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Interferometric Study on Natural Convection around an Isothermal Square Cylinder Having an Attached or Separated Plume

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광학간섭계를 이용한 附着 혹은 剝離된 熱上昇流를 갖는 등온수평정방형 실린더 주위의 自然對流에 관한 研究

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抄 錄

가열된 곡면에 의한 自然對流에서는 流動의 剝離現象이 존재하지 않음이 알려져 있다. 이에 반해 날카로운 모서리를 갖는 가열된 정방형 수평실린더에 의한 자연대류에서는 그라소프 數가 4.66×10^4 전후로 附着 혹은 剝離流動이 윗쪽 양 모서리 부근에서 일어남을 광학간섭계(Mach Zehnder Interferometer)를 이용하여 온도장을 가시화하고 이를 이용하여 좌우 대칭선상에서의 속도분포를 간단한 대수적인 방법으로 구하여 수평정방형 윗쪽 수평면 위에 유동의 박리현상을 시사하는 "쌍동이 소용돌이"의 존재를 입증하였고, 이에 의해 온도역전현상과 평균 열전달량의 급격한 증가를 설명할 수 있다.

Nomenclature

Gr_L : Grashof number, $g\beta\ (T_s - T_a)\ L^3/\nu^2$

K : Thermal conductivity

L : Characteristic length(=side length of the square)

$\bar{N}u_L$: Overall Nusselt number, $\bar{h}L/k$

Pr : Prandtl number, ν/α

Re_D : Reynolds number based on the diameter

T_a : Ambient temperature

T_s : Surface temperature

U : Characteristic velocity, L/α

V : Dimensionless velocities in y directions

X, Y : Cartesian coordinates

x, y : Dimensionless X and Y

α : Diffusion coefficient

β : Volumetric expansion coefficient

ϕ : Dimensionless temperature, $(T - T_a)/(T_s - T_a)$

ν : Kinematic viscosity

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1. Introduction

The problem of natural convection is one of the oldest science in heat transfer, and in the environment surrounding us, we are continually faced with heat transport in fluid, which is driven to motion simply by differences in the fluid density within the gravitational field.

In the natural convective heat transfer induced by a heated body, a very important factor is whether the flow is attached or separated from the body, because the heat loss from the body is completely dependent on the temperature gradient in the vicinity of the walls, which the temperature distribution is again strongly coupled with the flow field.

In order to study natural convection about a body, with or without the separated flow region in question, a two dimensional isothermal horizontal cylinder with square cross section provides an excellent example.

The present work discusses the temperature distribution experimentally observed in the natural convection caused by a heated horizontal square cylinder, with two horizontal and two vertical surfaces, placed in a quiescent infinite fluid medium. For this particular configuration, the overall thermal behavior can be considered to be the result of thermo-fluid interaction of the four heated side walls of the cylinder of finite size.

With respect to this particular geometry, the isothermal temperature distribution was visualized by Mach-Zehnder interferometer at $Gr_L=$ 57200 only, with the Grashof number based on the length of the square side walls, by Eckert and Soehngen(1) On the other hand, in order to demonstrate the existence of a laminar boundary layer above a horizontal semi-infinite plate, interferometry was carried out at moderate Grashof number by Rottem and Classen(2) by using a semi-focusing color Schlieren photograph. The layer broke down into a large eddy instability at some distance from the leading edge. Goldstein and Lau(3) studied the laminar natural convection about a horizontal plate by finite difference analysis, for Rayleigh numbers from 10 to 10^4. The stuides (2) and (3) suggest that the flow might not separated at the leading edge. Laminar and turbulent natural convection from smooth circular cylinders was reviewed in detail by Morgan(4). Kuehn and Goldstein(5) investigated the laminar natural convection heat transfer from a horizontal isothermal circular cylinder, by solving the Navier-Stokes and energy equations using an elliptic numerical procedure. Pera and Gebhart(6) suggested that the usual expression "flow separation" was not an appropriate term for the natural convection due to a heated curved surface. Chang, Won and Cho(7) investigated numerically and experimentally that, for the natural convection around a square cylinder placed concentrically in a horizontal circular cylinder, the flow around the inner square cylinder was truly attached for relatively low Rayleigh numbers.

