Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 10 (1976)

Artikel: Numerical calculation of the temperature distribution in hot gas plume from a window

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DOI: https://doi.org/10.5169/seals-10522

Numerical Calculation of the Temperature Distribution in Hot Gas Plume from a Window

Calcul numérique de la distribution des températures dans une colonne de gaz chaud s'échappant d'une fenêtre

Numerische Berechnung der Temperaturverteilung in einer aus einem Fenster ausströmenden Heissluftsäule

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1. INTRODUCTION

In order to prevent the fire spread to upstairs through broaken windows in a building, it is necessary to provide a fireproof spandrel between the windows. The estimation of its necessary height was once studied by YOKOI*[1], who conducted both dimensional analysis and small scale experiments on the behavior of the hot gas plume ejected from a window to find that the temperature distribution along its trajectory would be estimated by the normalized temperature Θ which is defined as

$$\Theta \equiv \Delta\theta r_0^{5/3} / \sqrt[3]{Q^2 \theta_0 / C_p^2 \rho^2 g} \quad (1)$$

where $\Delta\theta$: excess temperature of the trajectory (°C), Q: released energy rate from window (kcal/sec), θ_0: temperature of ambient air (°K), C: specific heat of air at constant pressure (kcal/kg°K) r_0: equivalent radius of window (m) and ρ: density of hot gas (kg/m³). Fig.1 summarizes the results of the small scale experiments for various geometries of window. This simple method gives good results for many cases, but when the refractoriness of a spandrel or the interaction between the spandrel and the plume is discussed, it will be also necessary to predict the temperature dis-

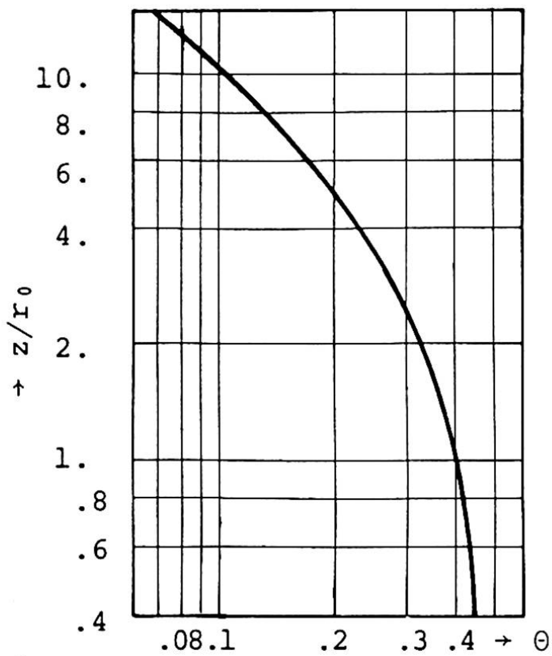

Fig.1 TEMPERATURE DISTRIBUTION ALONG THE TRAJECTORY OF HOT GAS PLUME*[1]

tribution in hot gas plume, especially near the spandrel above the window.

In this paper, we introduce the calculation method by the finite difference approximation of the governing differential equations on the behavior of hot gas plume and then show a calculation result **with** an experimental one carried out under the almost similar condition to the one for the numerical calculation.

2. GOVERNING EQUATIONS

The governing equations of a thermally expanding or contracting turbulent motion of gas are the following set of 6*[2].

EQUATION OF MOMENTUM:

$$\frac{\partial \overline{\rho u}_i}{\partial t} + \frac{\partial \overline{\rho u}_i \overline{u}_j}{\partial x_j} \simeq -\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\{\overline{\sigma}_{ij} + K(\frac{\partial \overline{\rho u}_i}{\partial x_j} + \frac{\partial \overline{\rho u}_j}{\partial x_i})\} - \delta_{i3}\overline{\rho}g \qquad (2)$$

where u:velocity(m/sec), P:pressure(kgm/sec^{2}m^2), σ:viscosity stress(kgm/sec^{2}m^2), K:eddy **coe**fficient(m^2/sec), i or j:tensor mark and δ:KRONECKER delta. Overbarred quantities denote the time-smoothed variables. The time-smoothed velocity is given by

$$\overline{u}_i \simeq \frac{\overline{\rho u}_i + K(\frac{\partial \overline{\rho}}{\partial x})_i}{\overline{\rho}} \qquad (3)$$

