A Fundamental Study on Flow Characteristics in Boiler Furnaces*

(2nd Report, A Quantitative Evaluation on Mixing Characteristics in Furnaces)

By Kazuhiro MURAI^{**}, Masao TAGA^{***}, Koji AKAGAWA⁺,
and Takafumi NAKAGAWA⁺⁺

In the first report the experimental results of the flow patterns and the concentration distribution of tracer fluid in a two-dimensional model on which perforated plates were installed instead of a tube bundle were reported. In the present report, in order to evaluate these characteristics quantitatively, numerical calculations of the flow pattern and the transient concentration distribution based on the turbulent energy model (one equation model) have been conducted. The effects of the magnitude of flow resistance of the tube bundle on the flow pattern and the mixing performance were clarified quantitatively referring the comparisons with the experimental results.

Key words : Boiler Furnace, Two-dimensional Flow, Turbulent Flow, Isothermal Flow, Numerical Calculation, Flow Pattern, Concentration Distribution

1. Introduction

An experimental study on a flow pattern in a two-dimensional furnace model was conducted in order to investigate fundamental characteristics of combustion gas flow in a marine boiler equipped with ceiling burners. In the furnace model shown in Fig.1, a jet blows down from an upper left nozzle and turns toward right through perforated plates, and then flows out of an upper right exit port. The left space corresponds to a combustion chamber, the perforated plates to water tubes, and the right space to a flue. The purpose of this study is to investigate the fundamental mixing characteristics based on the experimental results of the velocity distribution and the concentration distribution. In the first report, the experimental results were presented and the effects of the flow resistance of the perforated plates on the flow pattern in the model chamber were clarified. The mixing characteristics were studied by using the averaged concentration and the averaged dead time in the whole chamber.

In order to evaluate the mixing characteristics in a practical combustion chamber more precisely, it is necessary to make clear the local velocity and concentration distribution. Therefore, in this report, the characteristics are discussed by using the standard deviation of the local values of the velocity and concentration; furthermore, numerical calculations of the flow pattern and the concentration distribution are conducted in order to generalize the effects of the flow resistance of the tube bundles on the flow pattern and the mixing characteristics. The calculation is conducted by a turbulent energy model (one equation model with an assumption of a scale length of turbulence). The numerically calculated results by this turbulent energy model agree as a whole with the experimental ones. Thus, it is concluded the mixing characteristics can be predicted by the numerical method described in this report.

Fig. 1 Flow pattern
(experimental results)

* Received 20th November 1985.

** Lecturer Himeji Institute of Technology,
2167, Syosha, Himeji, 671-22 Japan

*** Professor Osaka Prefectural Technical
College, 26-12, Saiwai-cho, Neyagawa,
572 Japan

+ Professor Faculty of Engineering, Kobe
University, Rokkodai-cho, Nada-ku, Kobe,
657 Japan

++ Engineer Kawasaki Heavy Industries, Ltd.,
Higashikawasaki-cho, Ikuta-ku, Kobe,
650-91 Japan

Fig.2 Isoconcentration distribution
(experimental results)

2. Local Velocity Distribution and Mixing Characteristics

An example of flow patterns and velocity distributions in the two-dimensional model chamber with perforated plates is shown in Fig.1.

A large recirculation zone as bounded by several isostream lines ($\psi = \text{const.}$) appears nearly at the center of the left chamber owing to entrainment of the curved jet. The absolute velocity profiles V are shown by the arrows in this figure. Where, V is $\sqrt{u^2 + v^2}$; and u, v , the time averaged velocities in x and y directions respectively at each section.

In Fig. 2 is shown a typical example of isoconcentration lines at $t/t_s = 1/2$ measured by an optical concentration meter which is described in the previous paper (1). The lines were obtained at an instant of $0.5t_s$ after the stepwise injection of tracer solution (black ink) from the inlet nozzle at a constant flow rate, the flow rate (Reynolds number) and the resistance coefficient being the same as those in Fig.1. Where, t_s is the mean residence time. The three following fundamental characteristics on the model chamber have been examined.

(1) The high uniformity of the velocity distributions through the perforated plates in the model chamber is desired for the good heat convection from the combustion gas to the water tube bundles. The uniformity has been examined.

(2) The local distribution of velocities and concentration in the chamber is needed in connection with the shape and fullness of flames in the combustion chamber. It is important to determine the quantitative relation between the resistance coefficient, the homogeneity of the velocity distribution and the area ratio of dead zones in concentration distributions in order to evaluate the fullness of flame.

