Natural Convective Heat Transfer in an Inclined Rectangular Cavity*

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Experiments of the convective heat transfer in an inclined air filled rectangular cavity were carried out under the conditions of angle of inclination from 0° to 180° and a wide range of aspect-ratios ($H/W = 5 \sim 83$). Depending on the angle of inclination, three flow pattern modes of a three-dimensional Benard cellular flow, a screw type flow with the axis parallel to the direction of inclination and a two-dimensional boundary layer flow were identified by visual observations of two directions. In addition, useful correlations of non-dimensional heat transfer coefficients were derived in the relations between Nusselt number Nu_W and modified Rayleigh number $Ra_W \cos \theta$ or Nu_W and $Ra_W \sin \theta$.

Key Words: Heat Engineering, Experimental Study, Natural Convective Heat Transfer, Inclined Air Layer.

1. Introduction

The present study deals with the thermal natural convection in an inclined narrow rectangular cavity filled with air, whose two opposing isothermal walls are separated by width W and maintained at different temperatures in a wide range of inclination angles θ to the horizontal (heated from below). In recent years, increasing attention has been paid to the problem of natural convection in an inclined fluid layer. The occurrence of an inclined natural convective movement related to the motion of the atmospheric layer and the ocean as well as the heat transfer in buildings and in cooking vessel is rather common since rarely are the earth's surfaces aligned with geopotential lines. Determination of the rate of convective heat transfer in an inclined air layer is important to estimate the heat-loss through natural convection in a flat plate type solar collector.

Concerning this convective problem, firstly Degrrf and Van Der Held⁽¹⁾ considered experimentally the effect of inclination angle on flow and rate of heat transfer at small inclination angles. After that, a lot of experimental and analytical studies⁽¹¹⁾ on an inclined fluid layer have been carried out by some researchers up to date. Especially, Hart⁽¹²⁾ performed a series of flow visualization experiments from the top glass plate water jacket at various inclination angles to examine flow instabilities in water. He observed the existence of longitudinal rolls with axes directed up slope, roll-dominated turbulence and transverse travelling waves depending on inclination angles and temperature differences between

surface temperatures of the hot and cold walls. Clever and Busse⁽¹³⁾ investigated the stability of longitudinal rolls in an inclined convection layer. They reported three types of flow instabilities which were responsible for the transition from longitudinal rolls to three-dimensional flows of convection in different regimes of the parameter space.

However, in most of the previous works mentioned above, visual observation of the flow pattern in an inclined fluid layer has been performed only from one direction, for example, from the top cooling wall made of a transparent material (glass cover etc.) in a small range of inclination angles $\theta = 0^\circ \sim 90^\circ$. And little attention has been paid to the temperature profile measurements in the fluid layer, which are important to know the flow and heat transfer behaviors. The primary objective of this paper is to visualize the flow behaviors on two planes (X - Y plane and Z - Y plane) at right angles to each other in an air-filled inclined narrow rectangular cavity, to obtain the temperature profile of the inclined air layer, and to measure the heat transfer rate through the air layer. The present experiments were carried out under the following conditions; inclination angles $\theta = 0^\circ \sim 180^\circ$, aspect-ratios $H/W = 5 \sim 83$ and Rayleigh numbers $Ra_W = 1.2 \times 10^3 \sim 2 \times 10^6$. Moreover, useful non-dimensional correlation equations of heat transfer rate through the air layer are derived in wide ranges of inclination angles, aspect-ratios and Rayleigh numbers.

Nomenclature

D : depth of rectangular cavity (Z -direction)
 g : gravitational acceleration
 H : height of rectangular cavity
 H/W : aspect-ratio
 h : local heat transfer coefficient, $q/\Delta T$
 h_m : average heat transfer coefficient, $\frac{1}{H} \int_0^H h \, dX$

