COMPUTER SIMULATION OF THE MOTION OF HEAT FLOW INDUCED BY THE FIRE IN THE LONG-SCALE TUNNEL

Takashi HANDA⁺, Masahiro MORITA⁺⁺, Kenji HAYASHI⁺⁺ and Tadahiro ISHII⁺

Science University of Tokyo

1-3 Kagurazaka, Shinjuku-ku, Tokyo, Japan

+ Department of Applied Chemistry

++ Department of Applied Mathematics

ABSTRACT

In order to characterize the motion of the heat flow induced by fire in a real large-scale tunnel as well as the transport of the toxic gases, experimental and theoretical analysis the motion of the heat flow were investigated in a long-scale model tunnel. The computer simulation on the heat flow was conducted by using the Boussinesq approximation and Navier-Stokes' type formula as the viscous heat-conducting incompressible fluid. After recognition of a good correspondence on the heat flow properties between the simulated and experimental results, the computer simulation was scaled up by three times the length of the model tunnel. The life hazard of passengers was also discussed on the basis of the predicted CO gas concentration in the under-layer.

INTRODUCTION

Once a fire break out in a long express way tunnel or a railroad tunnel, it must bring about a great accident by a toxic and smokey flow of hot fire products. Actually, we have had so far several big tunnel fires which have caused serious disaster. The first is the notorious railroad tunnel fire which occurred at Hokuriku tunnel in 1972 with not less than 53 victims killed by thick smoke and

toxic gases and the second is the highway tunnel fire which occurred at Nihonzaka tunnel of Tomei express highway in 1979 with a enormous loss of burnt vehicles more than 70. The basic confrontation of the problem is to clarify the characteristics of the motion of hot products in a real long tunnel. Nevertheless, there are many experimental difficulties in reproducing full-size fires in a long-scale tunnel for the elucidation of the flow motion of smoke and toxic gases. Hence, we have to simulate the real situation from the numerical approach on the basis of the non-dimensional hydrodynamic differential equations utilizing the initial and boundary values which can be obtained from the data of the experiments in a scale model tunnel. Thereby, the atmost difficulty may exist in the estimation of the levels of smoke and toxic gases which must be calculated precisely down to their thin level (200 ppm for CO gas) regarding the mortality hazard in the safety evaluation.

The experimantal and theoretical analysis on the motion of heat flow were presented by Heskestad¹⁾, Alpert²⁾, and Handa and Hamada^{3),4),5)}. Alpert proposed the three-step region of fire-induced heat flow; the plume, the turning region and ceiling-jet. Handa and Hamada recognized the existence of the hydraulic-jump in the turning region, when modified Froude number (Fr^*) is larger than 1. In addition, it was revealed that the complicated motion of heat flow in the near field of the heat source was significantly influenced by the properties of the heat source. However, authors⁶⁾ indicated that the flow behaviors of the ceiling-jet could be approximated by the incompressible viscous fluid in the comparatively far field from the fire source. It is not too much of an exaggeration to say that the precise prediction of the time dependent change of the distribution of CO level in a long tunnel must be practically impossible with regard to the restricted conditions in that the initial and boundary values around fire-source are only given. Therefore, we have to pursue the calculation on the basis of the experimental values which were obtained in both near and far fields of the fire source during experiments in a scale model tunnel. Thereby, we can justify the background of our calculation by confirming the fit of the calculated results with the experimental data which were obtained in the middle field. After then, it is feasible to extend our calculational region to a further field.

In this paper, the numerical calculation was conducted under the assumption that the hot fire products flow like a viscous heat-conducting incompressible fluid. The computed results were compared with the experimental results, and used to predict the properties of heat flow in a long-scale simulated tunnel by extending the scale factor.

EXPERIMENTAL

The experiments were carried out in a rectangular model tunnel (1.7 m height, 1.45 m width and 150 m length) in regarding it as a single railroad line tunnel. The ceiling was made of the concrete-slab, the wall was made of the slate pannel and the floor was paved with concrete. The model train as the heat source was made of the rolling stock of iron (0.9 m height, 0.9 m width and 2.7 m length) with hard-board (3.5 mm thickness and 30.6 kg weight) inside linings of 5 mm apart from the wall, and 72 plywoods (30 cm x 30 cm x 5 mm and 10.3 kg in total weight) which were placed in two lines as the combustible seats. The combustible heat source was 40.9 kg in total weight, 16.8 kg/m^2 per floor space and 18.7 kg/m^3 per volume. The heat source was burned with a small quantity of alchool.