EQUATION OF CONTINUITY:

As the time-smoothed density is obtained from the equation of state in our calculation scheme, the equation of continuity should be transformed to the POISSON type equation for $\overline{P}$. This equation is obtained by substituting the equation of momentum into the **na**tural form of continuity equation $\partial\overline{\rho}/\partial t + (\partial\overline{\rho u}/\partial x)i = 0$.

$$\frac{\partial^2 \overline{P}}{\partial x_i^2} \simeq \frac{\partial^2 \overline{\rho}}{\partial t^2} + \frac{\partial^2}{\partial x_i \partial x_j}\{\overline{\sigma}_{ij} + K(\frac{\partial \overline{\rho u}_i}{\partial x_j} + \frac{\partial \overline{\rho u}_j}{\partial x_i}) - \overline{\rho u}_i \overline{u}_j\} - g\frac{\partial \overline{\rho}}{\partial x_3} \qquad (4)$$

CONSERVATION EQUATION OF ENERGY:

$$\overline{\rho}\frac{\partial \overline{h}}{\partial t} + \frac{\partial \overline{\rho u}_i \overline{h}}{\partial x_i} \simeq \frac{\partial}{\partial x_i}(\kappa\frac{\partial \overline{T}}{\partial x_i} + K\frac{\partial \overline{h}}{\partial x_i}) + \overline{Q} + h\frac{\partial \overline{\rho u}_i}{\partial x_i} \qquad (5)$$

where h:enthalpy of air(kcal/kg), κ:thermal conductivity(kcal/sec m) and Q:generation rate of heat(kcal/secm^3). The dissipation of kinetic energy is ignored for its minor role in the conservation of energy.

DEFINITION OF EDDY COEFFICIENT:

PRANDTL's dimensional relationship is applied to the modeling of eddy coefficient. In this model, eddy **coefficient is given by**

$$K \simeq \sqrt{q}\,\ell \qquad (6)$$

where the mixing length 'ℓ' may be determined geometrically and the turbulent energy is given from the conservation equation for it.

$$\frac{\partial \overline{\rho q}}{\partial t} + \frac{\partial \overline{\rho u}_i \overline{q}}{\partial x_i} \simeq \frac{\partial}{\partial x_i}(\overline{\rho}K\frac{\partial \overline{q}}{\partial x_i} + \mu\frac{\partial \overline{q}}{\partial x_i}) + K\frac{\partial \overline{\rho}}{\partial x_3}g - \overline{\rho\varepsilon} + K(\frac{\partial \overline{\rho u}_i}{\partial x_j} + \frac{\partial \overline{\rho u}_j}{\partial x_i})\frac{\partial \overline{u}_j}{\partial x_i} \qquad (7)$$

where μ:dynamic viscosity(kg/secm) and ε:turbulent energy decay rate(m^2/sec^3).

EQUATION OF STATE:

The change or variation of the pressure in fire is usually so small that the equation of state may be approximated correctly by

$$\bar{\rho} \simeq \frac{P_0}{R\bar{T}} \qquad (8)$$

where P_0:referential pressure(kgm/sec^{2}m^2), R:gas constant and T: absolute temperature of air(°K).

3. OUTLINE OF THE CALCULATION METHOD

The governing equations above introduced are of course so complicated for an analytical solution that we solve them simultaneously in a numerical manner. However,because we do not have enough space to describe everything about the calculation method, we present the outline of the finite difference calculation method which is detailed in REF.2.

In our numerical code,the unsteady equations (2),(3) and (7) are transformed into explicit finite difference equations, whilst the POISSON type equation for the pressure (4) is solved by an iterative method such as Over-Relaxation method. For the finite difference calculation of the spacially differentiated terms,the Cell Model in which the physical variables are arranged by the way as shown in Fig.2 is used. A stable marching of the unsteady calculation is achieved only when the finite increment of time satisfies the following criterion which is known as COURANT-FRIEDRICHS-LEWY condition.

$$\Delta t < \frac{1}{\left(\sum_{i}^{3} |\bar{u}_i/\Delta x_i|\right)_{max}} \qquad (9)$$

Then,the finite difference equations for (2)∿(8) are solved unsteadily by the procedure as shown in Fig.3.

