NATURAL CONVECTIVE FLOW BETWEEN HEATED VERTICAL PARALLEL PLATES

KUNIO KATO, TAKAYUKI TAKARADA, KEIZABUROU YOSHIE, MINORU FUKATSU, AND YASUTO EZURE
Department of Chemical Engineering, Gunma University, Kiryu, 376

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In various electronic systems such as telephone exchange units, circuit cards are aligned on a vertical plate. The cards are usually cooled by natural convection.

The local vertical velocity distribution of gas between vertical parallel heated plates was measured with a laser doppler velocimeter (L.D.V.).

The local gas velocity was affected by the distance between the heated plates, the temperature of the plates and the open ratio of the distributor plate attached to the top or bottom of the plates.

The average gas velocity between the plates was obtained from the measured velocity distribution.

An empirical equation for the average gas velocity between the vertical parallel heated plates was obtained.

Introduction

Recently, along with the remarkable development of electronic engineering, the microminiaturization of electronic devices has progressed. It is very important to remove the heat generated in the electronic devices and to control the temperature of the devices.

Electronic circuit cards like integrated circuits (I.C.) and large-scale integrations (L.S.I.) are quite sensitive to temperature. If the temperature of these circuit cards is higher than 110°C, the cards do not work normally. In electronic systems such as computers and telephone exchange units, these circuit cards are aligned on plates. The plates are arranged to form vertical channels. In the design of such electronic systems, it is very important to analyze the heat transfer from these devices. An electronic system such as a telephone exchange unit must be continuously used for more than 10 years, and is not permitted to

* Received January 30, 1989. Correspondence concerning this article should be addressed to K. Kato. K. Yoshie and Y. Ezure are now with Fujitsu Limited. M. Fukatsu is now with Ushio Elect. Co., Limited.

stop its operation by any accident.

These electronic systems are usually cooled by natural convection. Therefore, quantitative information about the natural convective heat transfer from the heated parallel plates is necessary. The natural convective heat transfer between the heated vertical parallel plates is determined by the natural convective flow between the plates.

Many studies[1-4,7-10] of the natural convective heat transfer between heated vertical parallel plates have been reported.

Recently, Kishinami and Seki[6] investigated the velocity distribution of natural convective flow in the case where vertical parallel plates were heated. Very fine particles were fed from the bottom of the plates and the locus of these particles was recorded by continuous photography.

In this study the axial velocity distribution induced by natural convection between heated vertical plates was measured with a laser doppler velocimeter (L.D.V.). The effects of the plate temperature, the open ratio of the distributor plate attached at the top or bottom of the channel and the distance between the plates upon the velocity distribution were investigated. The average axial gas velocity was obtained from the local gas velocity distribution. An empirical equation for the average axial gas velocity between heated vertical parallel plates was obtained.

1. Experimental Apparatus and Procedure

A schematic diagram of the experimental apparatus is shown in **Fig. 1(A)** and the main part of the vertical parallel plates is shown in Fig. 1(B). Two vertical parallel plates were placed a certain distance apart as shown in Fig. 1(B). Each plates was 60 cm high, 45 cm wide and 2 mm thick. Kanthal A wires were put into the plates in three places as heat source and the plates were heated isothermally. The temperature of the heated plates was controlled by electric power supplied to the wires. The surface temperatures of the plates were measured by copper-constantan thermocouples placed at the points shown in Fig. 1(B). Two other vertical plates were placed outside both heated plate 1 and opposite plate 3 at a certain distance from the heated plate or the opposite plate as shown in Fig. 1(A). The heated vertical plates were put into the cabinet 8, which was 210 cm high, 75 cm long and 85 cm wide as shown in Fig. 1(A). Perforated plates with suitable open ratio were attached at the top and bottom of the channel.

Axial gas velocity in the channel was measured with the L.D. V. **Figure 2** shows the gas velocity measurement system with the L.D.V. The measured points of gas velocity in the vertical direction (y direction) were 10 cm, 30 cm and 50 cm from the bottom of the channel. To change the measurement point in the vertical direction the experimental unit was moved vertically, and to change the measurement point in the horizontal direction the L.D.V. was moved horizontally. These movements were carried out very accurately. In this measurement of gas velocity, the system of forward scatter was used and the smoke of mosquito incense sticks (average particle diameter of 0.1 μm) was used as the tracer particles.