In the present work, the isothermal temperature distribution was measured in the ambient air by using the Mach-Zehnder interferometer, for the aforementioned horizontal square cylinder. The vertical velocity component above the upper horizontal surface of the body is calculated, along the line of symmetry, by using an analytic expression reduced from the energy conservation equation, which in turn requires information about the temperature gradients only. In addition, correlation between the Grashof number Gr_L and the overall Nusselt number $\bar{Nu}_L$ was obtained from the experimental data. All these available data are then consistently mobilized to support the possibility of separated flow in the natural convection about the configuration under question.

2. Experiments

A test cell in Fig. 2. was built for use in a 20cm Mach-Zehnder interferometer in Fig. 1 designed to operate at atmospheric pressure. Interferograms in infinite fringe mode were

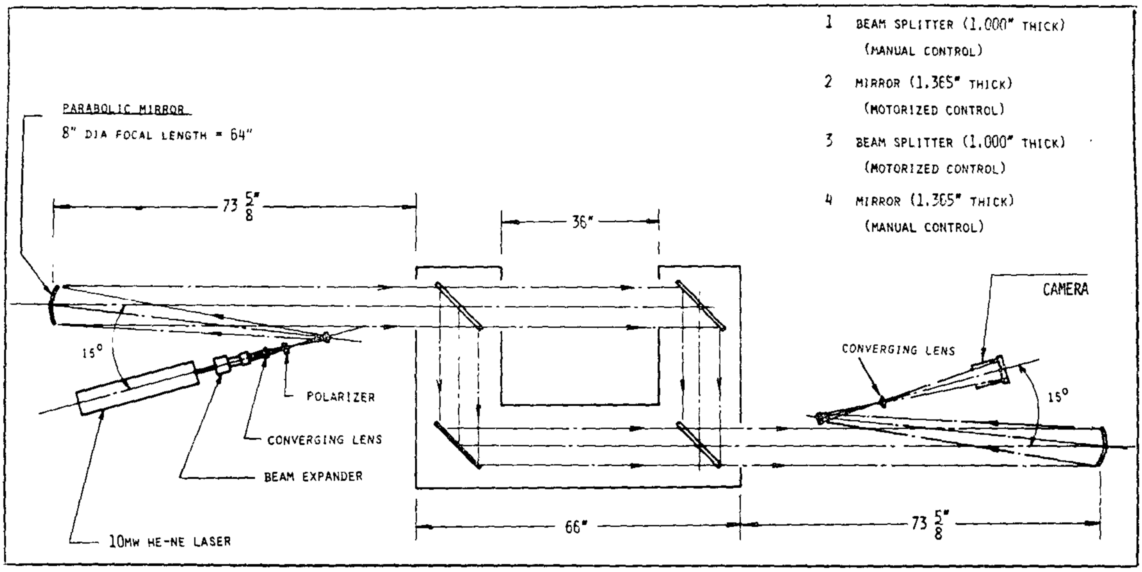


Fig. 1 Mach-Zehnder interferometer

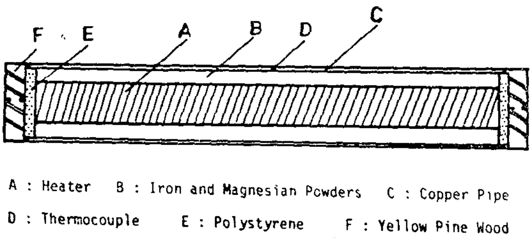


Fig. 2 Test cell

taken as the isothermal temperature distribution around the horizontal square cylinder. The assembled apparatus in the chamber (100cm× 100cm×26cm) was sufficiently free of external air disturbances.

