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A STUDY ON THE FLOW CHARACTERISTICS BETWEEN TWO CIRCULAR CYLINDERS IN CROSS FLOW BY LDV AND HOLOGRAPHIC INTERFEROMETRY

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Experimental investigation of the fluid flow and thermal flow pattern around two circular cylinders in cross flow has been carried out. Reynolds number was varied in the range of $100 \leqq Re \leqq 1000$ and the distance between the two cylinders in the interval of $2 \leqq L/D \leqq 4$. Velocity and turbulence intensity distributions in the x-direction were obtained by LDV and the information about isothermal distribution in the whole x-y thermal flow field was obtained by double-exposure holographic interferometry. The influences of Reynolds number and the gap spacing between the two cylinders were investigated. The characteristic flow pattern was found to depend on the distance between the two cylinders. When $L \leqq 3D$, the wake region between the two cylinders became quasi-stationary.

Key Words: Velocity, Turbulence Intensity, Isothermal Lines, Laser Doppler Velocimeter(LDV), Double-Exposure Holographic Interferometry

NOMENCLATURE

D	: Diameter of circular cylinder
L	: Gap spacing between tandem cylinders
L/D	: Longitudinal pitch-cylinder diameter ratio
Re	: Reynolds number$(=U_\infty \cdot D/\nu)$
U	: X-directional local mean velocity
U_∞	: Free stream velocity
$\sqrt{\overline{u^2}}$	: rms value of fluctuating velocity of U
x,y	: Coordinates
θ	: Angular position from the front stagnation point
ν	: Kinematic viscosity of air
ρ	: Density of air

Subscripts

∞	: Free stream

1. INTRODUCTION

The understanding of the characteristics of the flow and heat transfer around circular cylinders is very important for engineering application. Many investigations on two circular cylinders arranged in tandem, which is a representative arrangement of tube banks, have been carried out for a long time. Many previous works were mainly concerned with the fluctuating forces and vortical flow fields. (Kôstic and Oka, 1972, Nishimura and Kawamura, 1981, Zdravkovich, 1977) Recently several investigations were carried out on the fluid flow behavior around a downstream cylinder in the wake of an upstream cylinder. (Aiba and Yamazaki, 1976, Hiwada et al, 1982)

The purpose of this study is to understand the characteristics of flow around two cylinders arranged in tandem when the Reynolds number is low$(Re \leqq 1000)$. In this experiment, the Reynolds number was varied in the range from 100 to 1000 and the gap spacing between the two cylinders was varied in the interval of $2 \leqq L/D \leqq 4$.

Velocity and turbulence intensity distributions in the x-direction were obtained by LDV (Drain, 1980, Durst, 1976) and the distribution of isothermal lines in the whole x-y thermal flow fields was obtained by a double-exposure holographic interferometry. (Charles, 1979, Hariharan, 1984, Yang, 1985) To help understand the flow properties, the three-dimensional graphics of velocity and turbulence intensity distributions are presented.

2. EXPERIMENTAL APPARATUS AND METHOD

Experiments were conducted in an open cycle wind tunnel as shown in Fig. 1. The test section was 0.7m long, 0.2m high and 0.2m wide. The longitudinal turbulence intensity of the free stream was no more than 0.8% in the experimental range of the present investigation. Cylinder models, 12.7mm in diameter and 200mm in length, were placed horizontally in a tandem arrangement as shown in Fig. 1.

A dual beam, one-component LDV system was used to obtain the velocity and its rms values. The arrangements of the LDV system are shown in Fig. 2. The flow was seeded with about 1.0μm light oil particles produced by a smoke generator. A computer-controlled two-dimensional transverse mechanism was used for the movement of the measuring position. The measuring point could be traversed in the two orthogonal directions by moving the channel itself while the LDV system reamained stationary.

