Convective Smoke Spread in a Corridor

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ABSTRACT

Convective smoke spread in a corridor is experimentally investigated using thermocouples and visualization technique with a laser beam sheet. The speed of a smoke front under a ceiling is measured by a series of thermocouples. Visualization of the ceiling jet formation and of smoke filling process is carried out to observe the lowering of a smoke layer. From the results, a large-scale convective motion plays dominant roles for smoke spread in the vicinity of the end of the corridor from visualized photos along with temperature records. The large-scale convective motion of the smoke is generated from the impingement of the ceiling jet front on the end of the corridor, and thus turning the flows toward the floor. Such a circulating motion of fluid transports some smoke to some region where its momentum is effective. It is therefore shown that the conventional concept of lowering smoke in the two-layer zone model has some restrictions for a corridor because the lowering of smoke layer has been thought to be mass transport due to relatively small scale motions such as the decrease of buoyancy, mass diffusion and momentum exchanges.

KEY WORDS : Smoke spread, Corridor, Ceiling jet front, Visualization, Convective motion

1. INTRODUCTION

Smoke spread in buildings has been one of main interests of fire science and engineering. The phenomena of the smoke spread, as one factor of a life safety design, must be understood and estimated. There has been considerable research works in the area of smoke movement in multicompartment structures, and much of the attention has focused on the development of numerical models that are able to make reasonably accurate predictions from the time of ignition.[1-3] These numerical models are based on the two-layer zone concept in which it is assumed that there are two distinct zones or volumes in each compartment ; one consists of a relatively hot smoke and the other is a cold air. The postulate of the two-zone concept is that details within each of the zones are not important. It has thus been said that the smoke fro: fires enters into the hot layer, which is followed by the lowering of the smoke laye Physically such the lowering is believed to lie in the loss of buoyancy, mass diffusion ar momentum transfer.