For the experiments to be carried out in the moderate temperature ranges in air, two test models of different size were manufactured from welded copper square pipes by machining their surfaces. One square cylinder had the dimension $3.90\times3.90\times25.02cm^3$ with 0.31cm wall thickness, and the other had $2.43\times2.43\times30.1cm^3$. The cylinder was heated by passing direct current to a 20 ohm electrical resistance embedded internally with some conductive stuffing. Total ten thermocouples, with four placed in the plane of middle half with 90° spacing, one at the surface near each end and two at the center of the outside and the inside surface of each of the two end insulators, were embeded within the depth 0.1mm of the outer surface of the square cylinder. All thermocouples and heater wire were passed through two stainless-steel thin pipes with an outside diameter of 0.50cm which are used as a model support. The end insulators are made of polystyrene square disks and are kept to prevent any three dimensional effect near the end. The temperature uniformity was monitored throughout the experiment by a microcomputer receiving analog signals from the thermocouples mentioned above. To make the temperature on the surface of the square cylinder uniform, selection of the stuffing substances for the space between the copper pipe and the Nichrom resistance wire was important. It was not so difficult to control longitudinal temperature variation to a permissible level. Temperature uniformity in the azimuthal direction, whose uncontrollabillity was caused by the different heat fluxes on the side walls, was attained by selecting the stuffing substance to have variable conductivity in the azimuthal directions. In this work, iron and magnesian powders were used with different mixture ratio depending on the azimuthal directions. The proper mixing ratio was determined by trial and error. The individual thermocouples were calibrated to be read to within 0.05°C. The maximum wall temperature difference in the azimuthal direction was found to be 0.5% and that of the longitudinal direction 0.4%.

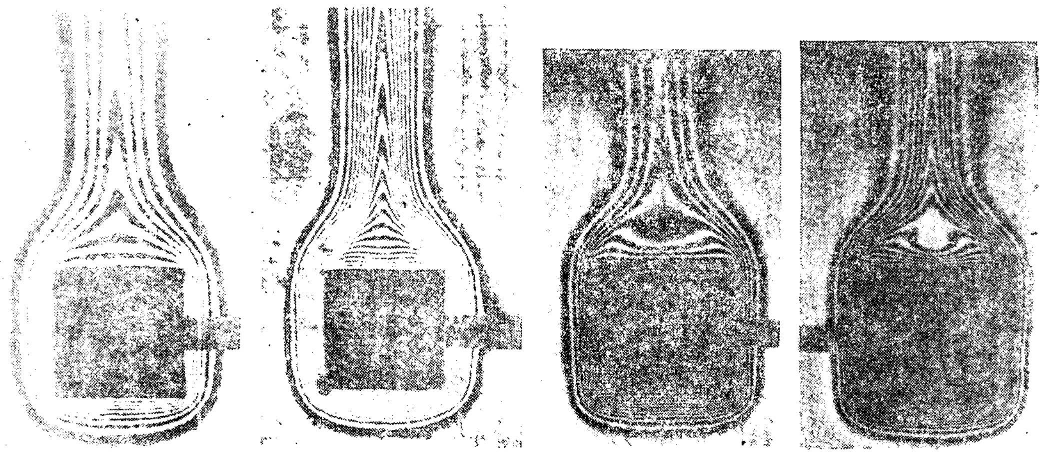
To establish ideal test conditions within the finite-sized test cell, where the thermal stratifications may cause adverse effect on the convection, some special measurement procedures were required. Because each increase of fringe numbers indicated a 3°C temperature variation in the 25cm optical path, a slight thermal stratification would disturb the pattern of the fringes noticeably. The thermal stratification was increased proportionally with increase of the temperature difference between the body and the ambient air, and with the duration of time before a steady state is reached. In running the experiment, the maximum thermal stratification was found to be 0.03°C per centimeter in the direction of gravity. This problem could be practically overcome mostly by reduction of the temperature differences and the preparation time required for attainment of steady state; the latter, in turn, required a large initial heating rate for the testing model cylinders. By using this procedure the maximum thermal stratification was reduced to 0.007°C per centimeter at best condition. The chamber was slightly insulated to reduce the adverse convective circulations but outdoor temperature variations caused a daily room temperature variation of 5-10°C. Thus, in order to achieve minimum temperature variation necessary for good infinite fringe field and to reduce the adverse convection, it was very necessary to reduce the running time. Consequently, the running time was shortened to about 2-3 hours.

