Flow and Heat Transfer of Natural Convection around Upward-Facing Horizontal Heated Plate Shrouded by Vertical Plates

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Abstract
Flow and heat transfer characteristics of the natural convection induced over horizontal heated plate were investigated experimentally. The main concerns were directed to the influences of vertical plates attached to the both ends of the horizontal plate. The flow fields and the surface temperatures of the heated horizontal plate were visualized with dye and liquid crystal thermometry. The local heat transfer coefficients of the horizontal plate were also measured. The experiments were carried out with the horizontal plates W=10 to 100mm wide, and with the vertical plates of H=1 to 200mm high. The test fluid was water at room temperature.

The visualization experiments depict that a pair of counter-rotating vortices appear over the horizontal plate when the ratios (H/W) beyond 0.2. These vortices enhance the heat transfer, in particular, from the central portion of the horizontal plate. The heat transfer results showed that average heat transfer coefficients of the horizontal plates increase with (H/W) and reach maxima at around (H/W)=0.5. The comparisons of average coefficients from the horizontal plates with and without vertical plates showed that a 15% higher coefficient is attained by installing the vertical plates of 10mm-high at the edges of the horizontal plate of 20mm-wide. The result suggests that optimum sizes of the horizontal and vertical plates exist for the heat transfer enhancement.

1. Introduction
When vertical plates are attached to the both edges of the horizontal, heated plate as is shown in Fig. 1(a), the natural convective flows induced around the horizontal plate will be altered substantially from those without vertical plates. The attached vertical plates will also exert serious influence on the heat transfer from the horizontal plate. The above flow configuration will be encountered in many industrial and environmental situations, such as cooling of printed circuit boards, chemical vapor deposition of silicon wafers, micro-scale meteorology in urban area and so on. However, to the best of the author’s knowledge, no worker has carried out intensive investigations with the above configuration. Thus, very little information is available on their flow and heat transfer characteristics. This motivates the present study.

Therefore, the authors can only cite some of the relevant studies in the below. The one of such studies is concerned with a natural

![Fig. 1 Configurations of flow](image-url)
convection induced around L-shaped corners, which consist with the vertical and horizontal plates as schematically illustrated in Fig. 1(b). For this configuration, some workers have conducted the experimental and/or analytical investigations.

For example, Rodighiero and de Socio [1] have treated natural convective flows around L-shaped corners, where an adiabatic horizontal plate was attached to the bottom edge of the heated vertical plate. They have measured the local heat transfer coefficients of the vertical plate and have reported that the coefficients become smaller by 25% than those without horizontal plate. Ruiz and Sparrow [2] have also carried out the heat transfer and flow visualization experiments on the natural convection around L-shaped corners, which consisted with an upward-facing horizontal plate and a vertical plate of equal dimension, where the both plates are heated isothermally. Their results showed that the horizontal plate decreases the average heat transfer coefficients of the vertical plate, while the vertical plate increases the average coefficients of the horizontal plate. Moreover, Angirasa & Mahajan [3] have conducted a two-dimensional analysis on the natural convection of air induced around the L-shaped corners, consisting with a heated isothermal vertical plate and an adiabatic or cooled horizontal plate at ambient fluid temperature. Summarizing the results, they have proposed the correlation equations for the local and over-all heat transfer from the heated vertical plate. Baraji & Venkateshan [4], and Rao et al. [5] have also carried out the two-dimensional numerical analysis on the natural convections around the isothermal horizontal plate, where vertical fins were attached onto the surface. By comparing the analytical results with the experiments, they have discussed the heat transfer characteristics of the vertical fins.

Reviewing these studies, it is apparent that the main concerns of the previous workers have been paid to the heat transfer from the heated vertical plates, and the effects of heated, cooled or insulated horizontal plates on the heat transfer from the vertical surface have been discussed. On the other hand, very little is known with the effects of vertical plate on the flow and heat transfer from the upward-facing, heated horizontal plates. Taking this into account, the present authors [6] have carried out the intensive experimental investigations on the latter problem through the visualizations of flow and temperature fields and the measurements of the heat transfer coefficients from the heated horizontal plate. The visualization experiments revealed that the vertical plate obstructs the inflow of ambient fluid from the top of the vertical plate, while that the flow entering from the open edge of the horizontal plate reaches to the vertical plate and covers the whole horizontal surface when the vertical plate is high enough. The heat-transfer-coefficients of the horizontal plate also showed marked dependency on the height of the vertical plate.