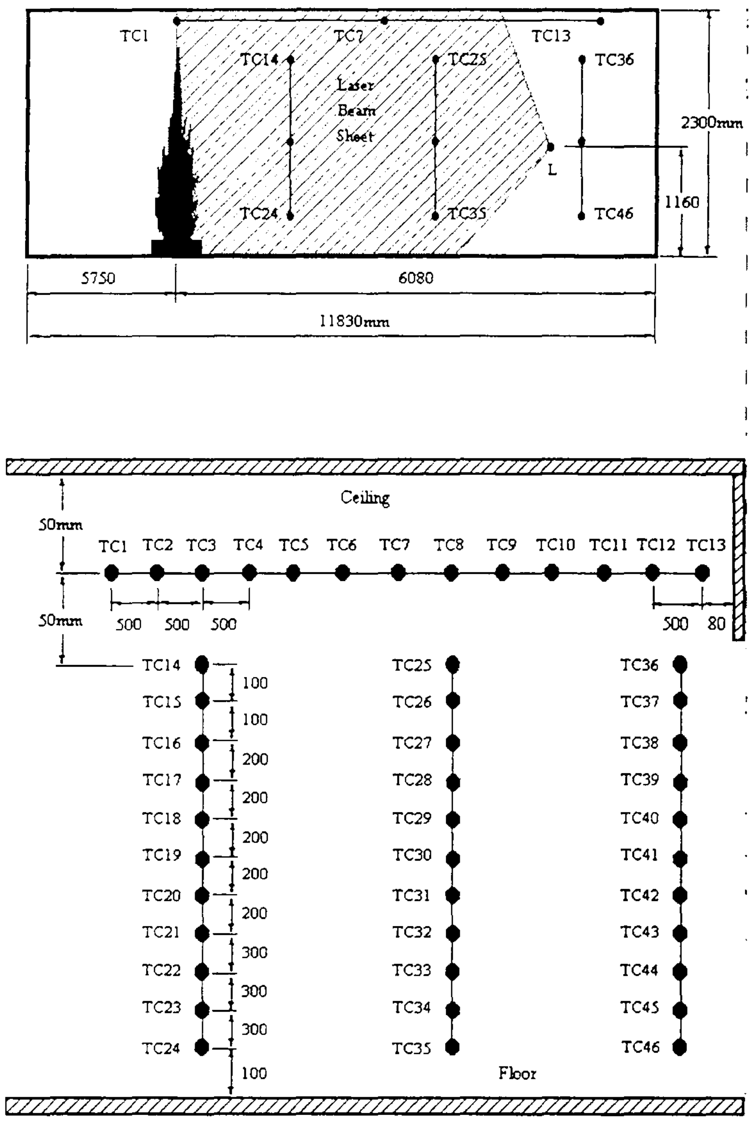

Fig.1 Schematic of the experimental lay out. The thermocouples "TC" and the laser bear sheet "L" are shown to indicate the type of data.

Corridor smoke filling is studied by several zone models and by experiments.[4] Among instrumentation to measure the smoke layer height, has been used one thermocouple tree. vertically installed thermocouples at only one position along the corridor. However, the t zone concept has basically some restrictions with the compartment like the corridor of wh length is large enough as compared with the height of the corridor. Because it will take so times for the front of the ceiling jet to reach the end wall of the corridor, the uniform lower of smoke from the ceiling can not be expected. In addition, in a tall compartment, hot ns plumes maybe become stagnant somewhere in certain circumstances because of heat transfer to surroundings. In both cases the assumption that each zone preserves uniform properties is not justified any more.

In the present study multi-thermocouple-trees and visualization technique with a laser beam sheet were preferred in order to observe the variation of the smoke layer along the corridor. The speed of the smoke front under the ceiling was measured by a series of thermocouples and compared with a known equation. The ceiling jet formation and smoke filling process were also visualized to show that the smoke spread in the corridor was controlled by a large-scale convective motion after the ceiling jet front reached the end of the corridor. Here, the large-scale motion signifies several activities to transport smoke by fluid flows themselves, not by small-scale motions such as the cooling of smoke, mass diffusion due to different concentrations and the transfer of momentum to the cool air.

2. EXPERIMENTAL PROCEDURE

The corridor was designed without any openings and an intentional leak, and an effort was made to minimize effects of an outside air on the smoke spread inside. The floor plan was 2.83×11.83 m, with a height of 2.3 m. A fire was simulated with a 15 cm liquid gasoline pool burner positioned on the floor. Experiments were carried out using thermocouples and Ar-ion laser beam in the type of a sheet. Thirteen thermocouples were installed 5 cm below the ceiling to measure the speed of front of the ceiling jet. Also, three thermocouple trees in which each tree consisted of 11 thermocouples, were used to trace smoke distribution in the corridor.

The laser sheet was adjusted to make a plane consisted of temperature measuring points. The plane and the axis of the fire center located at the midway of the width of the corridor. Smoke generating devices were not necessary since the laser sheet would visualize smoke movement by scattering of several particles contained in smoke. Instantaneous pictures of the smoke spread in the corridor were being captured by a video camera. The more detailed schematic of experimental layout is shown in Fig.1, where numbering of the thermocouples was done in favor of analysis.

3. RESULTS AND DISCUSSION

3.1 THE VELOCITY OF THE CEILING JET FRONT

To figure the fire size, as seen in Fig.2, the evaporation rate of fuel was represented to increase from the time of ignition and began to level out after about 120 s. The heat of combustion of gasoline is 4.39×10^4 KJ/Kg, and the combustion efficiency is suggested to be 0.73 for the fraction of the heat of combustion that is actually released in the fire.[5] The estimated fire size was shown in Fig.3.

Smoke from the fire was moving upward and reached the ceiling. There, the smoke flow was changed to go downstream along the ceiling. The arrival of the hot smoke front at each thermocouple was identified by the abrupt increase from the ambient temperature, as demonstrated in Fig.4. The traveling time over the corresponding distances could thus be obtained. The velocity of the smoke front was simply calculated and summarized in Table 1.

It was known that the average velocity in Table 1 decreased as the distance from the fire increased. This phenomenon is due to the cooling of the relatively hot smoke, the transfer of momentum to the cool air and frictional forces between the ceiling and the moving smoke. The cooling of the hot smoke along the downstream direction was clearly observed in Fig.5.