(3) It is necessary to evaluate not only the averaged mixing speed as described in the first report (1), but also the local mixing performance in order to understand the combustion process which is a simultaneous mixing

and reaction process between fuel and air in combustion chamber. Therefore, it is important to get a "mixing factor" which is expressed by the local value of concentration and its deviation from the averaged value and also to obtain the relation between the concentration transients and the resistance coefficient c_r .

3. Method for Numerical Calculation

The velocity distribution in steady state and the transients of the concentration distribution in a control volume AFGH shown in Fig.2 were calculated in order to generalize and to evaluate these characteristics which were obtained in the experiments described in the previous report (1).

3.1 Calculation for velocity distribution

The velocity distribution was calculated by a turbulent energy model (one equation model with a turbulent length scale distribution). The basic equations are as follows.

The vorticity and Navier-Stokes equation by time averaged values, and the equation for turbulent energy k are given by Eqs.(1), (2) and (3) in nondimensional form respectively (2) (3).

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = -\omega \quad \dots\dots\dots (1)$$

$$\begin{aligned} \frac{\partial \psi}{\partial y} \frac{\partial \omega}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial \omega}{\partial y} &= \frac{\partial^2}{\partial x^2} (\nu_{\text{eff}} \omega) + \frac{\partial^2}{\partial y^2} (\nu_{\text{eff}} \omega) \\ &- 4 \frac{\partial^2 \psi}{\partial x \partial y} \frac{\partial^2 \nu_{\text{eff}}}{\partial x \partial y} + 2 \frac{\partial^2 \psi}{\partial y^2} \frac{\partial^2 \nu_{\text{eff}}}{\partial x^2} + 2 \frac{\partial^2 \psi}{\partial x^2} \frac{\partial^2 \nu_{\text{eff}}}{\partial y^2} \\ &- C_s \left\{ \frac{\partial}{\partial x} (\nu \sqrt{u^2 + v^2}) - \frac{\partial}{\partial y} (u \sqrt{u^2 + v^2}) \right\} \end{aligned} \quad \dots\dots\dots (2)$$

$$\begin{aligned} \frac{\partial \psi}{\partial y} \frac{\partial k}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial k}{\partial y} &= \frac{\partial}{\partial x} \left(\Gamma_{\text{eff}} \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left(\Gamma_{\text{eff}} \frac{\partial k}{\partial y} \right) \\ &+ C_{\nu} k^{1/2} l \left\{ 4 \left(\frac{\partial^2 \psi}{\partial x \partial y} \right)^2 + \left(\frac{\partial^2 \psi}{\partial y^2} - \frac{\partial^2 \psi}{\partial x^2} \right)^2 \right\} - \frac{C_d k^{3/2}}{l} \end{aligned} \quad \dots\dots\dots (3)$$

The last term on the right side of Eq.(2) expresses the resistance term owing to the water tube bundles, that is, this is a term for calculating the flow resistance zone LONM of resistance plates as shown in Fig.2, and c_s is a resistance coefficient (refer to section 3.3).

Nondimensional turbulent effective kinematic viscosity ν_{eff} and the nondimensional diffusion coefficient Γ_{eff} , for k , are expressed by the following two equations owing to turbulent kinematic viscosity, $\nu_t = C_{\nu} k^{1/2} l$ (4) and turbulent Schmidt number for k , $\sigma_k' = \nu_t / \Gamma_{\text{eff}}$, respectively.

$$\nu_{\text{eff}} = \frac{\nu + \nu_t}{Re \nu} = \frac{1}{Re} + C_{\nu} k^{1/2} l$$

$$\Gamma_{\text{eff}} = \frac{\nu + \nu_t / \sigma_k}{Re \nu} = \frac{1}{Re} + \frac{C_{\nu} k^{1/2} l}{\sigma_k}$$

Fig.3 Grid for finite differences and boundary values

Equations (1) (2) and (3) were changed into difference equations by the upwind difference scheme for the convection terms and equations for ψ_P , ω_P and k_P at a center point P (as shown in Fig.3) were obtained and these equations were solved by the SOR method⁽⁵⁾ with a condition that the maximum deviation of the iteration is lower than 10^{-4} .

3.2 Boundary conditions

The resistance zone is LONM in the whole control volume, AFGH, as shown in Fig.2. Most of the calculations have been carried out under a 67×41 mesh in the directions x and y . Some calculations were conducted under a mesh of 133×81 , but the calculated results of the flow pattern did not differ from the above calculated results.