However, it should be noted that the flow and heat transfer characteristics around the L-shaped corners differ substantially from those around the present configuration. For the case of the L-shaped corner, the vertical plate will only block the inflow from the vertical plate. Thus, the flow entering from the open edge will cover the whole horizontal surface in stead. On the other hand, for the present case, the vertical plates will obstruct the flows from the both edges of the horizontal plate. Therefore, the flow fields over horizontal plate will differ substantially in between the above two cases. The above change in the flow fields will also cause marked variations in the heat transfer from the horizontal plate. Taking account of this, we have conducted the present investigations.

In order to obtain comprehensive information on the natural convective flows over upward-facing plate attached with two vertical plates, we have began with the visualization experiments on the flow and the surface temperatures of the heated, horizontal plate using fine-particles and a liquid-crystal thermometry, respectively. We have, then, carried out the measurements of local heat transfer coefficients from the heated plate. Comparing the results with and without vertical plates, the influences of the vertical plates on the natural convective flows induced over
heated horizontal plate and also on the heat transfer from the horizontal plate have been discussed.

2. Experimental Apparatus and Measurements

A schematic of the present experimental apparatus is illustrated in Fig.2. The horizontal plate consisted with a base plate of acrylic resin 10mm thick and ribbon heaters of stainless steel 30µm thick. The heaters were glued on the surface of the base plate and were heated with constant heat flux by supplying ac power through them. The width of the horizontal test plate \( W \) ranged as; \( W=10, 20, 30, 50 \) and 100mm, while its span was kept constant as 500mm. To inhibit a flow from the sides of the horizontal plate and also to make the flow configuration simpler, side plates high enough were installed at the both sides of the horizontal test plate. Meanwhile, vertical plates of arbitral heights \( H \) were attached to the both edges of the test plate. The height of the vertical plate \( H \) was varied to attain ratios of height to width \((H/W)\) as; \((H/W)=0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1.0 \) and 2.0. The test plate was placed onto a stage and the whole apparatus was submerged horizontally onto a bottom of a large water tank of 1m × 1m cross-sectional area and 1m-deep. The screws adjust the level of the apparatus.

The test fluid was water at room temperature. For the sake of the heat transfer measurements of the horizontal plate, Chromel-Alumel thermocouples of 100µm diameter were spot welded on the back of the stainless ribbon heaters and along the centerline of the plate. These thermocouples measure the local surface temperatures, \( T_{wx} \). The temperature of the ambient fluid, \( T_{∞} \), was monitored with the thermocouples placed just outside of the top of the vertical plate, where ambient fluid flows into the horizontal plate. From preliminary measurements, a conduction heat loss from the heaters to the back of the horizontal plate estimated as less than 3% of the total heat generation of the heaters. The loss was considered negligibly small, so that the surface heat flux of the horizontal plate, \( q_w \), was calculated as \( q_w = Q/A \), where \( Q \) and \( A \) stand for the electrical power input to the heaters and the total surface area of the heaters respectively. Then, by using the heat flux and the temperature difference between the surface and ambient fluid temperatures, \((T_{wx} - T_{∞})\), the local heat transfer coefficients, \( h_x \), were defined as:

\[
h_x = q_w / (T_{wx} - T_{∞})
\]

Meanwhile, for the visualizations of the flow and temperature in the later, suspensions of fine polystyrene particles of 50 µm diameter and a liquid-crystal sheet were used, respectively. The sheet was glued onto the surface of the heaters.

3. Results and Discussions

3.1 Visualization of flow over horizontal plate
In order to obtain comprehensive information on the flow over horizontal plate with the vertical plates, we began with the flow visualization using fine-particles as a tracer. Figure 3 shows representative results for the flow over horizontal plate of \( W=20\)mm wide. These photos were taken from the side with the exposure time of 8 seconds. A light-sheet...
illuminates the movement of the particles in the plane parallel to the main flow direction.

The result without vertical plate depicts the following flow occurs over the horizontal plate. Firstly, the ambient fluids enter from the both sides of the plate, and then, they merge at the center of the plate, and finally ascend away from the plate as are shown in Fig. 2(a). A similar flow field as above is obvious for the lowest vertical plates of \(H/W=0.1\). Meanwhile, when the ratio of the vertical plate \(H/W\) exceeds 0.2, the flows entering from the both sides begin to re-circulate behind the vertical plates, and a pair of counter-rotating vortices appears over the horizontal plate. These vortices appear consistently throughout the cases of higher vertical plate and their scales are almost equal to the height of the vertical plate as shown in the figures 3(d) to 3(h).