After the temperature in the channel reached steady state, local gas velocity was measured. The experimental conditions were as follows. The temperature of the heated plate was 100°C or 150°C. The opposite plate was non-heating, and heated at 60°C or 100°C. The distance between the heated plate and the opposite plate was 1.3 cm, 2 cm, 3 cm or 5 cm. The open ratio of distributor plates attached at the top and the bottom was in the range from 0.08–1.0.

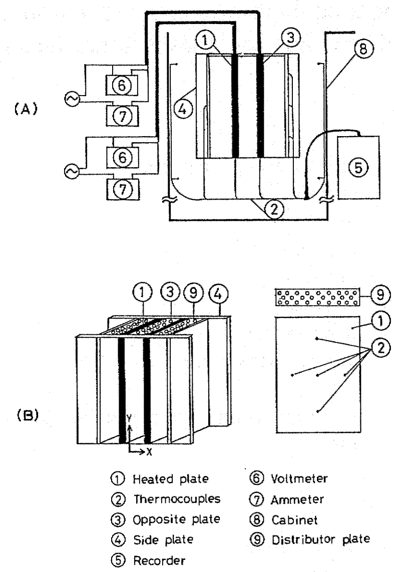

Fig. 1. Experimental apparatus

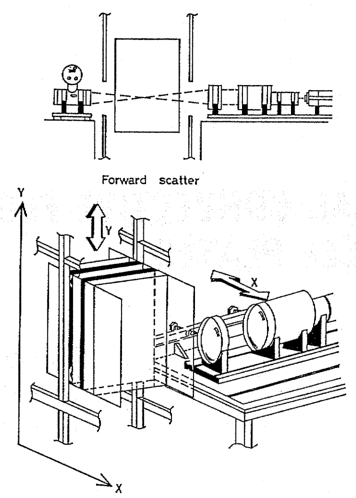

Fig. 2. Measuement system of gas flow by L.D.V.

2. Experimental Results

The axial velocity distribution between the plates was measured under various conditions. **Figure 3** shows the effect of y on the vertical velocity distribution in the case of $T_H=100°C$. The velocity distribution near the bottom of the channel is almost parabolic. When y increases, the peak point of the velocity appears near the heated plate. This tendency became remarkable when the channel distance was wide. The fluid near the heated plate was heated by the heated plate and the density of the fluid became low.

Figures 4(a), **4(b)** and **4(c)** respectively, show the effect of T_H upon the velocity distribution in the cases of $D=1.3$ cm, 2 cm and 3 cm. When the temperature of the heated plate increased, the axial gas velocity increased. However, the pattern of the velocity distribution in the case of $T_H=100°C$ was quite similar to the case of $T_H=150°C$.

Figures 5(a), **5(b)** and **5(c)** respectively, show the effect of y on the velocity distribution in the case of $D=1.0$ cm, 2.0 cm and 3.0 cm. The fluid near the heated and opposite plates was heated and the fluid velocity in these regions became fast. The maximum velocity exists near the heated and opposite plates in the cases of $D=2$ cm and $D=3$ cm. From these figures it is seen that the velocity of the fluid at $y=50$ cm was higher than that at $y=10$ cm. On the other hand, the temperature of the fluid at $y=50$ cm was also higher than that at $y=10$ cm. As a result, $\int \rho V ds$ at $y=50$ cm was almost the same as that at $y=10$ cm.

Figure 6 shows the effect of the open ratio of the distributor plates on the velocity distribution in the case of $D=2.0$ cm. The velocity in the channel decreases with decrease in the open ratio. The fluid velocity is more strongly affected by the open ratio of the plate attached at the top of the plate than that of the plate attached at the bottom of the plate. Rising flow near the opposite plate was scarcely observed in the case of $OT=0.08$. In this case, the velocity in the channel decreased drastically.