As shown in Figure 1, the model of the rolling stock was put on the center of the model tunnel, and temperatures, velocities and CO gas concentrations of heat flow were measured with C.A. thermocouple of 0.6 mm guage, Pitot tube, Gill's

Fig. 1 Outline of the model and simulated tunnel.

type flow meter and hot-wire anemometer, and IR detector, respectively, at the measuring positions A, B and C. These were located from heat source with distance of 10 m, 33 m and 65 m, respectively. Figure 2 shows measuring locations A, B and C at the cross section of the model tunnel.

Fig. 2 Representation of the setting condition of the sensors.

RESULTS

The vertical distribution of temperature versus time is plotted in Figure 3 at a distance of 10 cm, 40 cm and 110 cm from the ceiling at the locations A and C. There was no indication of any differences in data between the locations A and C. This indicates that the characteristics of the motion of heat flow is conserved. Variations in the vertical distribution of horizontal flow velocity vs. time are shown in Figure 4 with regard to a distance of 15 cm, 45 cm, and 105 cm from the ceiling at the location A, and with regard to a distance of 30 cm and 135 cm from the ceiling at the location C. It was recognized that there existed a natural air flow in the tunnel anyhow before the experiment (at $t=0$). The natural air flow was caused by the temperature gradient and pressure gradient in the tunnel depending on the wind condition in the open air.

Fig. 3 Time change curves of the temperature at the distance of 10 m and 65 m from the heat source.

Variation in the vertical distribution of CO gas concentration vs. time are shown in Figure 5 with regard to a distance of 15 cm and 135 cm from the ceiling at the locations A and C. The CO gas concentration in up-layer was governed by the situation of burning of the combustibile at the fire source. The CO gas concentration in the inflow air of the under-layer depended on the extent of mass transfer along the interface between the up-layer and the under-layer to which the mortality hazardness of passengers must be subjected. The observed CO gas concentration in under-layer was actually 50-100 ppm at a distance of 135 cm from the ceiling and 10 m from the heat source.

THEORETICAL CONSIDERATIONS

In order to derive the equations governing the fire induced-flow in the large-scale tunnel, these assumptions were made:

Fig. 4 Time change curves of the velocity at the distance of 10 m and 65 m from the heat source.

Fig. 5 Time change curves of the CO gas concentration at the distance of 10 m and 65 m from the heat source.

- (i) The change in the density ρ of turbulent flow can be scarcely with time.
- (ii) Turbulent flow of hot fire products can be treated as a viscous heat-conducting incompressible fluid except in the very near field of the fire source and obey the Boussinesq approximation. Irrespective of that, the turbulent heat flow contained bouyancy effect was regarded as coming from the defference in the gas density which depended only upon the temperature.
- (iii) Two - dimensional flow domain in a rectangular tunnel was taken for simplicity's sake in the numerical calculus.
- (iv) A Navier-Stokes' type formula are applied for the equation of motion. Thereby , in order to eliminate the difficulty in estmating the indefinite elements from the presence of natural pressure gradient in the tunnel, the equations were transformed to vorticity equations.

Governing Equations

Assume that the Cartesian coordinate system is chosen in such a manner that the x-axis is directed toward the tunnelend (horizontal coordinate) and y-axis is directed upward the tunnel-ceiling (vertical coordinate).

The governing equations are:

- (i) Continuity

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \quad \dots\dots\dots (1)$$

- (ii) Conservation of momentum

horizontal direction

$$\frac{\partial \rho u}{\partial t} + u \frac{\partial \rho u}{\partial x} + v \frac{\partial \rho u}{\partial y} = -\frac{\partial P}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad \dots\dots\dots (2a)$$

vertical direction

$$\frac{\partial \rho v}{\partial t} + u \frac{\partial \rho v}{\partial x} + v \frac{\partial \rho v}{\partial y} = -\frac{\partial P}{\partial y} + \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \rho g \beta \Delta \theta \quad \dots (2b)$$

- (iii) Conservation of energy

$$\frac{\partial \rho \theta}{\partial t} + u \frac{\partial \rho \theta}{\partial x} + v \frac{\partial \rho \theta}{\partial y} = \rho \alpha \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) \quad \dots\dots\dots (3)$$