A NEC PC-9801 personal computer was used for data collection, signal processing and graphics display. The configuration of the data acquisition and analyzing system is shown in Fig. 2. The bandpassed signals from a photomultiplier were

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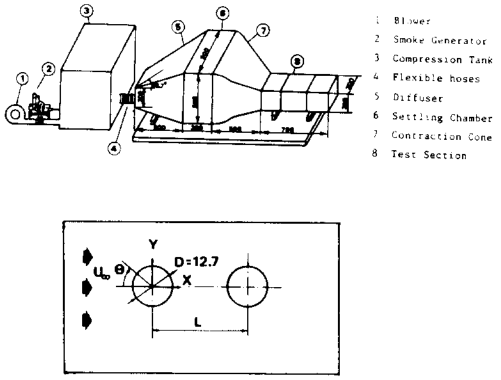

Fig. 1 The schematic diagram of a wind tunnel and its test section

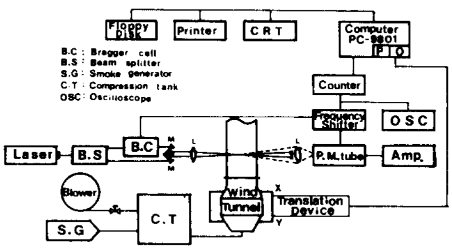

Fig. 2 The schematic diagram of the LDV system and data processing system

changed digitally by a counter and directly transfered to a personal computer, where the Doppler frequency was calculated. The sampling time at one measuring point was 1 minute and 100 sampled data were collected for each measuring point, which ensured the convergence of data. The mean velocity and turbulence intensity were calculated from a statistically sufficient number of sampled Doppler signals at each position and were displayed using three-dimensional graphics.

For visualization of the thermal flow field another heated cylinders were constructed. The electric heater, uniformly wound around backelite tube, was placed inside a thin walled brass tube. The constant heat flux on the cylinder surface was determined from the measured electric power of the heater.

The double-exposure holographic interferometry shown in Fig. 3 may be used to visualize the thermal flow field around two heated cylinders. In this arrangement, the beam from a 5mW He-Ne laser is split into two coherent beams by means of a beam splitter. One part of the laser beam (object beam) is directed to illuminate the test section while the other (reference beam) bypasses the test section and is sent directly toward a photographic plate. The two beams are combined on a glass plate film (KODAK 649F). The resulting hologram is a diffraction grating formed by the emulsion on the plate film. (Charles, 1979, Hariharan, 1984)

Two exposures of the photographic plate are made with a thermal load applied to the test section between the two exposures. If any changes in the coefficient of optical refraction of the medium in the test section are caused by the thermal load, an image of the thermal flow field is seen by a fringe pattern during the hologram reconstruction. Fig. 3 (b) shows the schematic diagram of the hologram reconstruction.

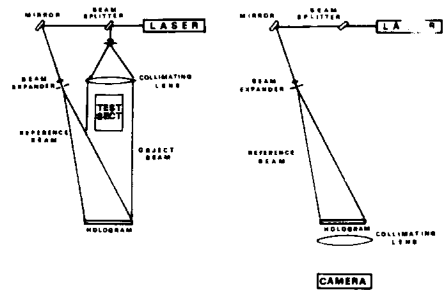

Fig. 3 The schematic diagram of the double-exposure holographic interferometry

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 shows the mean velocity profiles and turbulence intensity distributions for the four pitch ratios at $Re=1000$. Only the upper half of the distributions is shown since they exhibited symmetry with respect to the horizontal axis. The wake width from the upstream cylinder increases downstream and develops over the downstream cylinder. Also, the velocity gradient in the free shear layer perpendicular to the free stream decreases in the downstream direction as in the case of a free jet.

It has been demonstrated by Zdravkovich (1977) and Kostic (1972) that two kinds of different patterns exist at $L/D=3.5\sim3.8$. For $L/D\leqq3$, the velocities in the wake region between the two cylinders became nearly zero or very small. It means that the quasi-stationary wake region is formed between the two cylinders. For $D/N\geqq4$, the wake region between the two cylinders is no longer quasi-stationary and the downstream cylinder has little influence on the flow developing on the upstream one. In this case, it is conjectured that the pattern and mechanism of flow in the wake of the upstream cylinder is similar to those of a single cylinder.

