we understand the rules of fire as a whole.The duality of rules of fire could be demonstrated by taking the fire occurring as an example.If the combustible objects,environment conditions are given.It can be determined whether a specific fire source can cause a fire with the advanced scientific experiment and computer modeling.However,as a hazard,fire always covers a wide range to some extent.The human behavior,the variety of combustible objects,environment conditions and fire source,etc,inevitably give rise to the probability of fire occurring which makes it undeterminable to predict definitely whether or when or where the fire will occur.Thus,the reasonable goal of investigation is to provide the probability of fire occurring and its connections to various factors.Just as the fire occurring,fire growing and fire hazard also have both deterministic and probabilistic character.

The prime method to study the deterministic of fire is modeling research,and the main method to investigate the probability is statistic analysis.The modeling methods,composed of experimental modeling and computational modeling,are various,and so do the models applied in statistics analysis.The purpose of this section is not to review the existing modeling and statistic methods,but to try to propose a kind of theoretical framework which could contain various modeling methods and statistics methods and could give the combined influence of determinant and probability,and then combine the two components and show the dual-nature character of fire.Let's demonstrate this process in the case of study of the influence of combustible object property on the probability of human risk in a room.

Suppose that the gas layer will become hazardous to human body(i.e. reach to the hazardous status) whenever its temperature reaches to 473.15K or its height gets to 1.5m.The probability of each objects inside the room causing a fire are different, showing the probabilistic character of fire.These probabilities can be obtained only through statistics.The heat release rate of each object and its influence to the temperature and height of the hot layer can be obtained through experiments and zone method,showing the deterministic character of fire.Now,we aim at calculating the probabilities of fire hazardous to human being at a certain time.

Consider a room of 4m in both length and width,3m in height.Suppose the probabilities of the three kinds of furniture:bed,sofa and desk causing fire are 60%,30% and 10% respectively.The material of these three types are fibers,foam plastic and wood.The area of them are 2.5 m^2 ,2m^2 and 1m^2 .Their heat release rates which could be obtained by experiments,are showed respectively in figure 15 (a),(b) and (c).It can be calculated through the general formula[4]of zone method that the room reaches hazardous status at 255s,215s and 265s respectively after each kind of furniture ignited.It is almost impossible for the object inside the room to ignite each other before the hazardous status is reached.Therefore,the relationship between the time and the probability of the room reaching hazardous status can be obtained ,as shown in figure 16 .The curve b of this figure demonstrate the probability of the room reaching hazardous status for the materials of these three kinds of furniture are all wood.

It could be observed that the probabilities of combustible objects causing fire,the combustion property of furniture and the thermal property of the room have direct influence on the time and probability of room reaching hazardous status.

F.CONCLUSIONS

The FZ modeling and FZN modeling have provided new ideas and method for the computer simulation of fire processes in a building.Considerations are given to both computational economy and precision in these methods.

The combined modeling of Deterministic and probabilistic characters of fire correctly demonstrates the dual nature rules of fire and provide the mathematical framework for describing this character qualitatively.

This paper lays its emphasis on the basic idea and method of FZ,FZN and CDP modeling.The cases selected are demonstrative,which need further development and verification.

G.REFERENCE

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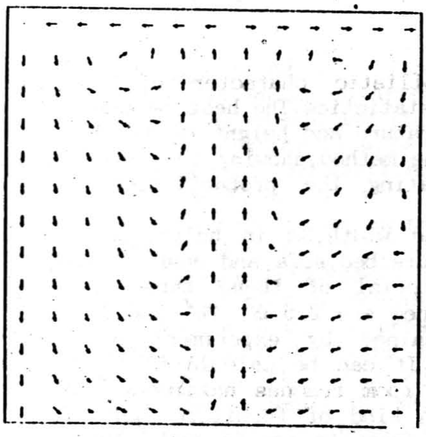