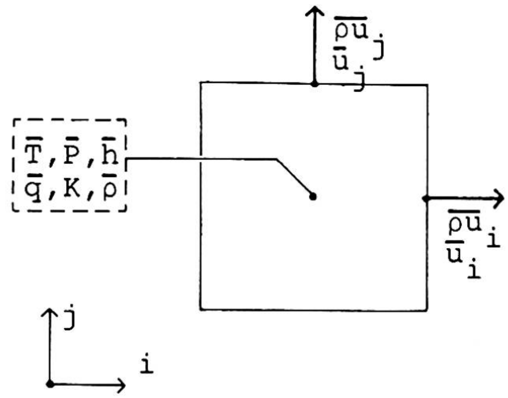

Fig.2 GRID ARRANGEMENT IN CELL MODEL

4. CALCULATION OF THE TEMPERATURE DISTRIBUTION IN HOT GAS PLUME

Now,we apply the calculation method above introduced to the estimation of the temperature distribution of a hot gas plume ejected from a broaken window.

It was suggested by YOKOI*[1] on the basis of the results of his small scale experiments that the hot gas plume from a wide opening would close to the wall or spandrel above it to be a possible cause of the fire spread to upstairs. This phenomenon which may be interpreted by the COANDA effect was also observed in the full scale experiment conducted recently by KAWAGOE et al*[3]. Such a phenomenon seems to be represented pertinently in a two-dimensional calculation,because we may conceptually replace a wide opening by a two-dimensional one without bringing any serious problem.

In this paper,we make a numerical calculation of the hot gas plume under the conditions which are determined according to KAWA-