Figure 5 presents the mean velocity profiles and turbulence intensity distributions according to the change of the Reynolds number. From Fig. 5 we see that the mean velocity profiles and turbulence intensity distributions in the quasi-stationary wake region between the two cylinders change little with increasing Reynolds number. But it can be seen that the turbulence intensity distributions over the downstream cylinder change remarkably at a Reynolds number larger than 450. The turbulence intensity distributions in Fig. 5 indicate that the maximum variation increases with an increasing Reynolds number for two pitch ratios.

The variations of local turbulence intensity (at radial positions of 2.0mm from the surface) with angular position θ in the downstream cylinder are shown in Fig. 6. It is seen that the turbulence intensity decreases for the region where $30^\circ\leq\theta\leq45^\circ$. However, the turbulence intensity retained by the shear layer from the upstream cylinder is strengthened by the presence of the downstream cylinder itself and reaches a maximum value at about 135°. This result suggests that the boundary layer on the surface of the downstream cylinder becomes more turbulent due to the effect of the wake of the upstream cylinder in spite of the fact that the Reynolds number is low. These results are effectively shown by the three-dimensional graphics of velocity and turbulence inten-

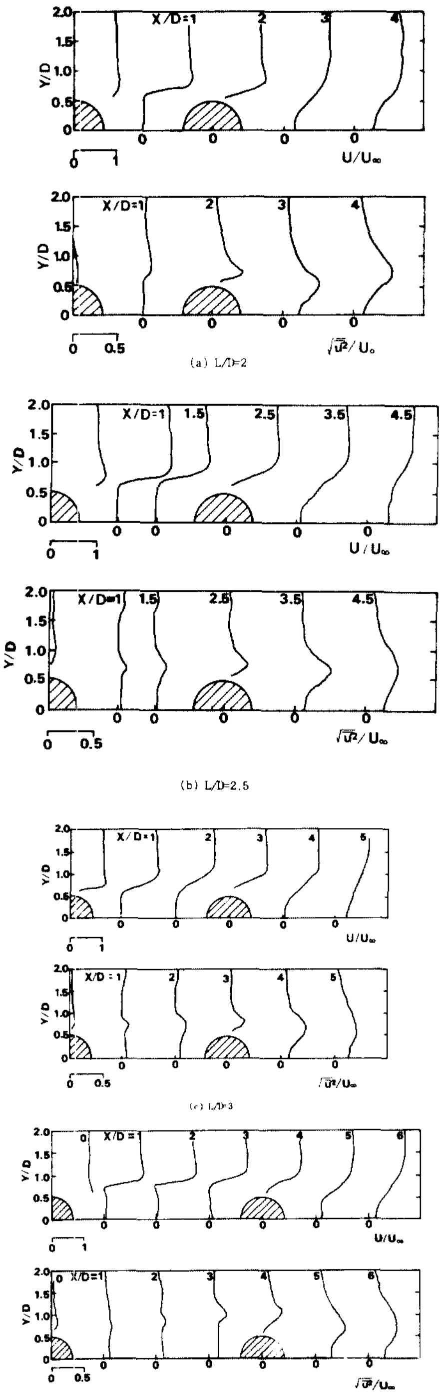

Fig. 4 Velocity and turbulence intensity profiles at $Re=1000$

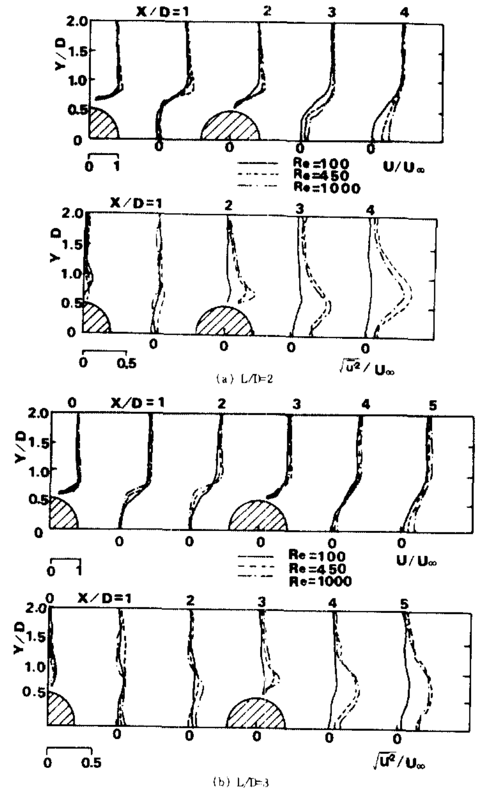

Fig. 5 Comparison of velocity and turbulence intensity profiles according to the change of Reynolds number