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- Nu_W : average Nusselt number, $h_m W / \lambda$
 q : local heat flux, $q_{cd} + q_{cv} = q_T - q_{\theta=180^\circ} + q_{cd}$
 q_m : average heat flux, $\frac{1}{H} \int_0^H q \, dX$
 q_T : total heat flux, $q_{cd} + q_{cv} + q_{ra} + q_l$
 q_{cd} : thermal conductive heat flux
 q_{cv} : convective heat flux
 q_l : heat flux based on the heat-loss of experimental apparatus
 q_{ra} : radiant heat flux
 $q_{\theta=180^\circ}$: total heat flux at $\theta = 180^\circ$
 Ra_W : Rayleigh number, $g \beta \Delta T W^3 / \nu \alpha$
 T : temperature
 ΔT : temperature difference, $T_h - T_c$
 W : width of rectangular cavity
 X, Y, Z : Cartesian coordinates
 α : thermal diffusivity
 β : thermal expansion coefficient
 λ : thermal conductivity
 ν : kinematic viscosity
 θ : inclination angle.
 Subscripts
 c, h ; cold and hot wall.

2. Experimental Apparatus and Procedure

The present experiments were carried out using inclined air-filled rectangular cavities, whose two opposing walls were kept at different temperatures while the other walls were thermally insulated. The main parts of the experimental apparatus consisted of a heating part, an air-filled test section and a cooling part as depicted in Fig. 1. Four kinds of test sections were constructed by inserting bakelite frames (15 mm thickness) of 580 mm (fixed height H) x 7 mm (aspect-ratio $H/W = 83$), 10 mm ($H/W = 58$), 20 mm ($H/W = 29$) and 58 mm ($H/W = 10$) (variable width W) section areas and 400 mm (depth D) between the heating and cooling parts. A center part of 200 mm in depth direction (Z-direction) was used as the test section and both sides (100 mm length) of the test section in the Z-direction were used as the guard parts.

In order to obtain two opposing heating and cooling boundary conditions with a uniform temperature, the hot and cold walls (copper plate of 5 mm thickness) were divided into five parts by bakelite frames of 5 mm thickness in the X-direction. The surface temperature of the hot wall was maintained at a uniform temperature using five independently controllable main mica electric heaters (maximum output power of 1 kW). The guard mica heaters were mounted on the rear side of the main heaters across a bakelite plate (5 mm thickness) to minimize the heat-loss from the main heaters to the environment. Moreover, ten guard heaters were provided on both sides of main heaters in the Z-direction so as to minimize the heat-loss from the main heaters. The surface temperature of the cold wall was maintained at a uniform temperature by inducing a temperature-controlled coolant (brine) into each of five separate cooling chambers attached to the rear side of the cold walls. Consequently it was possible to control the surface temperature gradients of the hot and cold walls in the X-direction within $\pm 2 \times 10^{-3}^\circ\text{C/cm}$. The temperatures at 50 measur-

Fig.1 A schematic diagram of experimental apparatus

Fig.2 X-Y plane and Z-Y plane for visual observation (hatched portions)

ing points (the hot and cold walls, the main and guard heaters) were measured with Cu-Co thermocouples (0.1 mm in diameter). In order to measure the temperature distributions of air layer, three traversing small probes (0.1 mm in diameter) which were movable in the Y-direction were set at the positions of $X = 145$ mm, 290 mm and 435 mm.

In order to minimize the heat-loss from the experimental apparatus, the experimental apparatus was covered with a styrofoam insulating material of 10 cm in thickness and was placed into the temperature-controlled room which was controlled to the average temperature of the surface temperatures of the hot and cold walls. The heat-loss from the experimental apparatus to the environment was ascertained to be less than $\pm 7\%$ from the results of the preliminary experiments, which were carried out by packing a liquid paraffin wax of thermal conductivity $\lambda = 0.0928$ W/mK at 20°C into the test section at the inclination angle $\theta = 180^\circ$ (heated from above) without natural convection. The hot and cold walls in the present study as a heat transfer surface consisted of well-polished copper plates. The experimental data were taken after the thermal and fluid-dynamic conditions had reached a steady state. The heat flux of the natural convective heat transfer at any inclination angle was determined by subtracting the total heat flux $q_{\theta=180^\circ}$ at $\theta = 180^\circ$ without natural convection from the total heat flux q_T at any inclination angle as expressed in Nomenclature. The physical properties which were used to determine the non-dimensional variables were evaluated at the average of the surface temperatures of the hot and cold walls.