Figures 7(a), **7(b)** and **7(c)** show the vertical velocity in the channel in the case of $T_W=100°C$ with OT or OB as a parameter. The vertical velocity was strongly affected by the open ratio of the distributor plate attached at the top or bottom of the channel. From Figs. 7(a), 7(b) and 7(c) it can be seen that the vertical velocity decreases with decrease in the open ratio. The vertical velocity was more strongly affected by the distributor attached at the top than that attached at the bottom. This tendency is the same as in the case where the opposite plate is non-heating. However, the mean velocity for T_W = non-heating is almost the same as that at $T_W=100°C$. It is considered that the mean velocity in the channel is strongly affected by the open ratio of the distributor, but is not affected by T_W.

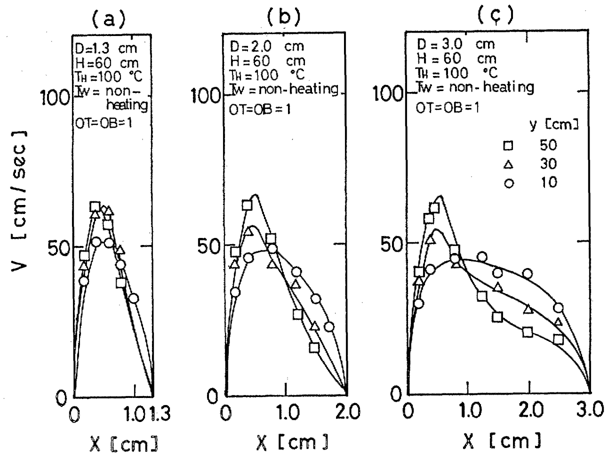

Fig. 3. Effect of y on vertical velocity distribution

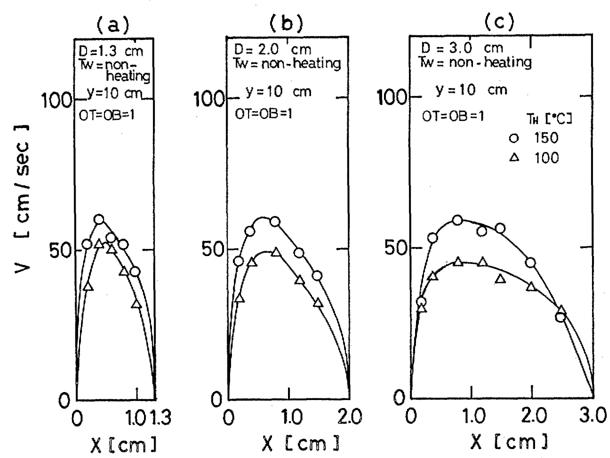

Fig. 4. Effect of T_H on vertical velocity distribution

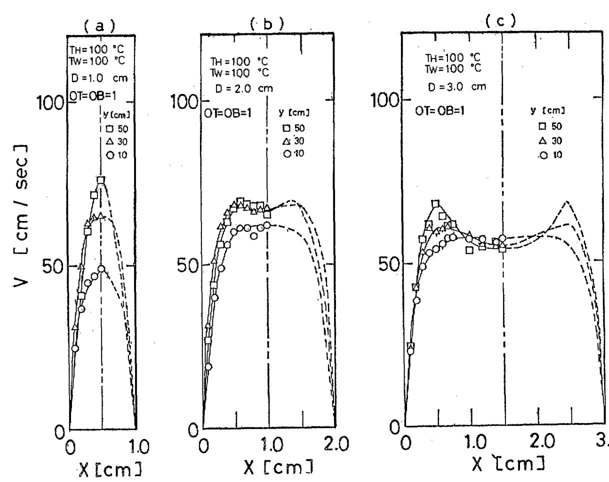

Fig. 5. Effect of y on vertical velocity distribution

Figures 8(a) and **8(b)** show the vertical velocity distribution in the case of $D=2.0$ cm with OT or OB as a parameter. There are two peak points of the velocity, near the heated plate and the opposite plate respectively. This tendency becomes remarkable when the distributor plate is attached at the top.