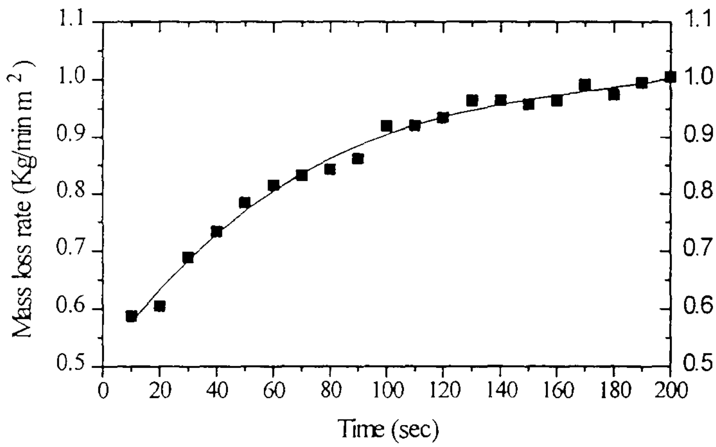

Fig.2 Mass loss rate of the gasoline pool fire

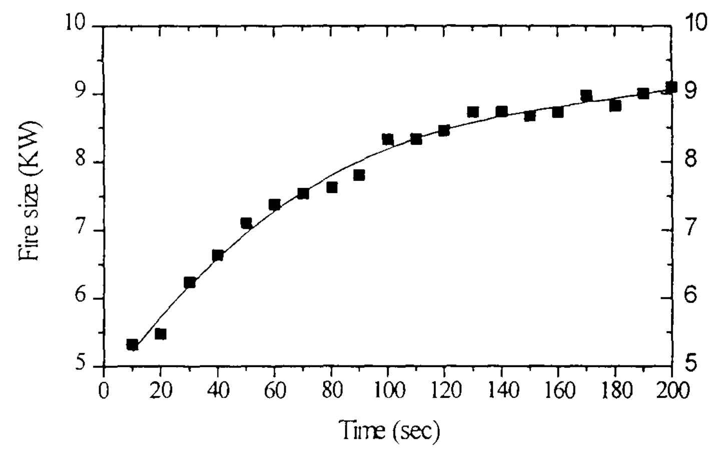

Fig.3 Fire size of the gasoline pool fire

Hinkley[6] has given a tentative theory for the flow of hot gases along a mall. It is assumed that the smoke layer will consist mainly of air heated by entrainment into the rising hot gases over the fire, and that any effects on the flow due to differences in composition between the hot gases and the cool air can be neglected. It is also considered that the hot gases are flowing only in one direction along the mall. In practice, the hot gases might generally be flowing in both directions away from the fire. The velocity of the hot gases in the layer will be determined by the buoyancy, frictional and inertia forces, the momentum transfer to the cool air and finally viscous forces. However it is suggested that the viscous forces may be neglected and that the flow pattern will then be a steady state problem governed by the Froude number ; the ratio of the inertial and buoyancy forces. In this way, an expression for the mean velocity of the gas layer moving under a ceiling in a mall becomes

$$v = 0.8\left(\frac{gQT_g}{\rho_a C_p T_a^2 W}\right)^{1/3}$$

where v = mean velocity of the gas layer

g = gravitational acceleration constant

Q = heat output of the fire

T_g = absolute temperature of the gases

ρ_a = density of the cool air

C_p = specific heat of air at constant pressure

T_a = absolute temperature of the cool air

W = width of a mall.

Table 1 The average velocity of the smoke front

Reference thermocouple No.	Corresponding thermocouple No.	Traveling distance (m)	The average velocity (m/s)
1	3	1.0	0.67
1	4	1.5	0.48
1	5	2.0	0.43
1	6	2.5	0.32
1	7	3.0	0.32
1	8	3.5	0.32
1	9	4.0	0.32
1	10	4.5	0.29
1	11	5.0	0.29
1	12	5.5	0.27
1	13	6.0	0.26

When the smoke front reached the end wall of the corridor, the properties required for the calculation of the front velocity by the above equation were T_g =313 K, T_a =300 K and Q =6,000 W. The calculated velocity was 0.31 m/s, while the measured one was 0.26 m/s. In spite of the difference in two velocities, the equation seems reasonable since it has been assumed in the theoretical derivation that smoke is going only in one direction along the ceiling.