- (iv) Equation of CO gas diffusion

$$\frac{\partial \rho c}{\partial t} + u \frac{\partial \rho c}{\partial x} + v \frac{\partial \rho c}{\partial y} = \rho D \left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} \right) \quad \dots\dots\dots (4)$$

(v) Equation of state

$$\rho = \rho_0 / (1 + \beta \theta) \quad \dots\dots\dots (5)$$

(vi) Equation of heat loss (ceiling and floor)

$$h(\theta_\infty - \theta_s) = -\lambda_w \frac{\partial \theta}{\partial n} \quad \dots\dots\dots (6)$$

These equations of motion (2a and 2b) are automatically satisfied by introducing the stream function ϕ and scalar vorticity ω in the usual way, these are:

(vii) Equation of stream function

$$\begin{cases} \frac{\partial \phi}{\partial x} = -\rho v \\ \frac{\partial \phi}{\partial y} = \rho u \end{cases} \quad \dots\dots\dots (7)$$

(viii) Equation of scalar vorticity

$$\omega = \left(\frac{\partial \rho v}{\partial x} - \frac{\partial \rho u}{\partial y} \right) = - \left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} \right) \quad \dots\dots\dots (8)$$

by eliminating the pressure term from the Navier-Stokes' type equation of motion, we have a vorticity transport equation of the form.

(ix) Vorticity transport equation

$$\frac{\partial \omega}{\partial t} + u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} = \nu \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) + \rho g \beta \frac{\partial \theta}{\partial x} \quad \dots\dots\dots (9)$$

where independent variables are the spatial coordinates x and y , and time t . The problem can be described in term of the following dependent variables; the velocity component u and v in the x and y direction, respectively, the density ρ , temperature θ , pressure P , acceleration of gravity g , volume coefficient of thermal expansion β , coefficient of viscosity μ , thermal diffusivity $\alpha = \lambda / \rho c_p$, CO gas concentration c , diffusion coefficient of CO gas D , heat transfer coefficient h , thermal conductivity λ , kinetic viscosity $\nu = \mu / \rho$, specific heat c_p . Thereby ν can be actually regarded as corresponding to the eddy coefficient.

Non-Dimensional Equations

The non-dimensional variables are;

$$\begin{aligned} X &= x/L & U &= \rho u / \rho_0 u_0 & T &= u_0 t / L \\ Y &= y/L & V &= \rho v / \rho_0 u_0 & \Theta &= (\rho \theta - \rho_0 \theta_0) / (\rho_{\max} \theta_{\max} - \rho_0 \theta_0) \\ C &= \rho c / \rho_{\max} c_{\max} & \Phi &= \phi / \rho_0 u_0 L & \Omega &= \omega / \rho_0 u_0 \end{aligned}$$

where small letters designate the original dimensional variables and L is the

representative length.

The non-dimensional governing equations are;

(i) Non-dimensional equation of stream function

$$\begin{cases} U = \frac{\partial \Phi}{\partial Y} \\ V = -\frac{\partial \Phi}{\partial X} \end{cases} \dots\dots\dots (10)$$

(ii) Non-dimensional equation of scalar vorticity

$$\Omega = -\left(\frac{\partial^2 \Phi}{\partial X^2} + \frac{\partial^2 \Phi}{\partial Y^2}\right) \dots\dots\dots (11)$$

(iii) Non-dimensional vorticity transport equation

$$\frac{\partial \Omega}{\partial T} + U \frac{\partial \Omega}{\partial X} + V \frac{\partial \Omega}{\partial Y} = \frac{1}{Re} \left(\frac{\partial^2 \Omega}{\partial X^2} + \frac{\partial^2 \Omega}{\partial Y^2} \right) + \frac{Gr}{Re^2} \frac{\partial \Theta}{\partial X} \dots\dots (12)$$

(iv) Non-dimensional equation of energy

$$\frac{\partial \Theta}{\partial T} + U \frac{\partial \Theta}{\partial X} + V \frac{\partial \Theta}{\partial Y} = \frac{1}{RePr} \left(\frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2} \right) \dots\dots\dots (13)$$