Fig.3 RECIRCULATION OF THE Z PLANE

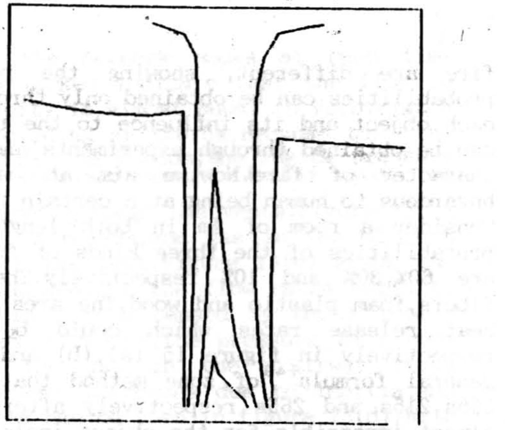


Fig.4 Z PLANE'S TEMPERATURE DISTRIBUTION

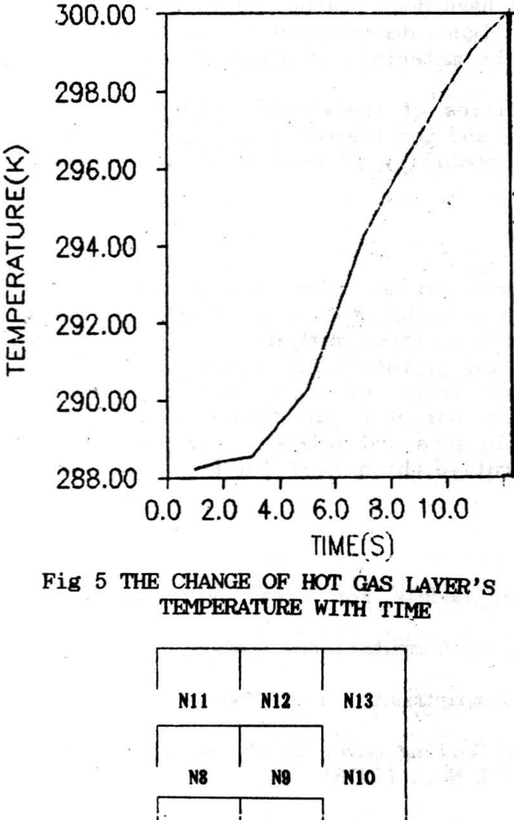


Fig 5 THE CHANGE OF HOT GAS LAYER'S TEMPERATURE WITH TIME

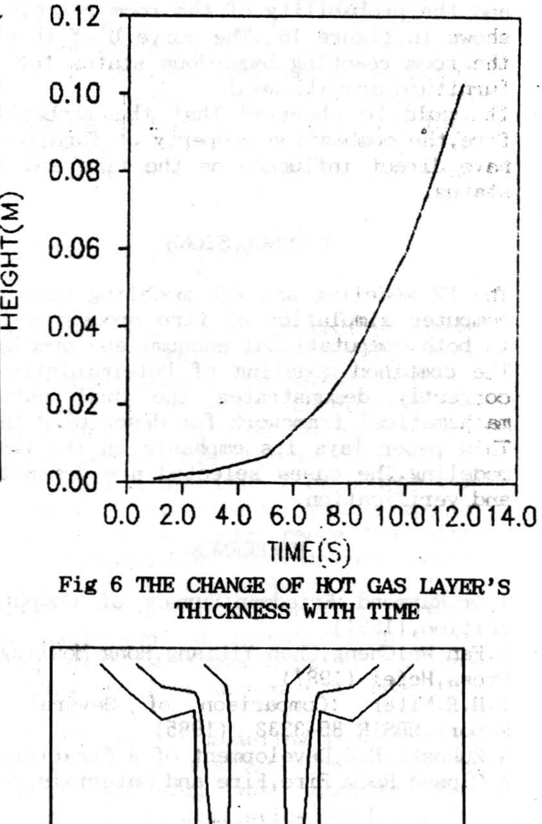


Fig 6 THE CHANGE OF HOT GAS LAYER'S THICKNESS WITH TIME

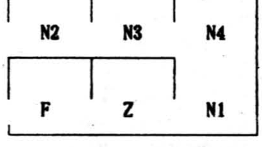


Fig.7.THE FIVE-STORIED BUILDING