3.2 SMOKE SPREAD BY VISUALIZATION

Visualization of smoke flows by the light scattering gets several advantages over the conventional method using a smoke generator that has the possibility of disturbing flow fields. Along with these disturbances will be produced a large amount of smoke that does not even relate to the heat release rate of fires. The stages in the formation of the smoke layer were depicted in Fig.6. Initially, Fig.6 (a), the fire gases were approaching vertically the ceiling, and, in turn, they were impinging on the ceiling in Fig.6 (b) and (c). The smoke flows turned their direction to go horizontally toward the end wall of the corridor. As presented in Fig.6 (d to (i), the ceiling jet was being developed, and Fig. 6 (i) was at the time when the front of the ceiling jet reached the end wall. From the shape of the ceiling jet, the depth of the layer increased along the corridor, which had been predicted analytically and shown by velocity and temperature measurements in other works[7,8]. From Table 1 and Fig.5, it was understood that as the velocity of the ceiling jet front decreased downstream due to cooling the depth of the layer increased to maintain the rate of flow of smoke. In Fig.6, the small bright parts at the lower right corner within each picture were the rays very near the laser source where the beam had a higher intensity, and also the bright and inclined straight lines in the upper parts were formed by the scattering from the ceiling. It can thus be known that the thickness of each line was that of the laser sheet.

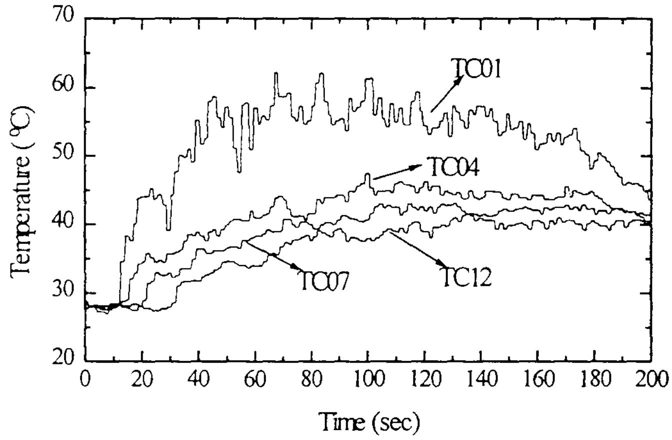

Fig.4 Temperature records of the smoke under the ceiling

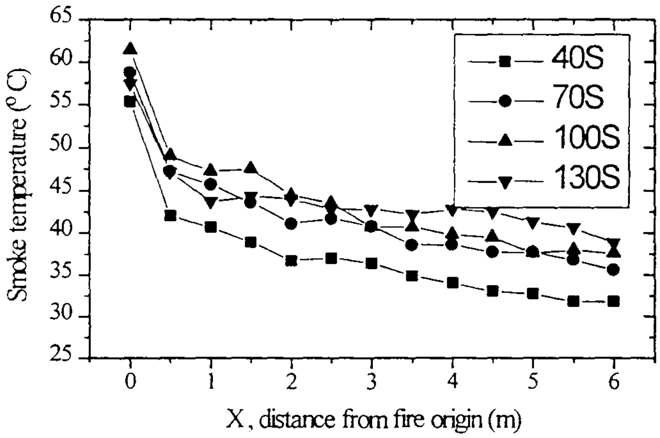

Fig.5 Longitudinal temperature distribution in the corridor

In the next stage, Fig.6(j), the layer depth suddenly increased near the end wall so that smoke was also observed around the laser source. This strange development of the layer, as seen from Fig.6(i) and (j), needed only a few seconds after the arrival of the smoke front at the end of the corridor. It may be noted that such a sudden change of the smoke layer does not