Another apparatus basically similar to the apparatus mentioned above was constructed in order to study visually the flow behaviors of natural convection. For vis-

ualization of flow pattern, the test sections were fabricated by inserting transparent frames (lucite frame of 10 mm thickness) of width $W = 22$ mm ($H/W = 5$) between the isothermal hot and cold walls (5 mm thickness) of fixed height $H = 110$ mm and depth $D = 200$ mm. The hot and cold walls were painted black so as to prevent the reflection of the light beam. To illuminate a X - Y or Z - Y plane of the test section as shown in Fig. 2, a parallel light beam was created by means of an optical set up and a light source of 300 W power. A water filter of 20 mm thickness was used to minimize the incoming radiation of infrared rays from the light source into the test section. The convection patterns were visualized by introducing cigar smoke through two ports in the test section at a very slow speed. Photographs were taken using a 35 mm camera with close-up and wide angle lenses and 400 ASA film. Typical exposure times at an aperture 1.4 were varied varied 1 ~ 5 s.

3. Experimental Results and Discussions

3.1 Temperature profile in air layer

Figures 3(a) ~ (e) show typical temperature distributions T in the Y -direction at inclination angles $\theta = 0^\circ, 30^\circ, 90^\circ, 120^\circ$ and 150° , respectively, at the fixed positions of $X = 145$ mm, 290 mm and 435 mm under the condition of $H/W = 10$. Distributions of in case of $\theta = 0^\circ$ are presented in Fig.3(a). It seems that these temperature distributions correspond with those of Benard convection. Existence of boundary layer flows in the horizontal direction along the hot and cold walls is presumed from a large temperature distribution in the Y -direction in the center core region outside of both boundary layer flows. At this angle $\theta = 0^\circ$, it is interesting to note that temperature distributions at each X -position make little difference. These behaviors of temperature distributions obtained might be explained from the fact that three probes for air temperature measurement don't traverse in the region of the ascending plume flows of hot air from the hot wall to the cold wall and the descending flows of cold air from the cold wall. Though the tendency of temperature distributions at $\theta = 30^\circ$ is basically similar to that at $\theta = 0^\circ$, there appear differences in temperature distributions at three measuring positions. These differences would mean that the local heat transfer rate on the hot wall becomes large as X decreases, since the temperature gradient in the vicinity of the hot wall decreases with an increasing X . On the other hand, the local heat transfer rate on the cold wall becomes large as X increases since the temperature gradient in the vicinity of the cold wall increases with an increasing X . Results at $\theta = 90^\circ$ show typical temperature distributions corresponding with a convective flow pattern of vertical air layer. The decrease and increase of temperature gradients with an increasing X appear apparently in the vicinity of the hot and cold walls, respectively. These behaviors of temperature gradients would indicate the existence of a boundary layer flow which ascends along

the hot wall or descends along the cold wall. Moreover, the difference in temperature distributions at three measuring positions at $\theta = 90^\circ$ becomes large as compared with that at $\theta = 30^\circ$. The temperature distributions at $\theta = 120^\circ$ in which the hot wall exists above and the cold wall exists below are shown in Fig.3(d). It would be understood that the convective heat transfer rate at $\theta = 120^\circ$ is low as compared with that at $\theta = 90^\circ$ since the temperature gradient of both walls is mild and the variation of temperature in the center core region is large at $\theta = 120^\circ$. It can be seen from Fig.3 at $\theta = 150^\circ$ that the influence of convection becomes small because of a decrease of temperature gradients in the vicinity of the hot and cold walls. Especially the temperature variation at $X = 290$ mm approaches a linear relationship between T and Y , which means a conductive heat transfer.

Fig.3 Temperature profiles for aspect-ratio $H/W = 10$ ($W = 58$ mm).

3.2 The flow behaviors in an inclined air layer

In order to obtain more detail information on the flow patterns, the present visual observations were performed by taking pictures of the flow patterns from two different directions. Smoke as a tracer particle was injected very slowly into the test section from two ports. After 2 ~ 5 minutes some photographs of the flow patterns were taken in order to overcome the problem of confusing smoke injection effects (the forced convection and diffusion of smoke) with unsteadiness of the natural convection. The visual photographs of comparatively stable flow patterns were obtained for $Ra_H = 3 \times 10^4$ and $H/W = 5$.