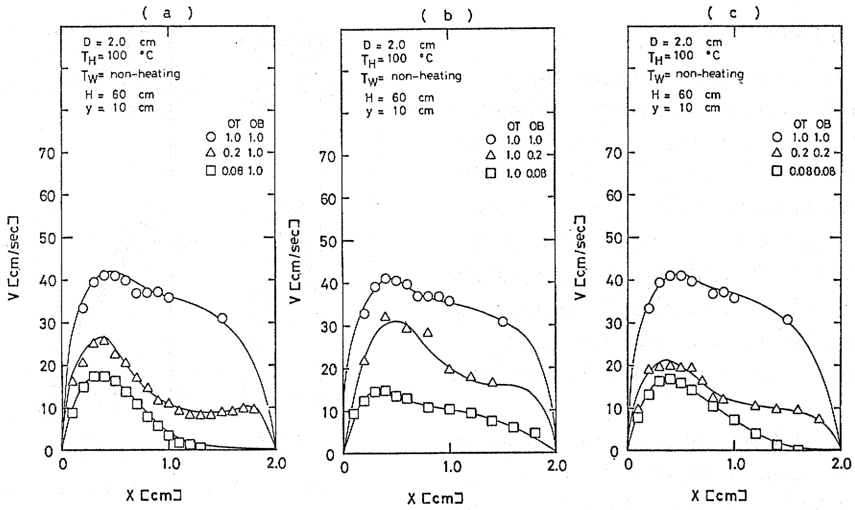

Fig. 6. Effect of *OT*, *OB* on vertical velocity distribution

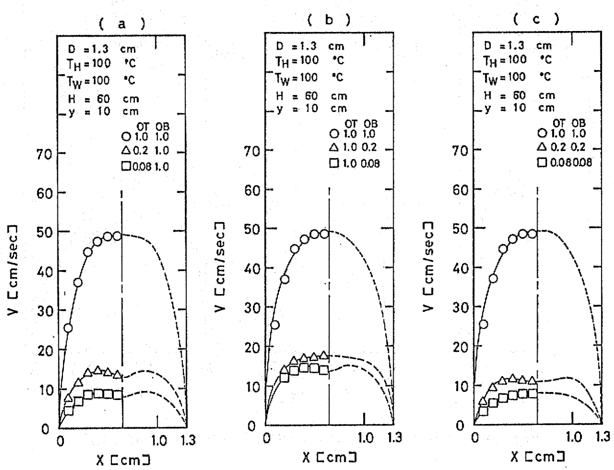

Fig. 7. Effect of *OT*, *OB* on vertical velocity distribution

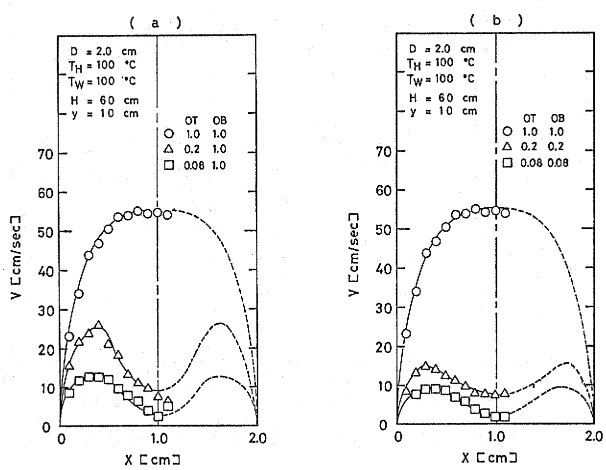

Fig. 8. Effect of *OT*, *OB* on vertical velocity distribution

3. Correlation for Average Vertical Velocity in the Channel

If the average vertical velocity in the channel is known, the average gas temperature in the channel

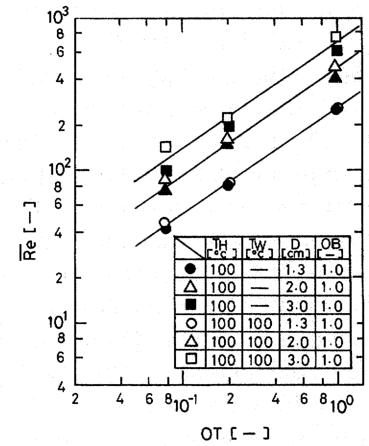

Fig. 9. Relation between $\overline{Re}$ and *OT*

can be calculated from the heat transfer coefficient from the wall. The average Reynolds number (Re) based upon the gas velocity in the channel may be affected by the Grashof number (Gr), D, OT, OB and $\theta(=(T_W-T_A)/(T_H-T_A))$, where θ is the dimensionless temperature of the opposite plate.