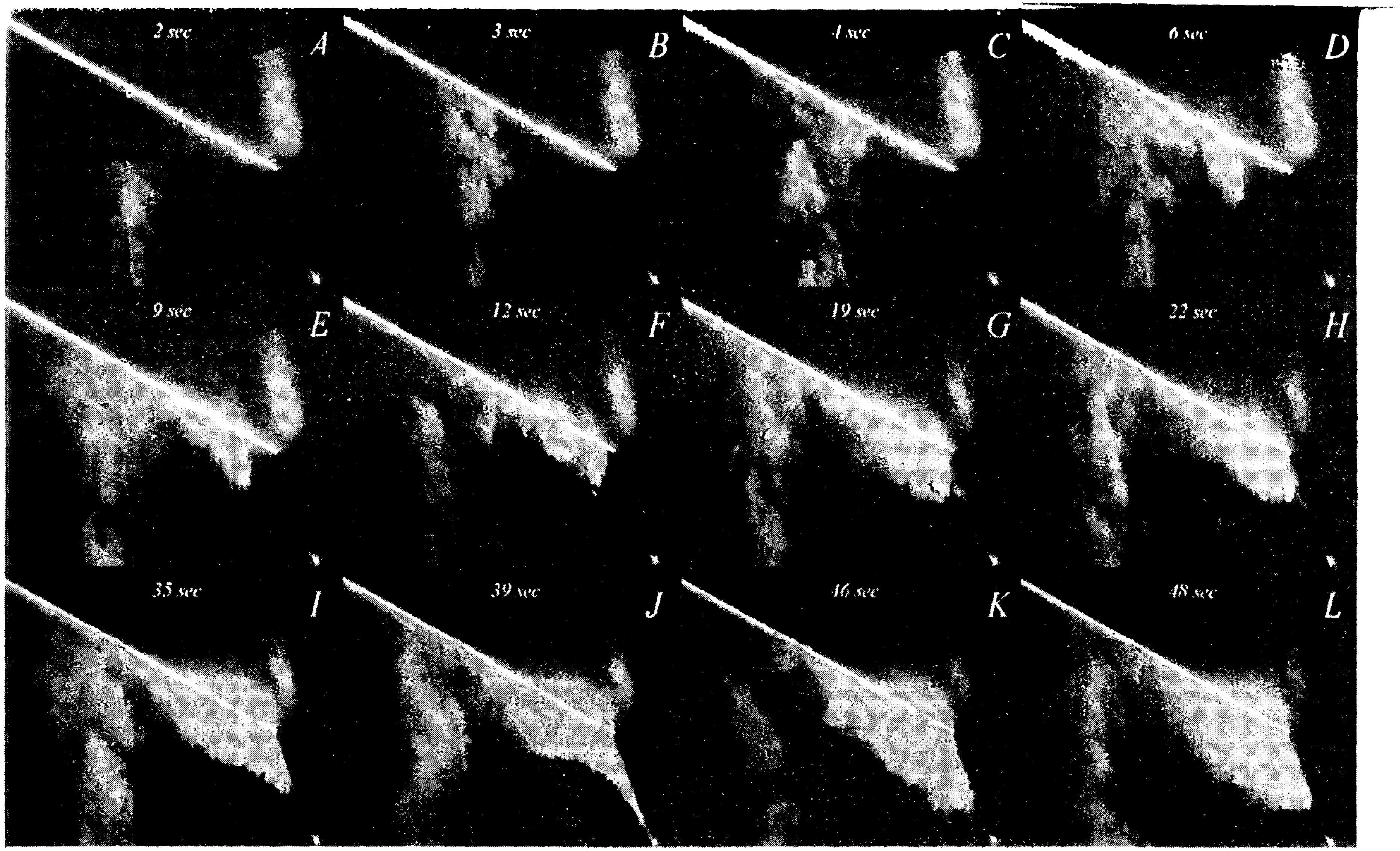

Fig.6 Smoke filling process in the corridor (to be continued)