In order to make the test cell air-tight so that no external air could not enter to disturb the designed flow, and to reduce any possible three dimensional effect, two circular optical windows (14cm diameter and 2.4cm thickness) made of BK-7 were installed in the side walls of the chamber where laser beam passes. The first square cylinder model was used for the relatively smaller Grashof number and the second for the larger number. All runs were carried out with moderate temperature difference in air in order to reduce minimally thermal radiation effect.

3. Results and Discussion

The isotherms around the horizontal square cylinder are shown sequentially in Fig. 3 as the Grashof number based on the hydraulic diameter or the width of the square cylinder is increased. The property values of the air are inserted into the Grashof and Prandtl numbers at the surface temperature on the cylinder.

In Fig. 3 (a), the isotherms around the horizontal square cylinder at $Gr_L=1.95\times10^4$ are globally similar to those around a horizontal circular cylinder found, for example, in the reference (5), the sharp corners where the conduction heat transfer has more dominant role than in other regions. In natural convection, it is common to find isotherms concave in the direction of the flow, or the phenomenon of temperature inversion, when there are two or more strong counter streaming in a confined area. Because the convective flow in the area above the upper surface may be tempted to explain that the dominant cause of the present shape of isotherms in due to conduction. Despite the fact that temperature inversion does not exist over the upper horizontal surface of square



(a) (b) (c) (d)

(a) $Gr_L=2.77\times10^4$, $Pr=0.704$ (b) $Gr_L=5.12\times10^4$, $Pr=0.696$
(c) $Gr_L=1.45\times10^5$, $Pr=0.706$ (d) $Gr_L=2.19\times10^5$, $Pr=0.700$

Fig. 3 Isotherms around a horizontal square cylinder

cylinders in Fig. 3 (a), the possibility of separated flow can not be excluded due to the downward concavity of isotherms. In order to determine the velocity profile, the flow pattern must be directly visualized or measured. However, because the induced flow is very weak, this proved to be an extremely difficult task for air. As a separate means, if the conductive temperature distribution is known, the flow pattern may by qualitatively predicted by comparing the two temperature distributions due to conduction and convection. However, for the particular configuration used in this work, even this is impossible since the steady state solution for pure conduction does not exist. We have devised, therefore, as a sure means of quick-checking of the flow quality, an analytic expression for the vertical velocity along the symmetry line, applicable to any general symmetric flow configuration if the convective temperature distribution is known. After some manipulation, the energy equation can be written demensionlessly as

$$V=\frac{\partial^2\phi/\partial x^2+\partial^2\phi/\partial y^2}{\partial\phi/\partial y} \quad (1)$$

The terms in the right-hand-side can be easily evaluated using the temperature distribution determined from the interferograms. The vertical velocity distribution along the upper symmetric line for the square cylinders is shown in Fig. 4. For $Gr_L=2.77\times10^4$, curve A, the value of the vertical velocity increases continously from

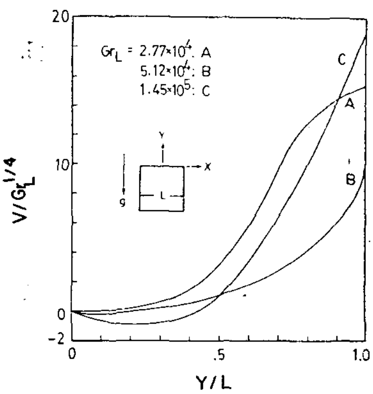


Fig. 4 Vertical velocity profiles along the upper symmetic lines

zero, which means that reversed flow does not exist over the upper horizontal surface i.e. the flow is all attached.