Typical examples of the change in the flow pattern with various inclination angles can be seen in Fig.4. At $\theta = 0^\circ$, both

visual photographs on the X - Y plane and Z - Y plane show three stable rolls (Benard cellular flows) which circulate in opposite direction to each other. For $\theta = 30^\circ$, a stable cellular flow on the X - Y plane appears at the lower part of the inclined cavity and an unstable flow pattern is observed at the upper part. Meanwhile on the Z - Y plane, four unstable rolls are recognized. For $\theta = 60^\circ$, the flow behaviors are presented in Fig.4(c). A comparatively stable unicellular flow is observed on the X - Y plane, while complex multi-cellular rolls are recognized on the Z - Y plane. These flow behaviors might correspond to the convoluted flow (spiral or coil flow) climbing up in the slope direction.

For $\theta = 90^\circ$, the boundary layer flow, that is, an ascending flow along the hot wall and a descending flows along the cold wall appear on the X - Y plane, and these flows are very stable. Meanwhile it is recognized that there exist very stable complicated flows on the Z - Y plane. Flow behaviors for $\theta = 120^\circ$ are similar to those at $\theta = 90^\circ$ but flow speed at $\theta = 120^\circ$ becomes slower than at $\theta = 90^\circ$. For $\theta = 150^\circ$, the flow behaviors are similar to those at $\theta = 120^\circ$, but these flow speeds become slower than those at $\theta = 120^\circ$.

From the results of flow visualizations for $H/W = 5$, it could be understood that multi-cellular flows (Benard convection) exist in the range of inclination angles below 30° , convoluted rolls (spiral flows) with axes oriented up to the slope are recognized in the range of $\theta = 30^\circ \sim 60^\circ$ and a unicellular boundary layer flow appears in the range of $\theta = 60^\circ \sim 150^\circ$, as depicted in Fig.5.

3.3 Local heat transfer in the X -direction on the hot wall

Figure 6 for $H/W = 10$ presents profiles for the local heat transfer coefficient h in the X -direction on the hot wall ($\theta = 0^\circ$), which were obtained by measuring each heat input to five independent heating surface as mentioned in the description of the experim-

Fig.4 Convective flow patterns at X - Y plane and Z - Y plane

Fig.5 Classification of flow patterns

ental apparatus. It is noted that the change of local heat transfer coefficient h is independent of the distance X at inclination angle $\theta = 0^\circ$, and the value of h at $\theta = 15^\circ$ and 30° decrease gradually with an increasing X . This independency or small dependency of the local heat transfer coefficient's distribution on the distance X could be explained as follows: At the small inclination angle, the heat transfer from the hot wall to the cold wall was carried out mainly by multi-cellular flows as could be seen in visual observations mentioned above, which reduced the distribution of local heat transfer rates on the hot wall since the hot air from the hot wall arrived at the cold wall through many short cut paths in the air layer due to the existence of multi-cellular flows. In case of $\theta = 60^\circ$, the value of h decreased gradually with an increasing in X . This tendency of h relative to X may come from the convoluted flow (spiral flow) as could be shown in photographs of Fig.4(c). For $\theta = 90^\circ$ and 120° , it might be understood that the descending rate of h relative to X becomes large for small X . This behavior of the local heat transfer coefficient's change could be explained by the fact that the value of h for small X becomes large and it decreases gradually with an increasing in X because of a collision of cold air from the cold wall with the hot wall in the range of small X and a development of a boundary layer flow along the hot wall as seen in photographs of Figs.4(d) and (e). The variation of h with X for $\theta = 150^\circ$ is similar to those at $\theta = 90^\circ$ and 120° , but the value of h becomes smaller than that at $\theta = 90^\circ$ or 120° .