The flow visualizations were also carried out for various widths of the horizontal plate \(W\), while keeping the ratio of \((H/W)\) constant. Figure 4 shows the typical results for \((H/W)=0.5\). Similar vortices as above are obvious over the horizontal plate. However, they gradually lose regularity, and instead, small and irregular vortices begin to appear near the corner of the vertical and horizontal plate with the increase in the width of the horizontal plate.

### 3.2 Visualization of surface temperatures

We subsequently carried out visualization of the surface temperatures using liquid crystal thermometry. The aim of the experiments is to obtain basic insight into the effect of vertical plates on the heat transfer of the horizontal plate.

Figure 5 represents typical results of the surface temperatures for the horizontal plate of 20mm wide, where the height of the vertical plates was varied from 0 (without vertical plate) to \((H/W)=1.0\). These photos were taken from the directly above the horizontal plate. Here, some explanations will be necessary to interpret.

![Fig. 3: Visualized flow fields over horizontal plate (W=20mm, \(q_w=2500\text{W/m}^2\))](image)

![Fig. 4: Visualized flow fields (H/W=0.5, \(q_w=2500\text{W/m}^2\))](image)

![Fig. 5: Visualized surface temperatures of horizontal plate (W=20mm, \(q_w=3,500\text{W/m}^2\))]
the results in Fig. 5. The liquid crystal sheet utilized here changes colors from dark red, green to blue with increasing temperature. We also note that the temperature patterns, at the same time, represent the distributions of the local heat transfer coefficients, because the present test plate was heated with a constant heat flux. Thus, the regions of dark-red and blue represent high and low heat-transfer regions, respectively.

We first mention the results on the horizontal plate without vertical plates. As is apparent from Fig. 5(a), the temperature pattern shows symmetry with respect to the vertical centerline, and also uniform in the span-wise direction of the plate. The temperatures are lowest in the vicinity of the edges, and highest at the center. The lowest temperature is due to the inflow of low-temperature ambient fluids, and gradual increase in the temperature is attributed to the development of thermal boundary layer over the plate as was demonstrated by the flow visualization in Fig. 3(a).

Meanwhile, when low vertical plates of \((H/W)=0.1\) were attached to the horizontal plate, small, spot-like patterns appear near the both edges. The patterns lined in double for \((H/W)=0.1\) change to single at \((H/W)=0.2\), and the spots gradually enlarge with further increase in \((H/W)\). We have observed that these spots change their shapes irregularly with time. Moreover, the flow visualization experiments confirmed that these spots are caused by the impingement of the low-temperature ambient fluids coming from the both sides.

The visualizations of the surface temperatures were also carried out for various widths of the horizontal plate \(W\), while keeping the ratio of \((H/W)\) constant. Figure 6 shows the results for \((H/W)=0.5\). The large low-temperature spots are apparent throughout the cases. The spots shown in Fig. 6(a) have comparative sizes of the width \(W\) of the horizontal plate and they line with almost equal pitch in the span-wise direction. Meanwhile, they gradually loose regularity and become fully disordered with the increase of the plate width \(W\).

![Fig. 6 Visualized surface temperatures of horizontal plate \((H/W)=0.5, q_w=3,500\text{W/m}^2\) (a) \(W=10\text{mm}\), (b) \(W=20\text{mm}\), (c) \(W=30\text{mm}\), (d) \(W=50\text{mm}\), (e) \(W=100\text{mm}\).]

### 3.3 Local heat-transfer-coefficients of horizontal plate

In light of the above visualizations, we next carried out quantitative measurements of the local heat transfer coefficients using thermocouples. The results are shown in Fig. 7 for the horizontal plate of \(W=20\text{mm}\) and \(q_w=2,500\text{W/m}^2\). The local heat transfer coefficients \(h_x\) are plotted in terms of the stream-wise distance \(x\) from the edge to the center of the plate. From the preliminary measurements, we have confirmed that the distributions of these local-coefficients become symmetry with respect to the centerline of the plate, so that the coefficients from the left half of the horizontal plates are represented in the figure. As is obvious from Fig. 7(a), the coefficients without vertical plates show highest value at the plate edge, and then, decrease monotonously with the distance \(x\). Meanwhile, the coefficients in the vicinity of the plate edge are decreased significantly by attaching the vertical plates. Such deteriorated heat transfer is attributed to the stagnation of flow behind the vertical plates. On the other hand, the coefficients in the central region of the horizontal plate are increased with the vertical plates. They show maxima at around \((H/W)=0.5\), and then, turn to decrease with further increase in \((H/W)\). The gradual increase in the
coefficients from \((H/W)=0.1\) to 0.5 is considered as the result of the direct impingement of low-temperature ambient fluids mentioned in the previous section. While, the decrease in the coefficients for higher \((H/W)\) will be due to the stagnation of flow by the vertical plates.