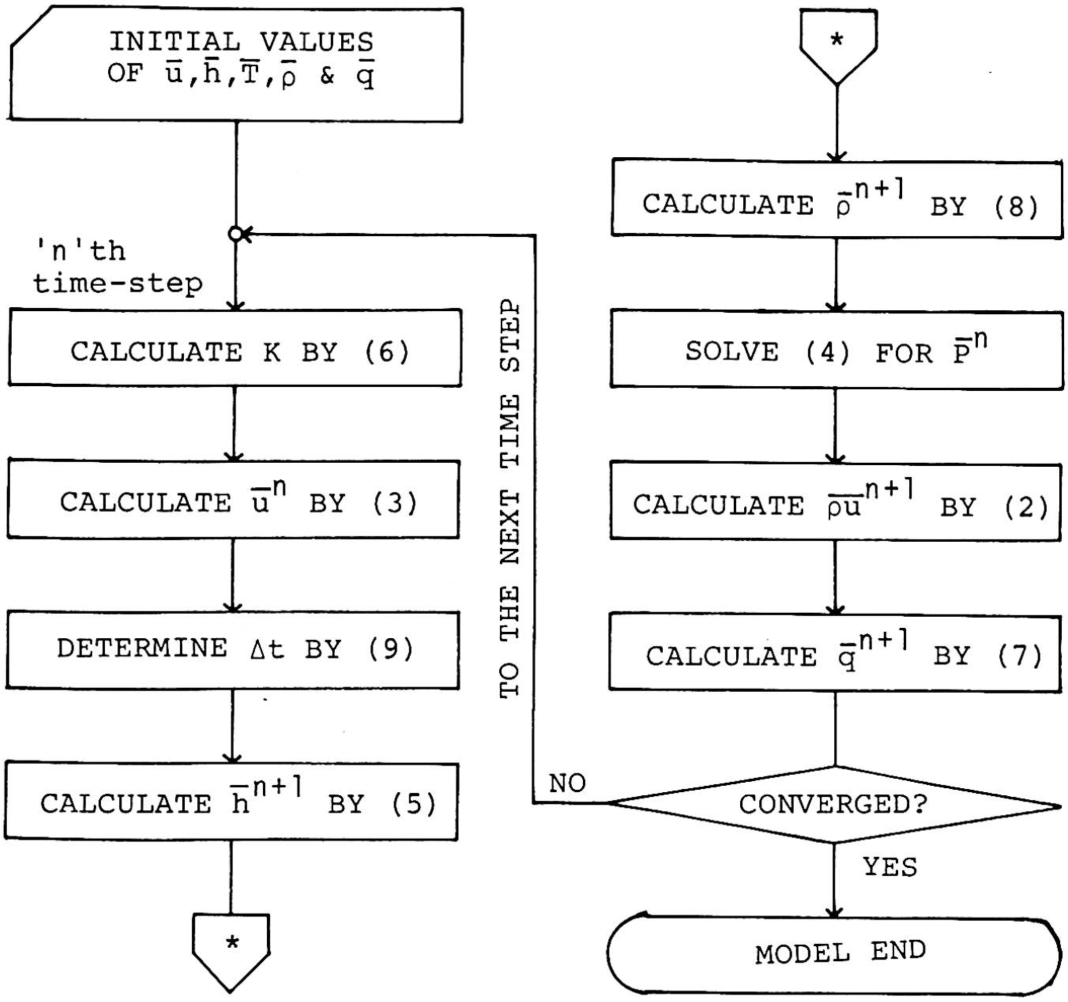

Fig.3 OUTLINE OF THE UNSTEADY CALCULATION PROCEDURE

GOE's experiment as shown in Tab.1 and then compare the calculation result with the experimental one. Among these conditions for the calculation,the height of neutral plane and the distribution of the mixing length are determined empirically and the spouting velocity is estimated by YOKOI's equation.

Tab.1 CONDITIONS FOR THE NUMERICAL CALCULATION

TEMPERATURE OF HOT GAS PLUME AT OPENING	900°C
TEMPERATURE IN UPSTAIRS ROOM	100°C
TEMPERATURE OF AMBIENT AIR	30°C
MASS FLUX RATE OF PLUME AT OPENING	$\rho U = \sqrt{2gh''(\rho_0 - \rho)}$ ρ_0:density of ambient air h":height from neutral plane
MIXING LENGTH	$\ell = 0.4y$, $\ell_{max} = 0.2H$ y:distance from boundary H:height of building

In Fig.4 are superimposed the calculated isotherms on the temperature field generated from the experiment. Although the discrepancy between the calculated and experimental distributions near the opening of the fire compartment is considerably great,the phenomenon above mentioned which may be a cause of the fire spread to upstairs is represented pertinently in the calculation result.