(v) Non-dimensional equation of CO gas concentration

$$\frac{\partial C}{\partial T} + U \frac{\partial C}{\partial X} + V \frac{\partial C}{\partial Y} = \frac{1}{ReSc} \left(\frac{\partial^2 C}{\partial X^2} + \frac{\partial^2 C}{\partial Y^2} \right) \dots\dots\dots (14)$$

(vi) Non-dimensional equation of heat loss

$$\Theta_s = Bi(\Theta_\infty - \Theta_0)/(1+Bi) \dots\dots\dots (15)$$

where non-dimensional parameters in the governing equation are:

$$Re = u_0 L / \nu \quad (\text{Reynolds number})$$

$$Gr = g \beta \Delta \theta L^3 / \nu^2 \quad (\text{Grashof number})$$

$$Pr = \nu / \alpha \quad (\text{Prandtl number})$$

$$Bi = h \Delta n / \lambda_n \quad (\text{Biot number})$$

NUMERICAL SOLUTIONS OF THE HEAT FLOW IN THE MODEL TUNNEL AND RESULTS

To obtain solutions of the non-dimensional governing equations, it is necessary to have boundary conditions specified over all boundaries of a calculational region. The numerical model is capable of handling boundary conditions of a very general nature. Two types to be considered in detail are solid boundary surface (ceiling and floor) and free boundary surfaces (locations A and C).

In order to generate a solution of the equations, initial values for the dependent variables must be specified. Initial values are prescribed from the

results of the measurements of the physical quantities subject to heat flow at the ignition time ($t=0$). The values of the boundary are prescribed by correction of observed physical quantities. Thereby, the correction was pursued firstly by averaging the observed values and secondly, by correcting the mean values on a computer so as to satisfy the equation of continuity (1) as well as the equation (5) because of the reason that those experimental values did not directly satisfy the equation of mass balance. Nevertheless, these boundary values did not yet give a complete description of the data probably because of the presence of the natural pressure distribution in the tunnel. Figures 3, 4 and 5 give the boundary values of the temperature, velocity and CO gas concentration, respectively, at the locations A and C in the tunnel.

The numerical calculation research in thermal-fluid mechanics has been sustained by various kinds of developments in the mathematical and computational techniques. The well known methods are the finite-element method⁷⁾ and the finite-difference methods^{8),9)}. In this paper, we have used implicit finite-difference method for numerical solution of the heat flow equations. By computing various conditions, differential equations are applied to backward implicit time-difference scheme for the time space; reliable numerical solutions of the diffusion term have been computed by the central-difference scheme; the upwind-difference scheme which employs forward or downward differencing for the nonlinear term according to the direction of the velocity vector, is applied to provide increased calculational stability even in high Reynolds number flows.

To obtain finite-difference equations, the flow domain is divided into a grid of rectangular cells. By choosing the cells so that the cell boundaries coincide with physical boundaries, the boundary conditions are easily treated.

Let Δx , Δy and Δt be increments of the variables x , y and t , where $\Delta x = x/I$, $\Delta y = y/J$, I and J being integers. The set of points in the x and y , t -plane given by $x = i\Delta x$, $y = j\Delta y$ and $t = n\Delta t$, where $i = 0, 1, 2, \dots, I$, $j = 0, 1, 2, \dots, J$ and $n = 0, 1, 2, \dots$, is called a grid whose mesh size is determined by Δx , Δy and Δt , and they are treated as small increments. The approximation to $F(i\Delta x, j\Delta y, n\Delta t)$ is denoted by $F_{i,j}^n$. One of the simplest difference equations approximating the non-dimensional governing equations of heat flow is as follows:

(i) Equation of stream function

$$\begin{cases} U_{i,j}^n = \frac{\phi_{i,j+1}^n - \phi_{i,j-1}^n}{2Y} \\ V_{i,j}^n = -\frac{\phi_{i+1,j}^n - \phi_{i-1,j}^n}{2X} \end{cases}$$

(ii) Equation of vorticity;

$$\Omega_{i,j}^n = -\left(\frac{\phi_{i+1,j}^n - 2\phi_{i,j}^n + \phi_{i-1,j}^n}{\Delta X^2} + \frac{\phi_{i,j+1}^n - 2\phi_{i,j}^n + \phi_{i,j-1}^n}{\Delta Y^2} \right)$$