The average Reynolds number $\overline{Re}$ was defined from Eq. (1) as

$$\overline{Re}=\frac{\bar{V}D}{\nu} \tag{1}$$

where $\bar{V}$ is the average vertical velocity in the channel and $\bar{V}$ is calculated from the vertical velocity distribution in the channel.

Figures 9 and **10**, respectively, show the relation between $\overline{Re}$ and the open ratio of the distributor plate attached at the top and bottom with D as a parameter. It is found that $\overline{Re}$ is, respectively, proportional to $OT^{0.69}$ and $OB^{0.57}$. $\overline{Re}$ was also affected by the distance between the plate and $\overline{Re}$ was proportional to $D^{1.0}$. However, $\overline{Re}$ was not affected by the temperature of the opposite plate.

Figure 11 shows the relation between $\overline{Re}$ and Gr with OT, OB as a parameter in the case of $T_W = 100°C$ where the Grashof number, Gr, is defined as follows.

$$Gr = \frac{g\beta(T_H - T_A)D^3}{\nu^2} \qquad (2)$$

From this figure, $\overline{Re}$ is proportional to $Gr^{0.31}$. The following empirical equation is obtained for the vertical average velocity between the symmetric or asymmetric isothermally heated vertical parallel plates with the distributor plate.

$$\overline{Re} = 10.0Gr^{0.31}D^{1.0}OT^{0.69}OB^{0.57} \qquad (3)$$

From **Fig. 12**, the average vertical velocity between the plates is well correlated by Eq. (3). The calculated value of $\overline{Re}$ by Miyatake[7,8] *et al.* is also shown in this figure. The calculated value by Miyatake *et al.* approximately agrees with this experimental result. The gas velocity between the plates was strongly affected by the distributor plates. The average gas velocity in the case where the distributor plates were attached became very low and the velocity distribution between the plates was not affected by H. Eq. (3) may be applicable in the range of H from 20 cm to 100 cm. The applicable ranges of Eq. (3) are from $Gr = 2 \times 10^3$ to 10^6, $D = 0.7$ cm to 4 cm, $\theta = 0.0$ to 1.0, and Ot and $OB = 0.06$ to 1.0.

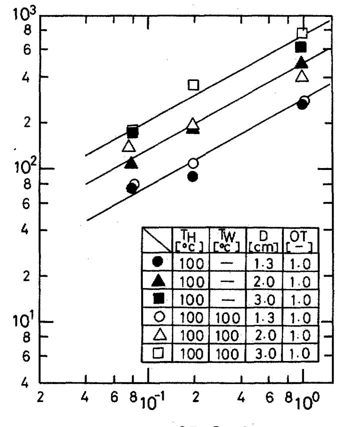

Fig. 10. Relation between $\overline{Re}$ and OB

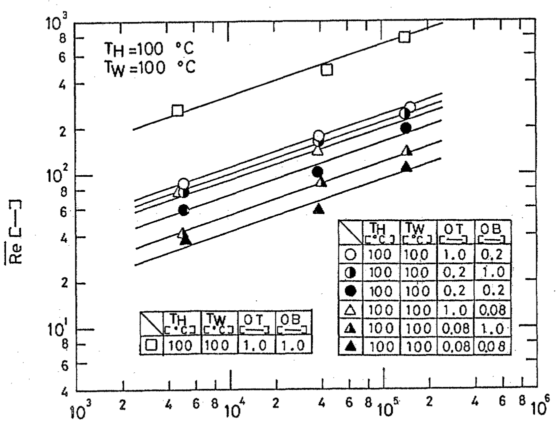

Fig. 11. Relation between $\overline{Re}$ and Gr

4. Discussion

The velocity distribution in the channel changed with the distance y from the bottom of the plates, and the peak point of the velocity was near the heated plates. The fluid near the heated plate is heated by the heated plate, its density becomes low and the gas velocity near the plate becomes low.

The gas velocity between the plates was strongly affected by the distributor plates. The velocity in the case where distributor plates were attached was drastically lower than that in the case where distributor plates were not attached. The gas velocity is decreased by the pressure drop due to the distributor plates. The fluid is heated to considerably high temperature near the bottom of the plate in the case of the distributor plate being attached and the velocity distribution between the plates is not affected by y.