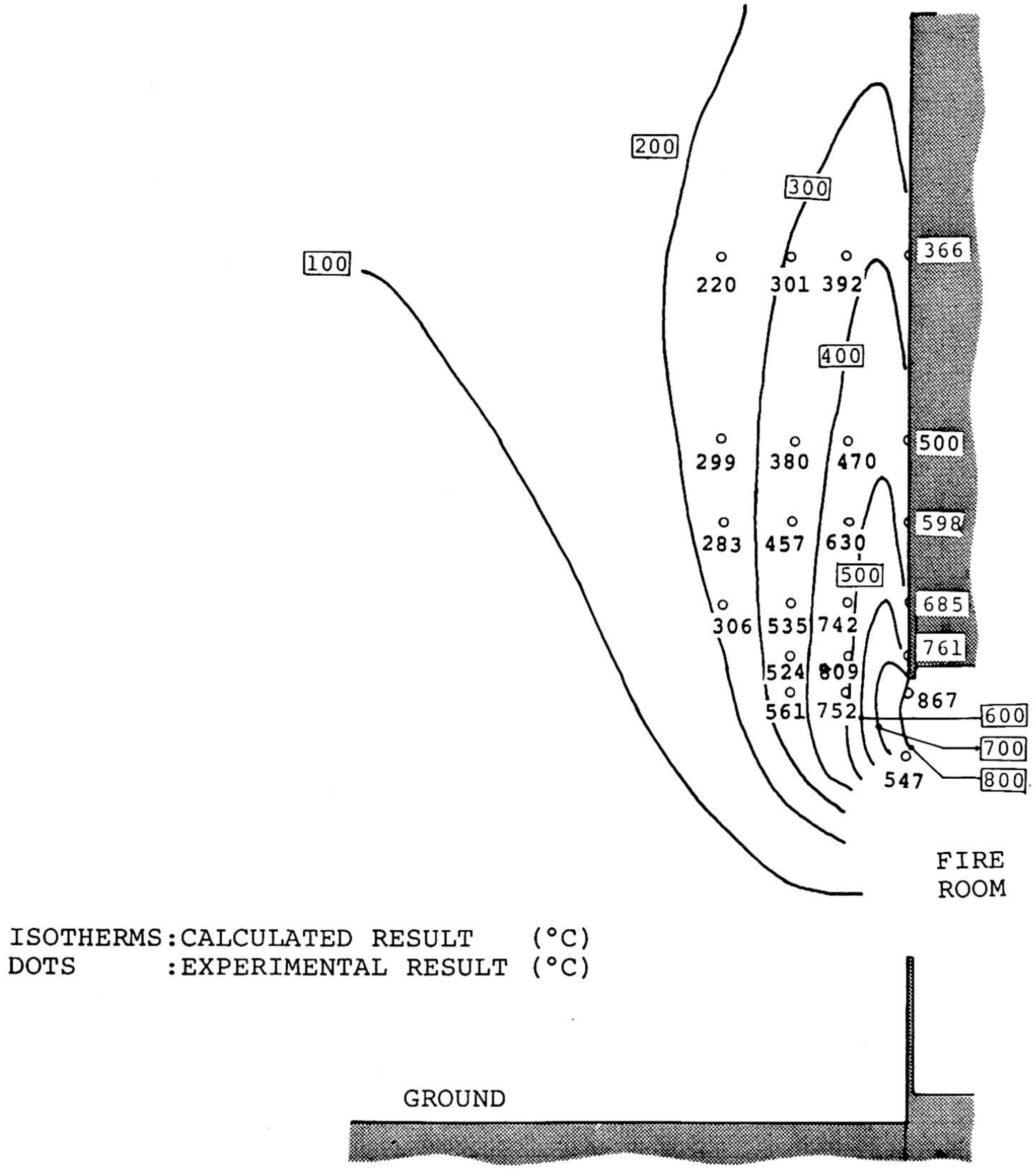

Fig.4 TEMPERATURE DISTRIBUTION IN HOT GAS PLUME FROM A WINDOW (COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS)

5. CONCLUSIONS

The temperature distribution in two-dimensional hot gas plume was calculated as an application of the prediction method. The use of a large EDPS will permit also a three-dimensional calculation, because the calculation method for the three-dimensional case does not differ basically from the one for the two-dimensional case which is introduced in this paper. Though some problems such as the calculation of the flame radiation are left as future subjects, we can utilize such a calculated temperature distribution for designing the height or refractoriness of a spandrel from the view point of fire safety.

REFERENCES

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3) KAWAGOE,K et al: "Report on '502' Fire Experiment", Science Univ. of Tokyo, 1975.

SUMMARY

This paper presents a method for the numerical calculation of the temperature distribution in a hot gas plume from a window. The calculation is given for a two-dimensional window and also compared with experimental results. Calculation and experiments show a good agreement.

RESUME

Cet article présente une méthode numérique pour calculer la distribution des températures dans une colonne de gaz chaud s'échappant d'une fenêtre. Le calcul est présenté pour une fenêtre à deux dimensions et est aussi comparé avec des résultats expérimentaux. La concordance entre le calcul et l'expérience est bonne.

ZUSAMMENFASSUNG

Der Autor beschreibt ein numerisches Verfahren zur Berechnung der Temperaturverteilung in einer aus einem Fenster ausströmenden Heissluftsäule. Die Berechnung wird für ein zweidimensionales Fenster vorgelegt und mit Versuchsergebnissen verglichen. Die Uebereinstimmung zwischen Berechnung und Versuch ist gut.