The boundary conditions are given in Table 1. The profiles of ψ and ω on the outlet port DE are given by the $1/7$ -th-power velocity distribution law. The boundary value of ω on AH in Table 1 is illustrated in Fig.3.

3.3 Empirical constants C_d , C_v , σ_k and turbulent length scale l and resistance coefficient c_s

The values of the empirical constants C_d , C_v , in connection with the dissipation term due to viscosity, and Schmidt number σ_k , in connection with the generation term of k , are given as follows according to Wolfshtein⁽⁶⁾:

$$C_d = 0.416, C_v = 0.22, \sigma_k = 1.53.$$

The model chamber is not a pure two-dimensional one and the flow in the chamber is affected by the boundary layers adjacent to the upper and lower walls of the chamber. Therefore, the practical turbulent length scale l cannot always be decided truly by only a simple distribution on the horizontal plane which is assumed as a function of the perpendicular distance from the side walls.

(a) Without resistance zone (b) With resistance zone

Fig.4 Distribution of turbulent scale lengths

However, the main purpose of this study is to generalize the effects of the resistance coefficient on the flow pattern and mixing characteristics. Therefore, the simple distribution of l as shown in Fig.4 is assumed in reference to the distribution which was already expressed by a function of locations⁽⁷⁾. That is, the distributions of l is assumed as follows:

$l = \lambda y_n$ adjacent to the wall, $l = l_{\max}(\text{const.})$ in the case that y_n is larger than $y_{\max}$ and l decreases from $l_{\max}$ to l_d from the relation of $l' = \lambda y'_n$, where y_n is a distance perpendicular to the wall.

However, it is necessary to decide the values of l_d , $l_{\max}$ and λ in order to fix the profile of turbulent length scale. There are the values which should be determined from the experimental data. However, in this study several numerical calculations with $l_{\max}$ ranging from 2 to 6, λ ranging from 0.4 to 0.6 and l_d ranging from 0.05 to 0.2 were carried out and the values were determined from comparison with the experimental results.

Fig.5 Flow patterns of numerical calculation with various λ

Table 1 Boundary conditions

	ψ	ω	k
BC	Linear (0-1)	0	$0.04^{(8)}$ (const.)
CD	1.0	in the same way as AH	$0^{(8)}$
DE	from $1/7$ th rule	from $1/7$ th rule	0
EFGHAB	0	(E x.) AH; Ref. Fig. 3 ⁽⁸⁾	0

As the result, a couple of empirical constants are selected as follows:

$$l_{\max} = 4, \lambda = 0.6, l_d = 0.8$$

An example of the flow pattern by the numerical calculation ($l_d = 0.2l_{\max}$) is shown in Fig.5. The value of λ in a circular tube which is usually used is 0.4. When the values of 0.4 and 0.5 were used in the calculation, the calculated results of the flow pattern were a little different from the experimental results as shown in Figs.5(b) and (c), that is, a part of the lower recirculation zone goes into the right chamber, though the circulating zone of the experiment occurs in only the left chamber. Also, the fact that the flow pattern by $\lambda = 0.6$ has two recirculation zones in the left chamber as shown in Fig.(a) is different from the experimental result as shown in Fig.1. However, the advantage of the agreement between the calculated concentration distribution and the experimental results (ref. Fig.10) and the behavior of recirculation zone of the left room exceed the above consistency, so that a value of $\lambda = 0.6$ is employed in every calculation.

The value of c_s in Eq.(2) is assumed as a coefficient of continuous resistance (LONM) instead of the perforated plates of L' in thickness. That is, the pressure drop per unit length is $-\partial p / \partial s = (1/L')(1/2)c_f \rho V^2$ according to the definition of c_f . Therefore, the derivatives of pressure by x and y , $-\partial p / \partial x$, $-\partial p / \partial y$ can be expressed as $-\partial p / \partial s \cos \theta = c_s \rho u V$, $-\partial p / \partial s \sin \theta = c_s \rho v V$ respectively. Consequently, flow patterns with a pressure drop of zone LONM can be calculated by substituting a value of c_s , given by c_f and L' which was obtained by preliminary experiment, into Eq.(2).