3.4 Overall heat-transfer-coefficients of horizontal plate

Similar heat transfer measurements as above were also carried out with various heat fluxes of the horizontal plate. Based on these data, overall heat transfer coefficients of the horizontal plate were calculated. The result is presented in Fig. 8, where the overall coefficients \(h_m\) are plotted with the ratios \((H/W)\).

The figure depicts that the overall coefficients increase first with \((H/W)\) and reach maxima at \((H/W)=0.5\), and then, turn to decrease with further increase in \((H/W)\). Moreover, the above variations in the overall coefficients are consistent for all wall heat fluxes. The result implies that the installation of the vertical plates can enhance the heat transfer from the horizontal plate when the height of the vertical plates is selected properly. The result will provide useful information for the heat transfer enhancement.

Taking account of this, we have further conducted the heat transfer measurements by varying the width of the horizontal plate, \(W\), as well as the height of the vertical plates, \(H\), systematically from \(W=10\) to 100mm, and from \(H=1\) to 200mm. Based on the results, the overall heat transfer coefficients, \(h_m\), of the horizontal plates were calculated and then, they were compared to those without vertical plates, \(h_{m0}\). Figure 9 represents the rates of heat transfer enhancement thus obtained, where the ratios \(\eta = (h_m / h_{m0})\) are plotted in terms of the parameter \((H/W)\).

Despite the wide variations in the width of the horizontal plate from \(W=10\) to 100mm, the ratios \(\eta\) show maxima at around \((H/W)=0.5\) and some of them exceed unity as shown in Fig. 9. In particular, the highest value of \(\eta = 1.15\) is attained for the case of \(W=20\)mm and \((H/W)=0.5\). When we consider the status that there is no practical way to enhance the heat transfer from the horizontal plate by natural convection except for the finned surfaces, the present result is considered worthwhile noting.
Concluding Remarks

The flow and heat transfer characteristics of the natural convection induced over horizontal heated plate were investigated experimentally. The influences of adiabatic vertical plates attached to the both ends of the horizontal plate were the main concerns of the present study. In order to obtain a basic insight into the flow and heat transfer for the present configurations, the flows over the horizontal plate and the surface temperatures of the heated horizontal plate were visualized by using the suspended fine-particles and the liquid crystal thermometry. The measurements of the local heat transfer coefficients from the horizontal plate were also carried out with thermocouples. The experiments covered the ranges of the horizontal heated plates of $W=10$ to $100\text{mm}$ wide, and of the vertical plates of $H=1$ to $200\text{mm}$ high. The test fluid was water at room temperature.

The following results were obtained from the present experiments.

1. The visualization experiments showed that the following flows occur over the horizontal plate when the parameter $(H/W)$ is larger than 0.2. Firstly, ambient fluids entering from the top edge of the vertical plates impinge directly onto the center of the horizontal plate. Then, the flows turn to the vertical plates, and, finally, ascend away from the vertical plates. As the result of the above fluid motion, a pair of large-scale vortices appears over the horizontal plate. Although these vortices are consistent over the horizontal plates, they gradually lose regularity with increasing the width of the horizontal plates.

2. The heat transfer experiments revealed that the local heat transfer coefficients of the horizontal plates show maxima at the center of the horizontal plates when $(H/W)$ is larger than 0.2. The result is attributed to the impingement of the low-temperature ambient fluids from the vertical plates.

3. Based on the above local coefficients, the average heat transfer coefficients of the horizontal plates were calculated. The result depicted that the average coefficients increase first with $(H/W)$, then show maxima at around $(H/W)=0.5$, and turn to decrease for further increase in $(H/W)$.

4. The above average coefficients were compared with those without vertical plates. The result showed that the coefficients are increased by the attached vertical plates, and, in particular, 15% higher coefficient was achieved when the vertical plates of $H=10\text{mm}$ were attached to the both edges of the horizontal plate of $W=20\text{mm}$. The result suggested that the optimum sizes of the horizontal and vertical plates exist for the heat transfer enhancement.

References