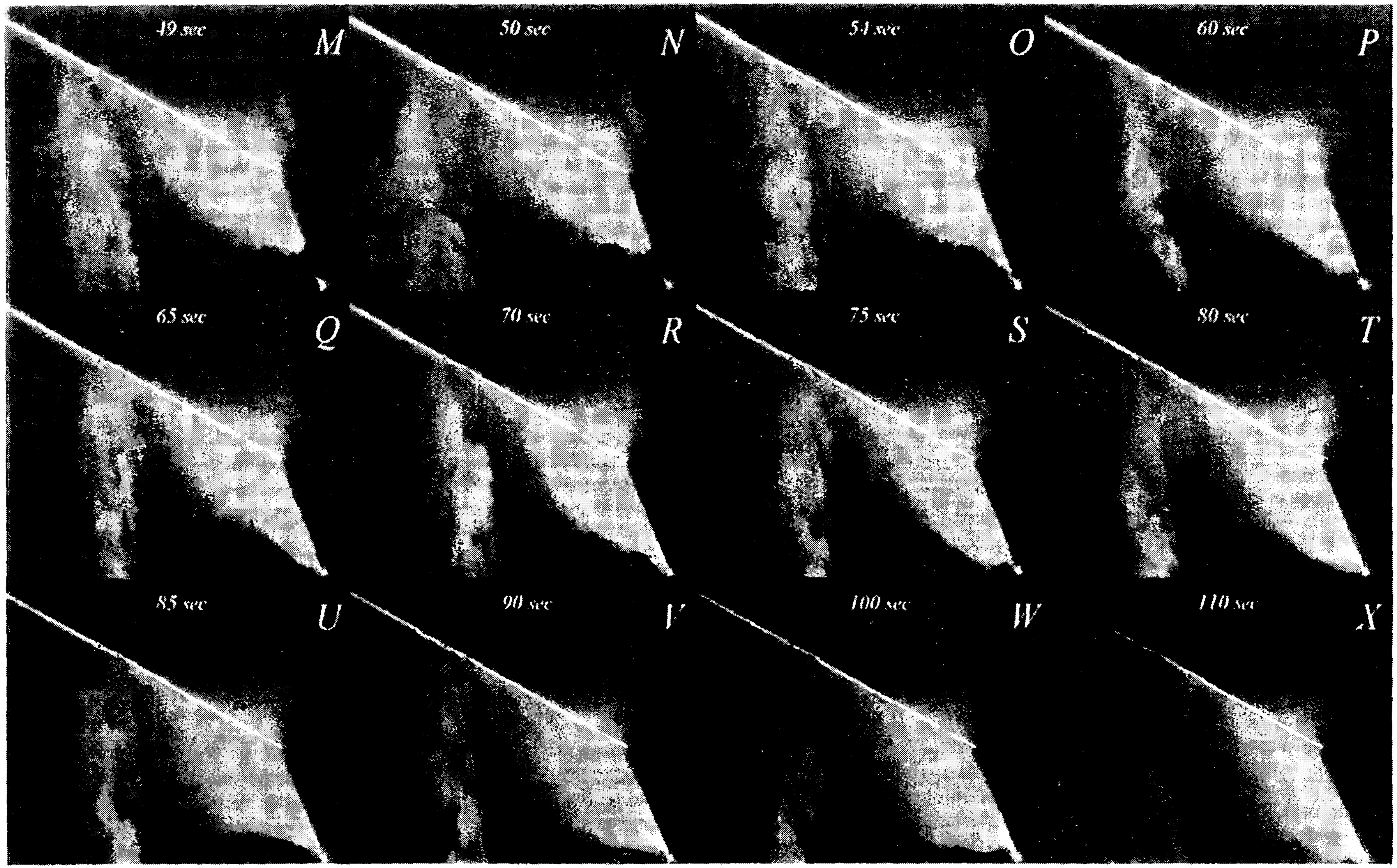

Fig.6 Smoke filling process in the corridor

come from the loss of buoyancy, but from recirculating motions generated by the impingement of the ceiling jet on the end wall. Furthermore, from Fig.6 (k) to (n), the smoke did not exist near the laser source, but following Fig.6 (o) surely showed smoke there. This fact seems due to oscillating behavior of the temperature at TC41 of Fig.7 (d), and the oscillation is believed to originate from so called vortex shedding[9-11] of pool fires. Since the large-scale turbulent eddies of plumes are periodically produced to affect the recirculating flow, instantaneously the low-density smoke can be there.