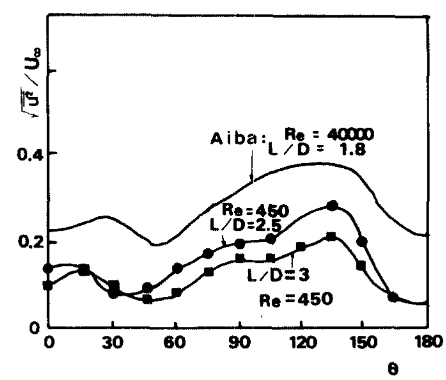

Fig. 6 Comparison of turbulence intensity with the angular position in the downstream cylinder

sity distributions in the whole x-y flow field.

Figures 7 and 8 present the three-dimensional graphics of x-directional velocity profiles and turbulence intensity distributions in the whole x-y flow field for the two pitch ratios at various Reynolds numbers. In Figs. 7 and 8, all the data were plotted using the digital output from the personal computer. These figures show that the local mean velocities are larger than the free stream velocity at about 90° from stagnation point of the upstream cylinder and become nearly zero or very small in the wake region between the two cylinders. It can be seen that the turbulence intensity over the upstream cylinder increases slightly while it increases rapidly over the downstream cylinder. We also see that the turbulence intensity reaches a maximum value at about 135° location.

The isotherms around two cylinders were obtained by using the double-exposure holographic interferometry sketched in Fig. 3. Figure. 9 presents the visualization of the thermal flow field around two cylinders in tandem for $L/D=2$ at $Re=100$, 450, 1000. The fringe patterns illustrate isothermal lines. The difference of temperature between the neighboring fringes can be calculated by the following equation: (Hauf and Grigull, 1970)

$$Tn(x,y)-T_\infty=\frac{N(x,y)\cdot\lambda}{(dn/dT)\cdot Lo} \tag{1}$$

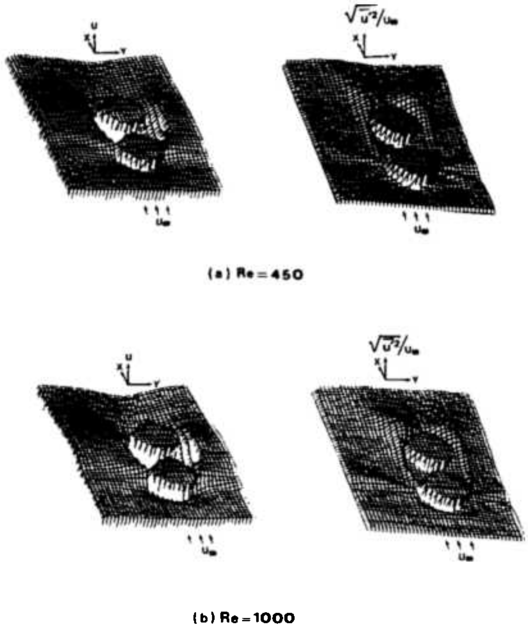

Fig. 7 Velocity and turbulence intensity profiles in the whole x-y flow field for $L/D=2.5$