In Fig. 3(b), it is observed that the isothermal lines are slightly pulled toward the wall over the center on the upper horizontal surface at $Gr_L=5.12\times10^4$. In Fig. 3(c)-(d), the Grashof numbers are larger and the central deppression of the isotherms is more apparent. These phenomenon may be interpreted due to the fact of a downwash of the convection stream near the symmetric line over the upper horizontal surface. This argument is supported by the vertical velocity profile along the central line of symmetry plotted as curves B and C in Fig. 4. The recirculating regions apparently grow larger as the Grashof number is increased. Consequently, it is evident that the deppression of isotherms in this region may be interpreted in terms of the "twin vortices", which means that the flow induced by the horizontal square cylinder is separated.

In fluid mechanics, it has been commonly observed that flow separates at an edge. But from Ref. (2-3), it was shown that in natural convection the flow may not separate at an edge. Hence, it could not be assured whether the flow will separate at the upper sharp corners in the horizontal square cylinder.

The correlation between $\overline{Nu_L}$ and Gr_L was reported in (1)

$$\overline{Nu_L}=0.327Gr_L^{1/4} \tag{2}$$

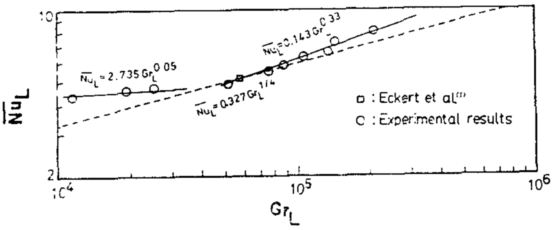


Fig. 5 Correlations between overall Nusselt numbers and Grashof numbers

which was determined by averaging the local Nu_L taken from the interferogram at $Gr_L=5.72\times10^4$ and assuming the power index to be 1/4. (dotted line in Fig. 5).

In Fig. 5, the slope of the present correlation abruptly increases at about $Gr_L=4.66\times10^4$ which can be determined by extrapolation of the two regression lines, respectively. Near the critical number, the depression of isotherms weakly occurs over the upepr horizontal surface. The correlation should now be duely devided into two parts:

$$\overline{Nu_L}=2.735Gr_L^{0.05}\quad (Gr_L<4.66\times10^4) \tag{3}$$

$$\overline{Nu_L}=0.143Gr_L^{0.33}\quad (Gr_L>4.66\times10^4) \tag{4}$$

The deviation between the experimental data and the least square regression is less than 2% in the present correlation. The maximum relative error of $\overline{Nu_L}$ between the values taken from the interferograms to average the local Nu_L and those evaluated directly the input power from consumed during the experiment was 8%. In the region of $Gr_L>4.66\times10^4$ where the isotherm depression exist, it is interesting to note that the power index is about 1/3 which is usually the power index corresponding to a finite horizontal flat plate.

4. Conclusion

Pera and Gebhart[6] suggested that the usual expression "flow separation" was not an appropriate term for natural convection induced by a curved surface. In this work, it is shown that this argument should be extended to include the possible flow separation which may develop about a body with sharp edges at high Grashof numbers.

In fluid mechanics, it is commonly observed that the flow does not separate at very low Reynolds number ($Re_D<5$), and as Re_D is increased a pair of fixed vortices is formed immediately behind a circular cylinder (5 to 15< Re_D<40). Similarly, for natural convection induced by the horizontal square cylinder, the flow does not separate at low Grashof number (Gr_L<4.66×10^4) but twin vortices are formed immediately over the upper horizontal surface for about Gr_L>4.66×10^4. Furthermore, it would not be difficult to envision that these vortices will alternate in unsteady motion, in an analogy with the shedded vortex in a forced convection, when the Grashof number is raised beyond the region of unsteady transitional oscillating flow.

As to the overall heat transfer, the slope of the correlation curve increases at the critical Grashof number Gr_L=4.66×10^4. This phenomenon could be explained only by the existence of a separated flow or by the flow pattern "twin vortices" over the upper horizontal surface, which is stigmatized by the deppression of the isotherms in this region.

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