Serial process from Fig.6 (k) to (r) illustrated that the air layer between the rising plumes and the ceiling jet was being filled with smoke and that the air layer was spreading upwards. Noting that the hot rising plumes may entrain the surrounding gases by vortex puffing[11], the large-scale coherent structure. The rest of Fig.6 revealed that the depth of the smoke layer was becoming uniform along the corridor and that the low-density smoke region between the upward plumes and the smoke layer formed from the ceiling jet was lasting. In a whole aspect, a clear height filled with a fresh air varied over the entire length of the corridor during the initial period of the fire, and the smoke boundary was clear vertically while obscure horizontally near the upward fire plumes.

3.3 SMOKE SPREAD BY THERMOCOUPLE TREES

Smoke spread is examined from measurements using three thermocouple trees positioned along the corridor. The first tree consisted of 11 thermocouples was standing 1.0 m apart from the axis of the fire plumes, and locations of other two trees and of each thermocouple within each tree were expressed at detail in Fig.1. Unless the ceiling jet reaches very fast the end of the corridor, the spreading of smoke will vary along the corridor because the smoke lowering occurs simultaneously with moving of the ceiling jet front downstream. Each graph of Fig.7, a series of temperature records at the same height above the floor, showed that the smoke detection times at particular level were different along the corridor. For instance, the ceiling jet front took about six seconds from the location of TC3 to TC8, and simultaneously about one second for the smoke lowering from TC3 to TC17. From TC8 to TC28 of the same height as TC17, it will also take some time. By these reasons it was observed that the rate of the smoke lowering is slowest near the end of the corridor as in Fig.7 (a) and (b).

However, the above situation had not continued after the arrival of the ceiling jet front at the end of the corridor from the rest of Fig.7. The impingement of the ceiling jet front upon the end of the corridor will turn the convective motion of smoke to the floor. Such a recirculating flow will carry smoke to the places where its momentum is still effective. Comparing with the smoke lowering caused by the loss of buoyancy and by mixing among different concentrations, the above large-scale motion means the convective transport of smoke. It was thus clear that the rate of the smoke spreading was fastest near the end of the corridor in Fig.7 (c) to (e), which was exactly an opposite trend to Fig.7 (a) and (b). Also, the oscillating temperature of TC41 that would closely related to the convective flow, seemed to be responsible for the strange behavior of smoke in the vicinity of the laser source, earlier mentioned in the section of the visualization.

Consequently, smoke spread in the corridor is controlled by the small-scale actions such as the cooling of the smoke, mass diffusion and momentum transfer to the cool air during the initial period of the fire, i.e. before the impingement of the ceiling jet front upon the end of the corridor. After the initial period, the large-scale activity becomes governing smoke spread according to the convective transport of it.