3.4 Calculation for concentration distribution

The transient concentration profiles in the control elements are obtained by solving Eq.(4) numerically. For the calculation the steady state velocity

Fig.6 u-distribution of flow through perforated plates

Fig. 7 Reverse flow rate and distance corresponding to inlet flow rate

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = \frac{1}{S_c} \times \left\{ \frac{\partial}{\partial x} \left(\nu_{\text{eff}} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_{\text{eff}} \frac{\partial c}{\partial y} \right) \right\} \dots \dots (4)$$

distribution, obtained from Eqs.(1), (2) and (3), was used. Equation (4) is a nondimensional governing equation for mass transfer under constant density. Here, a turbulent Schmidt number $S_c = \nu_{\text{eff}} / D$ is assumed to be 0.76, and D is a turbulent diffusion coefficient.

The transient concentration distribution is calculated as follows: In the difference equation for Eq.(4) an explicit difference scheme was used for time, central difference scheme for space and upwind difference scheme for convection terms. The concentration at the inlet port is put as $c=1$ at $t>0$ and the initial concentration in the whole chamber, c is zero. The change of concentration distribution in space and in time in the chamber was calculated during the mean residence time, t_s . Where, t in Eq.(4) is a normalized time by B/V_0 .

4. The Quantification and the Generalization of the Flow Characteristics for the Calculated and Experimental Results

4.1 Consideration on the uniformity of the flow distribution through the resistance

The calculated results of the flow pattern shown in Fig.5 agree qualitatively with the experimental ones, and changing the values of parameters of $l_{\max}$, λ and l_d the calculated results can be made to coincided with the experimental ones. Thus the method described above was confirmed to be effective for the generalization of flow pattern characteristics. Therefore, at first, the general feature of the uniformity of the velocity component u through the perforated plates along the L_0 axis (as shown in Fig.2) will be discussed according to the calculated results. The calculated results of u -distribution shown by broken lines for various magnitudes of c_f agree well with the experimental ones as shown in Fig.6. Here, u is normalized by the inlet velocity V_0 , and the experimental values of u are obtained as 0.46 times the measured value which was obtained at the center of each hole of 71 in the perforated plates, because the opening

Table 2 Key number of concentration

Key No.								
1	2	3	4	5	6	7	8	9
0.11	0.21	0.32	0.42	0.53	0.63	0.74	0.84	0.95

C/C_0 : Non-dimensional concentration

ratio of the perforated plates is 0.46. It can be seen that a reverse flow from the right chamber to the left chamber occurs at the upper part and a normal flow occurs at the middle and lower parts, and the reverse flow decreases and the uniformity of the flow distribution increases with an increasing value of c_f . In order to express the above feature quantitatively, experimental and calculated results of a nondimensional reverse flow rate Q_r/Q_0 and a distance ratio $P_{\psi 1}O/L_0$ (here, Q_r is the reverse flow rate, Q_0 is the inlet flow rate and $P_{\psi 1}$ is the point of intersection of the stream line $\psi=1$ with the axis L_0) are shown in Fig.7. As can be seen in Fig.7 the reverse flow rate decreases and the distance ratio increases with an increase of c_f and approaches a constant value at $c_f=10$. Thus, it is clear that the flow becomes uniform with an increase of the flow resistance.

4.2 The Homogeneity of velocity distributions

The homogeneity of the normalized velocity V/V_0 and its frequency distribution are examined. The relation between the standard deviation of V , s and the resistance coefficient c_f is shown in Fig.8. The standard deviation of V , s decreases slightly with an increasing c_f in the region of 0-10. That is, the homogeneity of velocities in the chamber proves to be improved with an increase of c_f .

Next, the area A_d which is defined as an area where the concentration c/c_0 is lower than 0.63 at t_s is called dead zone and a ratio of A_d to A_L of the left chamber is examined. The effect of c_f on the ratio, A_d/A_L is shown at the upper part in Fig.8. The value, A_d/A_L decreases in the region of 0.5-0.39

with an increasing c_f . That is, it is clear by numerical calculated results and experimental results that the dead zone ratio decreases and the fullness of fire

Fig. 8 Standard deviation and dead zone ratio

(a) $t/t_s=1/8$ (b) $t/t_s=1/2$ (c) $t/t_s=1/1$
 Fig.9 Distribution of concentration transients $Re=2 \times 10^4$
 $N=5$
 $C_f=18$

Fig. 10 Averaged concentration on time
 flames increases with an increasing c_f .