(iii) Equation of motion (vorticity transport);

$$\begin{aligned} & \frac{\Omega_{i,j}^{n+1} - \Omega_{i,j}^n}{\Delta T} + U_{i,j}^n \left(\frac{\partial \Omega}{\partial X} \right)^{n+1} + V_{i,j}^n \left(\frac{\partial \Omega}{\partial Y} \right)^{n+1} \\ &= \frac{1}{Re} \left(\frac{\Omega_{i+1,j}^{n+1} - 2\Omega_{i,j}^{n+1} + \Omega_{i-1,j}^{n+1}}{\Delta X^2} + \frac{\Omega_{i,j+1}^{n+1} - 2\Omega_{i,j}^{n+1} + \Omega_{i,j-1}^{n+1}}{\Delta Y^2} \right) \\ &+ \frac{Gr}{Re^2} \left(\frac{\theta_{i+1,j}^n - \theta_{i-1,j}^n}{2\Delta X} \right) \end{aligned}$$

(iv) Equation of energy (thermal diffusion);

$$\begin{aligned} & \frac{\theta_{i,j}^{n+1} - \theta_{i,j}^n}{\Delta T} + U_{i,j}^n \left(\frac{\partial \theta}{\partial X} \right)^{n+1} + V_{i,j}^n \left(\frac{\partial \theta}{\partial Y} \right)^{n+1} \\ &= \frac{1}{RePr} \left(\frac{\theta_{i+1,j}^{n+1} - 2\theta_{i,j}^{n+1} + \theta_{i-1,j}^{n+1}}{\Delta X^2} + \frac{\theta_{i,j+1}^{n+1} - 2\theta_{i,j}^{n+1} + \theta_{i,j-1}^{n+1}}{\Delta Y^2} \right) \end{aligned}$$

(v) Equation of CO gas diffusion;

$$\begin{aligned} & \frac{C_{i,j}^{n+1} - C_{i,j}^n}{\Delta T} + U_{i,j}^n \left(\frac{\partial C}{\partial X} \right)^{n+1} + V_{i,j}^n \left(\frac{\partial C}{\partial Y} \right)^{n+1} \\ &= \frac{1}{ReSc} \left(\frac{C_{i+1,j}^{n+1} - 2C_{i,j}^{n+1} + C_{i-1,j}^{n+1}}{\Delta X^2} + \frac{C_{i,j+1}^{n+1} - 2C_{i,j}^{n+1} + C_{i,j-1}^{n+1}}{\Delta Y^2} \right) \end{aligned}$$

(vi) Convection term;

$$\begin{aligned} \left(\frac{\partial F}{\partial X} \right)^{n+1} &= \begin{cases} \frac{F_{i,j}^{n+1} - F_{i-1,j}^{n+1}}{\Delta X} & \text{for } U_{i,j}^n \geq 0 \\ \frac{F_{i+1,j}^{n+1} - F_{i,j}^{n+1}}{\Delta X} & \text{for } U_{i,j}^n < 0 \end{cases} \\ \left(\frac{\partial F}{\partial Y} \right)^{n+1} &= \begin{cases} \frac{F_{i,j}^{n+1} - F_{i,j-1}^{n+1}}{\Delta Y} & \text{for } V_{i,j}^n \geq 0 \end{cases} \end{aligned}$$

$$\left\{ \frac{F_{i,j+1}^{n+1} - F_{i,j}^{n+1}}{\Delta Y} \quad \text{for } V_{i,j}^n < 0 \right.$$

The flow diagram used for the computational solutions in the partial differential equation is given in Figure 6. In this case, the calculational domain with 18 X 276 grids is placed by the region with boundary locations (A and C) in the large-scale model tunnel.

Fig. 6 Flow diagram for the computational solutions in the governing nondimensional equations.

Re	7.14E4
Gr	1.84E10
Pr	0.72
Sc	0.5
Bi	2.5
L	1.00 m
U _o	1.00 m/sec
ρ _o	1.23E-3 gr/cm ³
θ _o	0 °C
c _o	0 ppm
ρ _{max}	2.13E-3 gr/cm ³
θ _{max}	200 °C
c _{max}	1000 ppm

Table 1 Physical parameter values.