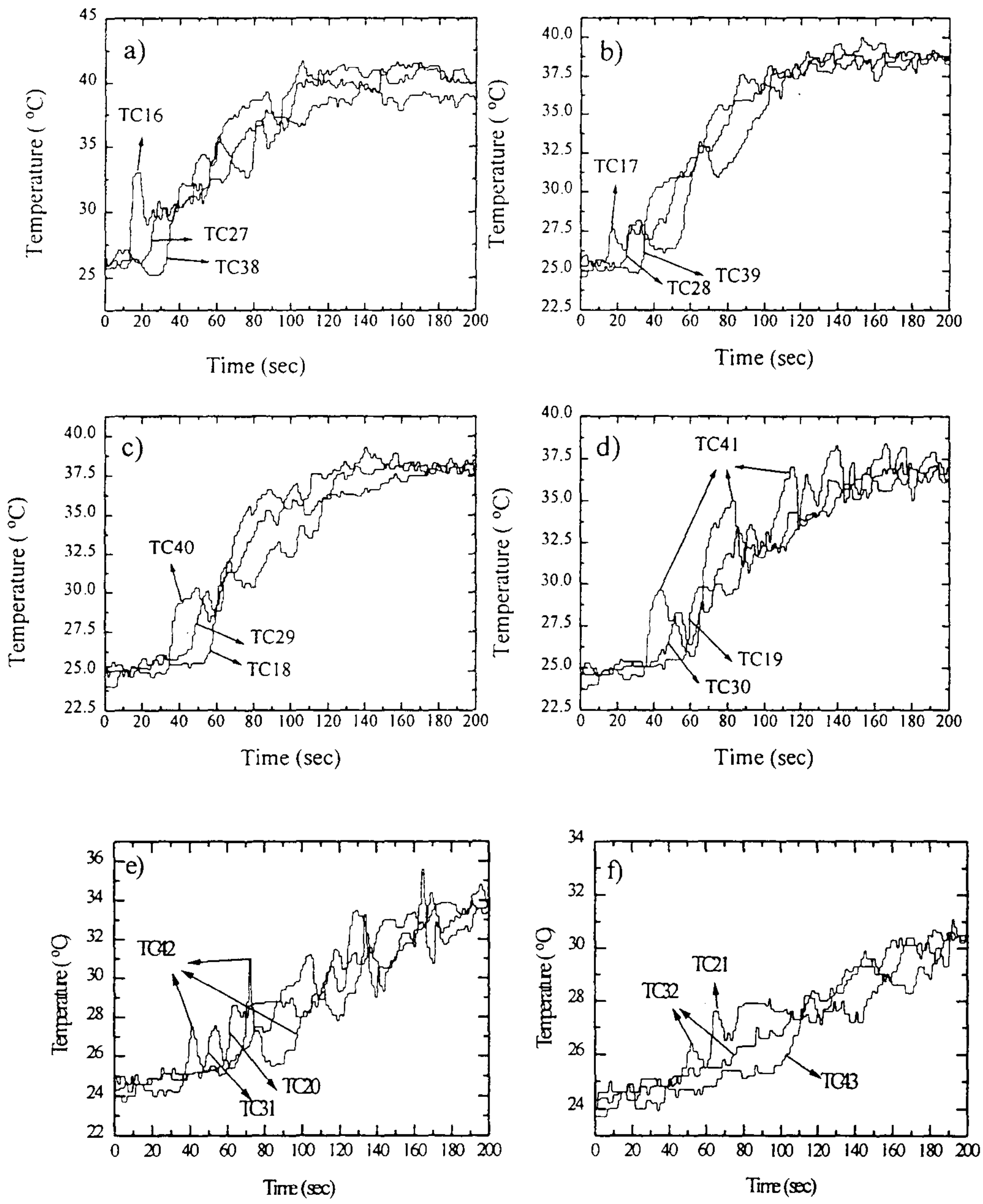

Fig.7 Temperature records at the same level

4. CONCLUSIONS

Smoke spread in the corridor is analyzed by thermocouples and by the laser beam sheet th is able to visualize smoke flows. The formation of the smoke layer is described to be divide into two steps, that is, the developing period of the ceiling jet and the period after t impingement of the ceiling jet front upon the end of the corridor. Along with the observations characteristics of the ceiling jet are discussed in the velocity of its front, t depth of its layer and temperature distribution along the corridor.

In the first phase of smoke spread, it is found that the smoke lowering, caused by the cooling of smoke, mass diffusion and the transfer of momentum to the cool air, controls the spreading phenomena. The rate of the smoke lowering is slowest in the vicinity of the end of the corridor because the lowering has already begun from the upstream parts of the developing ceiling jet. It is then discovered in the next stage that smoke spread is governed by the recirculating flow due to the impingement of the ceiling jet front upon the end of the corridor, not by the smoke lowering. Downward-moving flows the impingement has made transport some smoke near the end of the corridor to the lower locations, which leads to the fastest smoke filling around the end, exactly opposite to the case of the first period.

It is therefore sure that the conventional two-zone concept does not always apply to a corridor during the developing stage of the ceiling jet. Also in view of the smoke spread mechanism, the conventional concept of the smoke lowering or of the smoke filling is not available any more to the spreading of smoke in a corridor after the impingement.

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