5. The Comparison of the Experimental Results with the Calculated Results on the Mixing Characteristics and the Evaluation by a Mixing Factor

In Fig.9 are shown the calculated results about the isoconcentration lines c/c_0 at $t/t_s = 1/8, 1/2$ and 1 when the concentration at the inlet is changed stepwise from zero to c_0 . It can be seen that the higher concentration zone spreads with time. The magnitude of the nondimensional concentration is shown by a key number 1, 2, ..., 9 as shown in Table 2. The whole tendency of the calculated concentration distribution in Fig.9(b) agrees with the experimental results in Fig.2, though some small difference exists between them, for example, the low concentration zone of key number 2, 3 in the left chamber which exists in the experiment does not appear in the calculated results. Therefore, the characteristics of the concentration distribution for different conditions can

Fig. 11 Mixing factor on time

be predicted by the calculation presented above. For example, the calculated results of the transients of $\bar{c}_L/c_0$ which were obtained by using the value $\lambda = 0.6$ shown by broken lines in Fig.10 agree with the experimental results at every value of c_f . Then, in order to evaluate the performance of mixing characteristics based on the local and transient concentration distributions, a mixing factor, M_L , which is defined as $\bar{c}_L/s_c$, is proposed. The change of the value, M_L in time is shown in Fig.11. In the case of $c_f = 0$, the value of M_L increases from 0.9 to 2.3 during the time of $t/t_s = 0.125 - 1.0$, and in cases of $c_f = 9$ and 18 the value of M_L increases from 1.0 to 2.65. Furthermore, the effects of c_f on $\bar{c}_L/c_0$ and M_L at $t/t_s = 1$ are shown in Fig.12. The tendency of both values increasing with an increasing c_f can be seen clearly, thus the mixing characteristics depending on c_f can be expressed in a generalized form.

Fig.12 Concentration and mixing factor on resistance coefficient

6. Conclusions

The uniformity of the flow rate through the perforated plates, the homogeneity of velocity distribution in the model chamber, and the mixing factor have been investigated concerning the mixing characteristics in a marine boiler furnace. The numerical calculation have also been conducted to generalize the characteristics. Then the following results have been obtained.

(1) The numerical calculated results by the turbulent energy model agree with the experimental ones of the velocity distribution and the concentration distribution, when the following values are used:

$$l = \lambda y_n \text{ in the range } y_n < 6.67$$

$$l = l_{\max} = 4 \text{ in the range } y_n > 6.67$$

$$l_d = 0.8 \text{ at the resistance zone}$$

where, λ is 0.6.

(2) The uniformity of the velocity distribution through the perforated plates increases and the reverse flow rate from the right chamber to left chamber decreases with an increasing resistance coefficient.

(3) The value of the standard deviation of the absolute velocity, which represents the homogeneity of the flow in the chamber, decreases with an increasing

c_f till $c_f = 10$ and takes an approximately constant value at $c_f > 10$. The area ratio of the dead zone of flow also decreases with an increasing c_f . (4) The mixing factor $M_L = \bar{c}_L/s_c$ ($\bar{c}_L$, s_c ; concentration of left chamber, and the deviation for concentration respectively) increases with an increase of c_f in the range of $c_f = 25$ and the homogeneity of the concentration increases.

References

- (1) Murai, K. et al., JSME paper (in Japanese), vol. 51, NO. 465 ('85), 1574.
- (2) Mitsunaga, S. et al., JSME Conf. of Symposium Proceeding (in Japanese), NO. 8, NO. 760-18, ('76-11), 175.
- (3) Mitsunaga, S. et al., JSME Conf. of Proceeding (in Japanese), NO. 240, ('79-11), 81.
- (4) Gosman, A. D. et al., Heat and Mass Transfer in Recirculation Flows, ('69), 82, Academic Press.
- (5) Smith, G. D., Numerical Solution of Partial Differential Equations, ('65), 29, Oxford Univ. Press.
- (6) Wolfshtein, M., Trans. ASME, Ser. D, 92-4 ('70), 915.
- (7) Yamamoto, K. et al., JSME Conf. of Proceeding (in Japanese), NO. 11, NO. 760-18, ('76-11), 133.
- (8) Yoshikawa, A. et al., Trans. of S.H.A.C and S.E.J (in Japanese), NO. 48, NO. 10 ('74), 11.
- (9) Nomura, T. et al., ibid., 27.
- (10) Yamasaki, et al., JSME Proceeding (in Japanese), NO. 750-5 ('75-4), 145.