Table 1 gives the physical parameters and constants for the numerical calculation. As it is impossible to obtain the physical values of the heat flow which contains thick smoke and gases, we have used the physical values of the air and given Biot number by experimental values. In order to estimate the accuracy of computation, we have compared the computed results of B location with the observed values there utilizing initial values at the locations A and C. Figures 7, 8 and 9 show the distribution of flow velocity, temperature and CO gas concentration, respectively, at the locations B (distance of 33m from the heat source), A and C. There were not observed any recognizable differences in values between the experimental and calculational results. Therefore, the computer simulation

on the basis of the present scheme will give us a satisfactory prediction for the motion of the hot fire products in the large-scale model tunnel, particularly with regard to CO gas concentration in under-layer, provided that the initial values at two measuring locations can authentically depict the situation of bouyant flow specific to tunnel fires.

Fig. 7 Vertical distribution profiles of the velocity in the model tunnel.

Fig. 8 Vertical distribution profiles of the temperature in the model tunnel.

Fig. 9 Vertical distribution profiles of the CO gas concentration in the model tunnel.

TUNNEL-LENGTHENING PROCEDURE AND CALCULATIONAL RESULTS

For the prediction of the flow behaviors of hot products in a long-scale tunnel, we attempted to confirm the extent to which the precision of computed results can be preserved on the basis of the present scheme of calculation by lengthening the calculus region onto an artifact annex of the real tunnel, thereby, the following two conditions were assumed to be preserved in the simulation.

- (i) The basic equations of the heat flow are also applied in the annex tunnel, that is, the properties of the heat flow can be conserved here.
- (ii) The physical environments are comprising boundary conditions not changed in the annex tunnel.

These conditions must be confirmed by the correspondence of the computed results with the model of the bouyant flow. In this paper, we have confirmed the consistency of the calculated modified Froude number Fr^* , stress shares at the ceiling and the free boundary surface of heat flow τ_w and τ_s , and the kinetic and heat energy K and Q , respectively.

In extending the calculus region, we have been prolonged the real length (enclosed between locations A and C) of the tunnel to the locations outside the tunnel. They corresponds to the locations E and F as shown in Figure 1. First, the calculus region in the simulated tunnel was covered between the locations D and E, where D is the middle location between the locations A and C. We have been ended the simulation from the coincidence of the computed results between the former calculus (AC) and the latter calculus (DE) for the overlapped region DC. By repeating the same procedure from D, E to F and etc., we have been gradually lengthened the extent of the calculus region outside the real model tunnel.

There are several methods for the calculation of the boundary and initial values such as a exterpolation of the calculational results, a regular falsi and a interpolation of basic governing equations, et al. In this paper, we have adopted the exterpolation method, because this method has surpassed the interpolation and regular falsi method in its iteration counts of computation.

Flow diagram for the tunnel-lengthening procedure is shown in Figure 10, where the criterion ϵ of tunnel-lengthening calculation is prescribed at a value of 0.1.

Figures 11, 12 and 13 show the calculational results of the distribution of

Fig. 10 Flow diagram for the tunnel-lengthening procedure.

Fig. 11 Vertical distribution profiles of the velocity in the simulated tunnel

Fig. 12 Vertical distribution profiles of the temperature in the simulated tunnel.

Fig. 13 Vertical distribution profiles of the CO gas concentration in the simulated tunnel.

Fig. 14 Contour map of the stream line in the model and simulated tunnel.

Fig. 15 Contour map of the temperature in the model and simulated tunnel.

Fig. 16 Contour map of the CO gas concentration in the model and simulated tunnel.

velocity, temperature and CO gas concentration of the heat flow in the simulated tunnel at a distance of 100 m and 175 m from the heat source, respectively. Figures 14, 15 and 16 show the calculational results of the contour map of the stream line, temperature and CO gas concentration in the long-scale model tunnel, respectively.

DISCUSSION

In justifying the precision of simulated results in the extrapolated calculus for a series of artifact locations E, F and G for which no experimental data exist to be compared with the computed values, we have to examine, as to whether the computed results satisfy the foregoing two assumptions for the calculus, namely, the established model for the physical properties of heat flow and the environmental physical conditions. As for the description of the physical properties of heat flow concerned in the discussion, the following quantities were introduced:

(i) Reynolds number;

$$Re = \frac{\delta \bar{v}}{\nu} \quad \bar{v} = \frac{1}{\delta} \int_0^{\delta} v d\xi$$