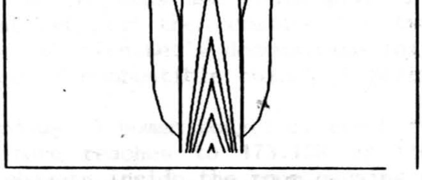


Fig.8 Z PLANE'S TEMPERATURE DISTRIBUTION

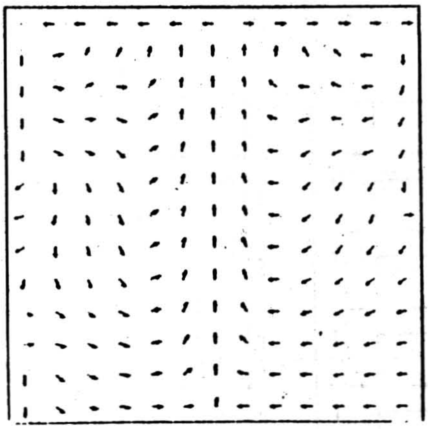


Fig.9 RECIRCULATION OF THE Z PLANE

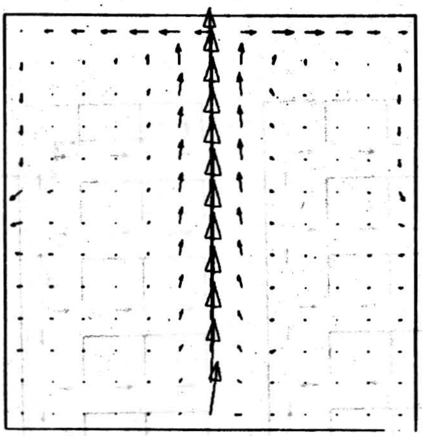


Fig.10 Z PLANE'S VELOCITY DISTRIBUTION

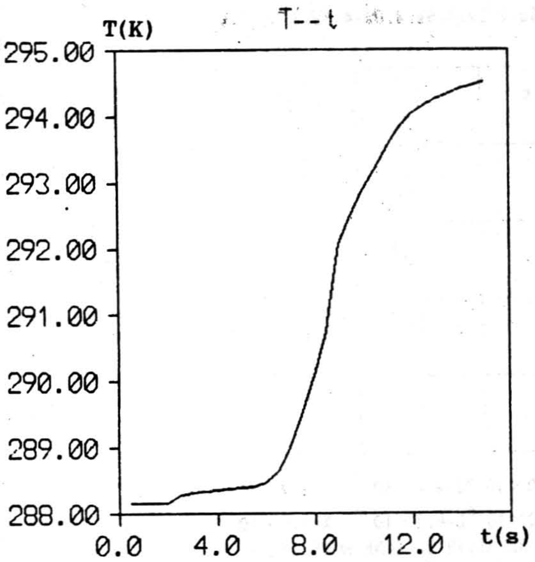


Fig 11 THE CHANGE OF HOT GAS LAYER'S TEMPERATURE WITH TIME

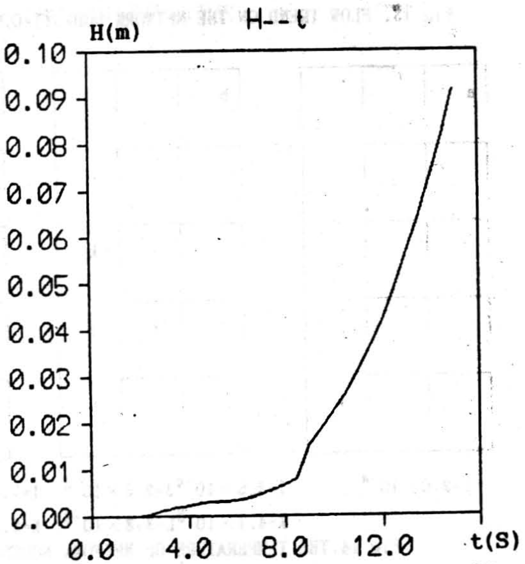
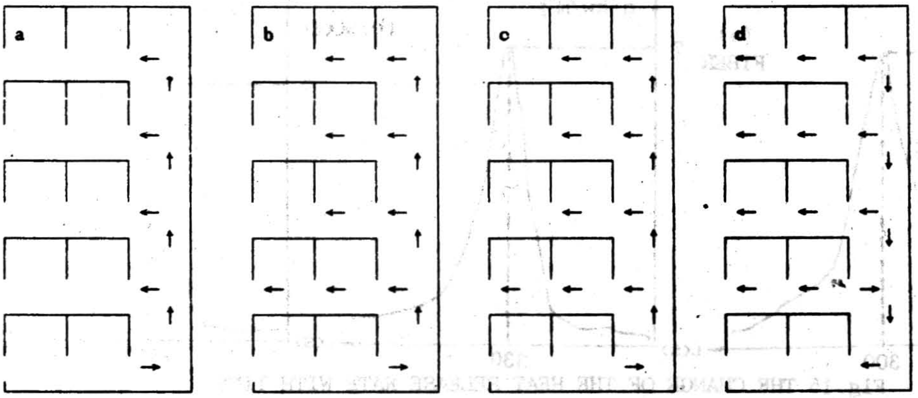