Fig.6 Local heat transfer coefficient distributions in the X -direction on the hot wall

3.4 Effect of the aspect-ratio H/W on the average Nusselt number Nu_W

Figure 7 shows the relationship between aspect-ratio H/W and average Nusselt number Nu_W for various inclination angles under the conditions of the temperature difference between the hot and cold walls $\Delta T = 102 \sim 105^\circ\text{C}$. From this figure, it would be noted that the value of Nu_W decreases steeply with an increasing H/W in the range of $H/W < 40$ at the aspect-ratio H/W above 40, it decreases gradually with an increasing H/W , and finally at $H/W = 83$, the value of Nu_W becomes unity, which means only a conductive heat transfer. In a special case of $H/W = 83$, the convective flow is restrained by viscous shearing force from the rigid boundaries because of small width ($W = 7 \text{ mm}$) of the rectangular cavity, and consequently the conductive heat transfer predominates in the air layer. On the other hand, the contribution of the convection to the heat transfer in the air layer increases with a decreasing H/W since the restriction of the convection is mitigated with a decreasing H/W (corresponding to an increase of width under the fixed height).

Fig.7 Relationship between average Nusselt number Nu_W and aspect-ratio H/W

3.5 Effect of inclination angle θ on the average Nusselt number Nu_W

Figure 8 presents relationship between the inclination angle θ and the average Nusselt number Nu_W for various aspect-ratio H/W under the temperature difference $\Delta T = 102 \sim 105^\circ\text{C}$. For small aspect-ratios $H/W = 10$ and 29, the value of Nu_W increases slightly with an increasing inclination angle from $\theta = 0^\circ$ to 15° and has a maximum at about 15° . The value of Nu_W decreases steeply with an increasing θ from $\theta = 30^\circ$ to 75° , next the decreasing rate of Nu_W becomes small in the range of $\theta = 75^\circ \sim 120^\circ$, and finally in the range of $\theta > 120^\circ$ the value of Nu_W decreases again. These complex behaviors of Nu_W against θ could be explained as follows: For $0^\circ \leq \theta < 30^\circ$, the development of multi-cellular flows (Benard convection) with inclination angle θ would induce a slight increase of Nu_W as could be seen in the flow patterns in Fig.4(a). For $30^\circ \leq \theta \leq 75^\circ$, the existence of convoluted flows (spiral flow)

Fig.8 Relationship between Nu_W and inclination angle θ

with their axes oriented to up-slope causes a steep decrease of Nu_W with an increasing θ since the short-cut flows through the air layer become less as the inclination angle increases. For $75^\circ < \theta \leq 120^\circ$, the boundary layer flow (a unicellular flow) developing in the vicinity of the hot wall or cold wall would bring about a small decrease of Nu_W to θ . For $\theta > 120^\circ$, the decreasing rate of Nu_W with θ becomes large since the contribution of the convection to the heat transfer is reduced steeply with an increasing degree of the heating from above.

From these results, it would be also understood that the decreasing rate of Nu_W with θ becomes small for large aspect-ratio $H/W = 58$ and 83. At $H/W = 58$, the value of Nu_W becomes unity in which the contribution of the convection to the heat transfer is negligible at about $\theta = 75^\circ$, while it becomes at about 15° for $H/W = 83$.

3.6 Non-dimensional correlation equations of heat transfer through the air layer

In many previous studies, the relationship between Nu_W and $Ra_W \cos \theta$ has been used to non-dimensionalize heat transfer in inclined enclosures. However, this non-dimensional correlation is useful only at small inclination angle θ since the value of $\cos \theta$ decreases as the value of θ approaches 90° ($\cos \theta = 0$ at $\theta = 90^\circ$). Therefore, the present study is undertaken to derive new correlation equations of the heat transfer in the range of large inclination angles. At an inclination angle θ below 60° in which multi-cellular flows or convoluted flows predominate in the air layer as mentioned above, the previous and present data are plotted with the relationship between Nu_W and $Ra_W \cos \theta$ in Fig.9. From these results of heat transfer in Fig.9, it could be understood that three non-dimensional correlation equations of the heat transfer are derived depending on the range of $Ra_W \cos \theta$ with some accuracy for the sake of simplicity as follows:

- (a) Post-conductive region ($2.5 \times 10^3 \leq Ra_W \cos \theta \leq 6.0 \times 10^3$)

Fig.9 Relationship between Nu_W and $Ra_W \cos \theta$ for $0^\circ \leq \theta \leq 60^\circ$

$$Nu_W = 1 + 1.21 \left(1 - \frac{2500}{Ra_W \cos \theta} \right) \dots\dots\dots(1)$$

The present equation (1) fits well the data reported by Hollands⁽³⁾

(b) Laminar flow region ($6 \times 10^3 < Ra_W \cos \theta \leq 4 \times 10^5$)

$$Nu_W = 0.199 (Ra_W \cos \theta)^{0.258} \dots\dots\dots(2)$$

Dropkin's⁽²⁾ and Mull's⁽⁴⁾ data for $\theta = 0^\circ$ are a little below the present data and correlation equation (2).