(ii) Grashof number;

$$Gr = \frac{g \beta \Delta \bar{\theta} \delta^3}{\nu^2} \quad \Delta \bar{\theta} = \frac{1}{\delta} \int_0^{\delta} (\theta - \theta_0) d\xi$$

(iii) Kinetic energy;

$$K = \int_0^{\delta} \frac{d}{dt} \left[\int_t^{t+\Delta t} \frac{1}{2} l_w \rho v^3 dt \right] d\xi \approx \frac{1}{2} l_w \int_0^{\delta} \rho v^3 d\xi$$

(iv) Heat energy;

$$H = \int_0^{\delta} \frac{d}{dt} \left[\int_t^{t+\Delta t} c_p l_w \rho v \theta dt \right] d\xi \approx l_w \int_0^{\delta} c_p \rho v \theta d\xi$$

where $\bar{v}$ is the mean value of velocity, δ is the width of heat flow, ξ is the spatial coordinate downward from the ceiling, $\Delta \bar{\theta}$ is the mean value of excess temperature at ambient temperature, l_w is the width of tunnel, $\delta_{\max}$ is the width of the heat flow at its maximum velocity.

The established Froude model on the heat flow, namely, the consistency of Re vs. $\sqrt{Gr}$ relation was confirmed by the plot in Figure 17. The plot gave a linear

line in a first approximation with an intercept ($Re \approx 1000$) on the ascissa indicating that there must be natural flow of air inherent to a long-scale model tunnel. Therefore, by transferring the origin of the coordinate to the intercept point ($Re \approx 1000$ and $Gr=0$), the modified Froude number was found to be conserved as 0.43 covering all Re and Gr values from the observed values of $\bar{v}$ and $\Delta\bar{\theta}$ in both the real tunnel and those from the numerical computation for the extended calculus region in the artifact annex. The consistency of the relation between kinetic energy K and the heat energy Q of the bouyant flow was also confirmed by a linear plot in Figure 18 covering all values of K and Q from the observed as well as the computed values of $\bar{v}$ and $\Delta\bar{\theta}$. The intercept value on the abscissa meant that the fire products still moved even after they lost bouyancy also due to the presence of natural air flow in the model tunnel.

Fig. 17 Correlation plots of Reynolds number vs. $1/2$ power of Grashof number in the model and simulated tunnel.

Fig. 18 Correlation plots of kinetic energy vs. heat energy in the model and simulated tunnel.

Furthermore, the following quantities were examined for the justification of the precision of computed results:

(v) Total stress share;

$$\tau_t = l_w \frac{d}{dt} \left[\int_0^\delta \rho v^2 d\xi \right]$$

(vi) Stress share at the free boundary surface;

$$\tau_s = l_w \frac{d}{dt} \left[\int_{\delta_{\max}}^\delta \rho v (v_\infty - v) d\xi \right]$$

(vii) Stress share τ_w at the ceiling surface;

$$\tau_w = \tau_t - \tau_s$$

The balance between τ_s and τ_w is shown by a linear plot in Figure 19 covering all values of τ_s and τ_w from the observed profiles of v in the model tunnel and simulated ones of v in the artifact annex. The linear plot surpassed the origin and gave a slope value of 0.38.

These facts insist that the precision of computed results must also be preserved in the simulation on the concentration of intermixed CO gas in the inflowed air covering the extended calculus region. Therefore, it is not too much of an exaggeration to say that the prediction of the concentration of CO gas intermixed in the under-layer of inflowed air is possible with some precision provided that the velocity, temperature as well as CO gas concentration profiles

expected to happen in the carline stage of vehicle fire as a moiety of the enclosure fire with a small opening where the depletion of oxygen must occur. Meanwhile, as the opening will be enlarged by the breaking of the window glass of the vehicle in the passage of time, the fire grows up and the drifting thick CO gas and smoke near to the firing vehicle will be pushed forward to downstream with growing bouyancy. This will cause the true hazard for the life safety of the passengers staying not too far from a firing vehicle.

In conclusion, the calculational results so far will predict that, when the CO gas concentration in the upper-layer amounts to 0.5% or above close to the fire source, the life of passengers remaining within a distance of 500m downstream from the source must be virtually exposed to a serious hazard. Therefore to combat the worst kind of accident, for example, a fire in a train in a long tunnel, a light vehicle should be equipped to safely secure the quick evacuation of passengers from the hazardous zone which extends gradually with time.

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