Fig 12 THE CHANGE OF HOT GAS LAYER'S THICKNESS WITH TIME



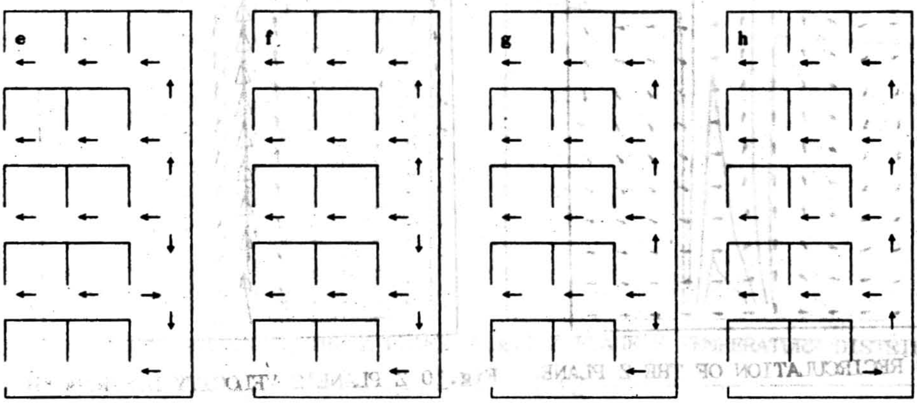
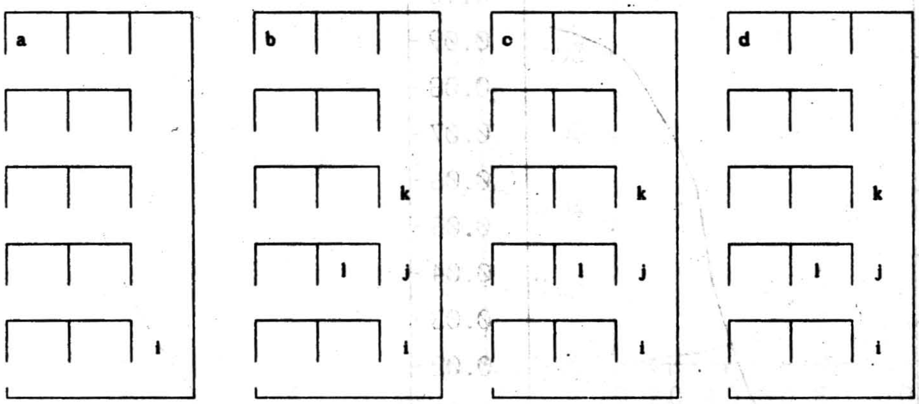


Fig 13. FLOW TREND ON THE NETWORK NODES(T=0.5s,2.5s,3.5s,4.0s,4.5s,5.0s,5.5s,6.0s)



I=2.0×10^{-4}

I=4.5×10^{-4} J=2.5×10^{-6} K=4.7×10^{-8} L=3.8×10^{-8}

I=7.0×10^{-4} J=8.0×10^{-6} K=8.0×10^{-8} L=6.1×10^{-8}

I=1.2×10^{-3} J=1.2×10^{-5} K=1.0×10^{-7} L=7.8×10^{-8}

Fig 14. THE TEMPERATURE OF NETWORK NODES RELATIVE TO ZONE MODELING ROOM (T=16.25S, 16.5S, 17.0S, 17.25S)

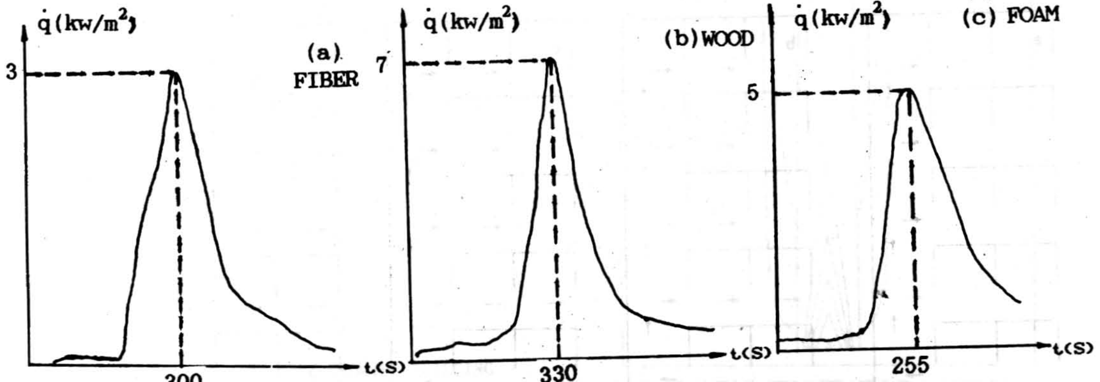


Fig.15 THE CHANGE OF THE HEAT RELEASE RATE WITH TIME

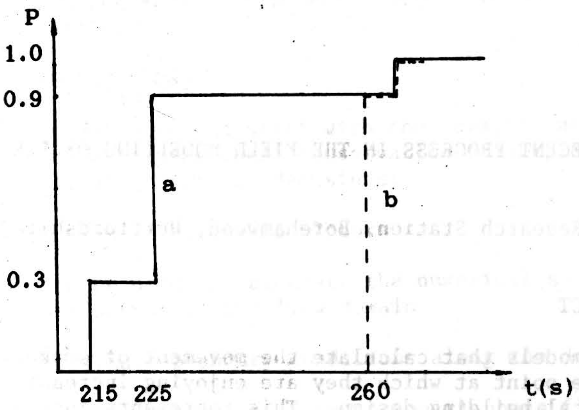


Fig.16 THE CURVE OF THE PROBABILITY-TIME