(c) Turbulent flow region ($4 \times 10^5 < Ra_W \cos \theta$)

$$Nu_W = 0.0785 (Ra_W \cos \theta)^{0.330} \dots\dots\dots(3)$$

In this figure, the flow in the air layer becomes turbulent and the increasing rate of Nu_W with $Ra_W \cos \theta$ becomes larger in comparison with the results of laminar flow region in equation (2). The data agree with equations (1) ~ (3) within a maximum deviation of 7.5 %, and these equations can be applicable in the range of $0^\circ \leq \theta \leq 60^\circ$.

At an inclination angle θ above 60° , the previous and present data are plotted with the relationship between Nu_W and $Ra_W \sin \theta$ as seen in Fig.10. In this figure, it could be understood that the value of Nu_W depends on not only the $Ra_W \sin \theta$ but also aspect-ratio H/W . From these results, the following non-dimensional correlation equation can be derived with some accuracy for the sake of simplicity:

$$Nu_W = 0.271 (H/W)^{-0.21} (Ra_W \sin \theta)^{0.250} \dots\dots\dots(4)$$

for laminar flow region ($5 \times 10^3 \leq Ra_W \sin \theta \leq 1.2 \times 10^6$ and $5 \leq H/W \leq 83$).

Fig.11 shows the relationship between $Nu_W (H/W)^{0.21}$ and $Ra_W \sin \theta$ from the result of equation (4). The data agree well with equation (4) within a maximum deviation of 5 %. At $Ra_W \sin \theta$ above 1.2×10^6 , the data of Nu_W with $Ra_W \sin \theta$ would mean the occurrence of a turbulent flow.

4. Conclusions

Flow and heat transfer behaviors in an inclined air layer have been clarified experimentally by the flow visualizations and the measurements of temperature profiles and heat transfer through the air layer in wide ranges of inclination angles, aspect-ratios and Rayleigh numbers.

(1) three types of flow patterns in the laminar flow region are recognized depending on

Fig.10 Relationship between Nu_W and $Ra_W \sin \theta$ for $60^\circ < \theta \leq 120^\circ$

Fig.11 Relationship between $Nu_W (H/W)^{0.21}$ and $Ra_W \sin \theta$ for $60^\circ < \theta \leq 120^\circ$

the inclination angle. For $\theta = 0^\circ \sim 30^\circ$, there exist mainly multi-cellular flows (Benard convection). For $\theta = 30^\circ \sim 60^\circ$, the convoluted flows (spiral flow) with axes directed to up-slope are recognized in the inclined air layer. For $\theta = 60^\circ \sim 150^\circ$, a unicellular flow (boundary layer flow) exists in the air layer.

(2) It is clear that aspect-ratio H/W has an important role in the convective heat transfer in the laminar flow region for large inclination angles.

(3) For small aspect-ratios $H/W = 10 \sim 29$, it is clear that the change of Nusselt number Nu_W to an inclination angle θ becomes complex because of the difference of flow patterns mentioned above, that is, the value of Nu_W has a maximum value at about 15° , it decreases steeply with an increasing θ for $\theta = 15^\circ \sim 75^\circ$, the decreasing rate of Nu_W with θ becomes small in the range of $\theta = 75^\circ \sim 120^\circ$, and the value of Nu_W decreases again for $\theta > 120^\circ$.

(4) The data on heat transfer are non-dimensionalized with the relationship between Nu_W and $Ra_W \cos \theta$ for $0^\circ \leq \theta \leq 60^\circ$. On the other hand, for $60^\circ < \theta \leq 120^\circ$ they are non-dimensionalized with the relationship between Nu_W and $Ra_W \sin \theta$, as pointed out by Ayyaswamy⁽¹⁹⁾. Four kinds of non-dimensional correlation equations of heat transfer rate are derived depending on the range of $Ra_W \cos \theta$ or $Ra_W \sin \theta$.

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