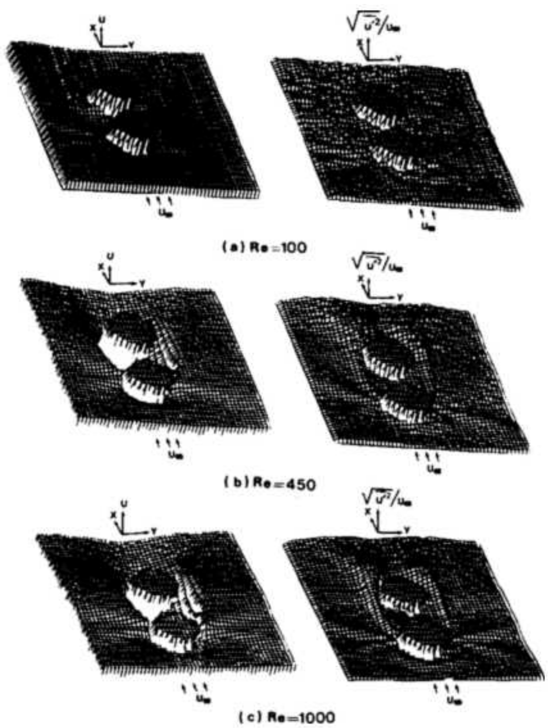

Fig. 8 Velocity and turbulence intensity profiles in the whole x-y flow field for $L/D=3$

where, $Tn(x,y)$: Temperature of N-th fringe
T_∞ : Temperature of the free stream
$N(x,y)$: Number of fringes
λ : Wavelength of laser beam
n : Refractive index of air
dn/dT : Change in refractive index with temperature
Lo : Length of phase object

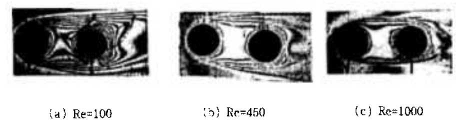

Fig. 9 Isothermal distribution according to the change of Reynolds number for $L/D=2$

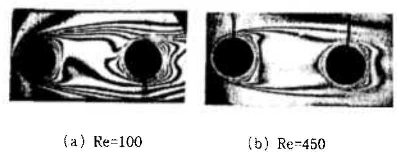

Fig. 10 Isothermal distribution according to the change of Reynolds number for $L/D=3$

In this experiment, the difference of temperature between the neighboring fringes is 4.26℃ according to the equation above. Thermal boundary layer and the wake generated by the upstream cylinder could be clearly observed from the interferogram. As the distance between the neighboring fringes becomes smaller, the gradient of temperature becomes larger. This means that the heat transfer takes place actively. Figure 9(a) shows that the thermal boundary layer becomes larger in the downstream of the first cylinder and the thermal flow remains nearly stationary. It is found that the thermal boundary over the upstream cylinder is reduced slightly and the number and distance between the neighboring frines are also reduced. Thus, we see that the heat transfer takes place more actively as the Reynolds number increases.

Figure 10 shows the variations of the thermal flow field for $L/D=3$ at $Re=100$, 450. The thermal boundary layer for $L/D=3$ over the downstream cylinder becomes thicker than that for $L/D=2$. A peculiar fringe fringe pattern suggestive of the boundary layer separation at about 120° position is also voted. Figures 9 and 10 clearly show that the fringe patterns are smoothly connected between the upstream and downstream cylinders, which indicates that the wake of the upstream cylinder directly interacts with the thermal boundary layer of the downstream cylinder.

4. CONCLUSIONS

The characteristics of the fluid and thermal flow around two circular cylinders arranged in tandem were experimentally investigated in the low Reynolds number region ($Re \leqq 1000$). The following conclusions were obtained.

(1) The fluid and thermal flow in the wake region between the two cylinders became quasi-stationary as the gap spacing between the two cylinders is equal to or smaller that $3D$. In this range, the effects of the Reynolds number on the flow was insignificant.

(1) As the gap spacing between the two cylinders increased for a given Reynolds number, the heat transfer in the wake region between the two cylinders became more active and the turbulence intensity beyond the downstream cylinder increased.

(3) The three-dimensional graphics of velocity and

turbulence intensity profiles were very useful in understanding the flow characteristics.

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