The temperature of the heated plate, the average

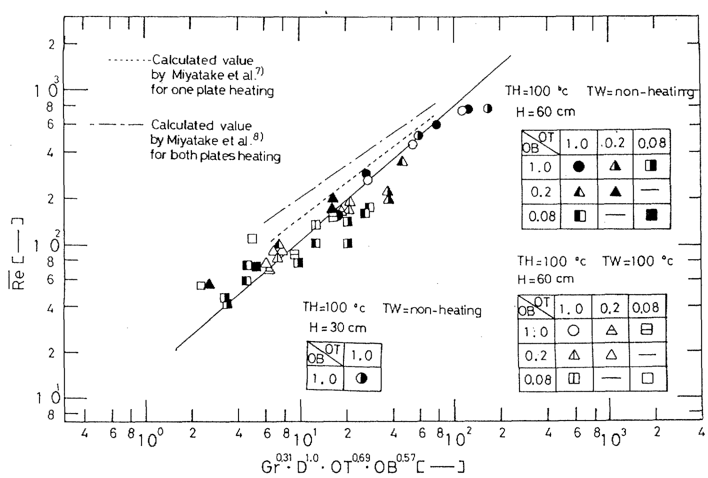

Fig. 12. General correlation

gas velocity in the channel and vertical gas temperature distribution are calculated by using both empirical equation (3) for the average velocity in this work and the empirical equation for the average Nusselt number presented by Kato *et al.*[5] as follows.

$$Nu = 0.446 Gr^{0.28} (H/D)^{-0.22} OT^{0.26(1+\theta)^{-1.2}} OB^{0.19 OT^{0.7}(1+\theta)^{-1.4}} \quad (4)$$

First, the following equation was obtained from the heat balance with respect to the heated vertical plate.

$$\frac{1}{2} Q = \bar{h} A (T_H - T_A) \quad (5)$$

where Q is heat duty to the plate. If the temperature of heated plate, T_H, is assumed, the average heat transfer coefficient, h, is calculated by using equation (4). And if h is substituted in Eq. (5) when the heat balance of Eq. (5) is satisfied, T_H is the correct value. The average heat transfer coefficient in the channel and the temperature of the plate surface are calculated by this method. It is possible to calculate the average gas velocity from Eq. (3). The outlet average gas temperature between the plates is calculated from the average gas velocity and Eq. (5).

Conclusions

The local vertical velocity distributions between the vertical parallel plates with symmetric or asymmetric heating were measured quantitatively with the L.D.V.

The local velocity distribution was affected by the distance between the vertical parallel plates, the temperature of the plates and the open ratio of the distributor plate attached at the top or bottom of the plates.

The average gas velocity between the channel was obtained from the measured velocity distribution. The Reynolds number based upon the average gas velocity was affected by the Grashof number, the distance between parallel plates, the open ratio of the distributor plate and the temperature of the plates. The empirical equation for the average Reynolds number was obtained.

Nomenclature

A	= heat transfer area	[cm^2]
D	= distance between plates	[cm]
g	= gravitational acceleration	[cm/s^2]
Gr	= Grashof number $D^3 g\beta(T_H - T_A)\nu^{-2}$	[—]
H	= axial distance of plate	[cm]
$\bar{h}$	= average heat transfer coefficient	[W/cm^2 K]
Nu	= average Nusselt number	[—]
OB	= open ratio of distributor plate attached at bottom of channel	[—]
OT	= open ratio of distributor plate attached at top of channel	[—]
Q	= heat duty to the plate	[W]
$\overline{Re}$	= average Reynolds number	[—]
T_A	= room temperature	[°C]
T_H	= temperature of heated plate	[°C]
T_W	= temperature of opposite plate	[°C]
$\bar{V}$	= vertical average velocity	[cm/s]
V	= vertical velocity	[cm/s]
X	= horizontal coordinate	[cm]
Y	= vertical coordinate	[cm]
β	= volumetric coefficient of expansion	[1/K]
ρ	= density of fluid	[g/cm^3]
ν	= kinematic viscosity of fluid	[cm^2/s]
μ	= viscosity of fluid	[g/cm s]
θ	= dimensionless temperature of opposite plate $(T_H - T_W)/(T_H - T_A)$	[—]

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