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# A METHOD OF SKIN FRICTION DETERMINATION OF A CIRCULAR CYLINDER IN A WATER FLOW FIELD

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Using a partially-heated cylinder with a thin heat transfer sensor, it is clarified that the skin friction coefficient of a cylinder in water can be calculated by the Brown's equation, when the profile of its pressure coefficient has been measured. It is also revealed that the separation angles of the boundary layer on the cylinder surface can be determined by the skin friction profiles. These results are ascertained to be reliable by a flow visualization method.
KEYWORDS Local heat transfer Pressure coefficient Skin friction Circular cylinder Water flow.

## INTRODUCTION

The transition of the boundary layer around a cylinder has been an important problem in fluid mechanics or chemical engineering and it has been examined in various ways. They include the measurement of mass transfer in electrolytes and the measurement of skin friction estimated by the local heat transfer rate in air (e.g. Son and Hanratty, 1969; Mizushina, 1971). In the latter case, the skin friction has sometimes been measured by a "film sensor technique" in air flow fields and the relations between the local heat transfer rate and the coefficient of skin friction have usually been examined (e.g. Bellhouse and Schultz, 1966; Brown, 1967; Achenbach, 1968; Achenbach, 1975; Yano, *et al.*, 1985). However, such measurements in liquid flow fields have never been carried out. In addition it might be impossible to determine the skin friction coefficient in a liquid flow fields by measuring the local heat transfer with a film sensor technique, because its heat capacity is very small. Moreover, the temperature evaluation of the film sensor is very difficult.

In this work, the coefficient of skin friction was tried to calculate by the equation proposed by Brown. For its calculation, both distributions of the local Nusselt number and the pressure coefficient should be measured at the same Reynolds number. Therefore, in this work, a thin heat transfer sensor was installed parallel to the cylinder axis and several thermocouples were embedded radially and the profile of the local heat transfer rate of this "partially-heated" circular cylinder was examined.

The local static pressure distributions around a cylinder, on the other hand, were determined by an unheated circular cylinder with a pressure transducer. Comparing the experimental results with the skin friction coefficient obtained from a boundary layer approximation, the reliability of the present method was ascertained. Moreover, the separation angles of the boundary layer around the cylinder were determined from the profile of its skin friction coefficient and the results were ascertained by a flow visualization technique with dye injection. Thus, the present method to measure the skin friction by a partially-heated cylinder was revealed effective and useful.

## EXPERIMENTAL APPARATUS AND METHOD

### *Circulating Flow System*

Block diagram of the circulating flow system (water tunnel) for this experiment is shown in Figure 1. The water tunnel consists of a water tank, a pump, circular piping and two rectangular pipes of a flow straightener section and a test section. The temperature of circulating water was controlled by a cooling system (a refrigerator system) and was checked by a copper-constantan thermocouple.

### *Cylinder Tested*

The diameter of all test cylinders used in this experiment was 20 mm. The cylinders with smooth surface were set vertically (normal to main flow direction). The test cylinders were attached to the conduit walls with a ball bearing and two O-rings, to prevent water leakage while being driven by a computer-controlled stepping motor.

The detailed dimensions of the cylinders are shown in Figure 2. The left one was used for measurement of surface pressure distribution. For pressure measurement, a pressure transducer of semiconductor type was screwed into the lower part of the test cylinder which was made of brass. This cylinder has a

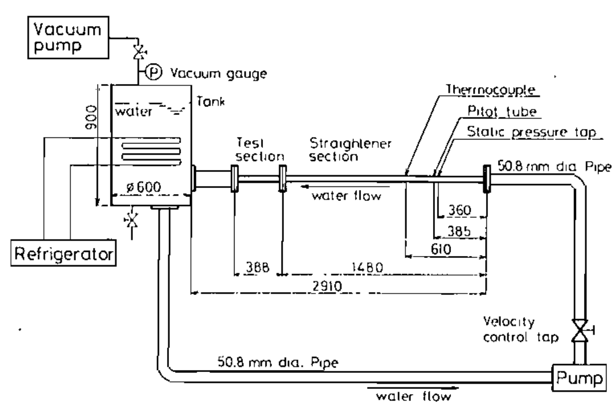


FIGURE 1 Block diagram of circulating system.

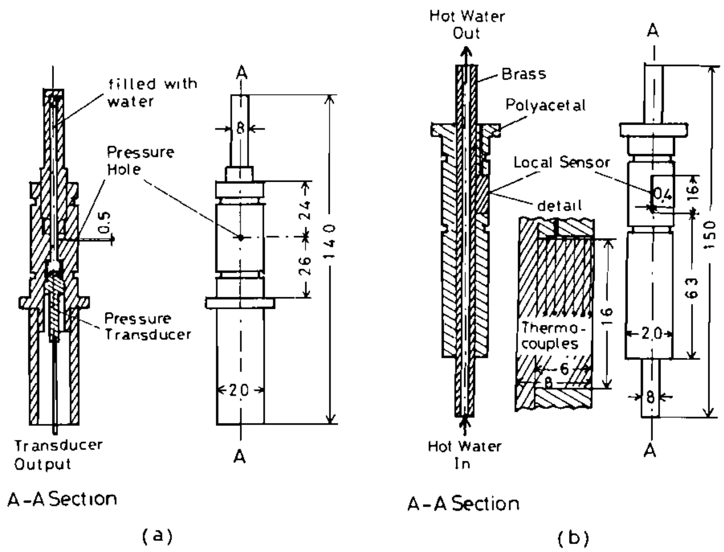


FIGURE 2 Details of cylinder tested, (a) for pressure measurement and (b) for heat transfer measurement.

pressure tap of 0.5 mm in diameter to measure the static pressure and the pressure fluctuation on the cylinder surface. The right one was used for measurement of local heat transfer profile. The test cylinder is referred to as a "partially-heated cylinder". For heat transfer measurement, a local heat transfer sensor was installed on the cylinder surface. In the experiment, the sensors of the two kinds of thickness (2 mm and 0.4 mm) were used. Hot water of 60°C was circulated through the cylinder from a constant-temperature water bath. The remaining part of the cylinder surface except the sensor was insulated by plastics. The length of the heat transfer sensor was made 20% shorter than the height of conduit to prohibit the affect of conduit wall.

### *Measurement of Flow Velocity*

The velocity profiles on the horizontal or vertical line in the center of the conduit cross-section were measured by a Pitot tube.

The velocity fluctuation rate of main flow in the conduit was measured by a hot-film sensor in the center of the conduit cross-section.

### *Measurement of Surface Pressure Distribution and Local Heat Transfer Profiles*

Block diagram of the measuring system of the hydraulic pressure on the test cylinder is shown in Figure 3(a). The cylinder was rotated every 5 degrees by a computer-controlled stepping motor. The output of the pressure transducer was amplified and processed by a micro-computer via $A/D$ converter at each angle.

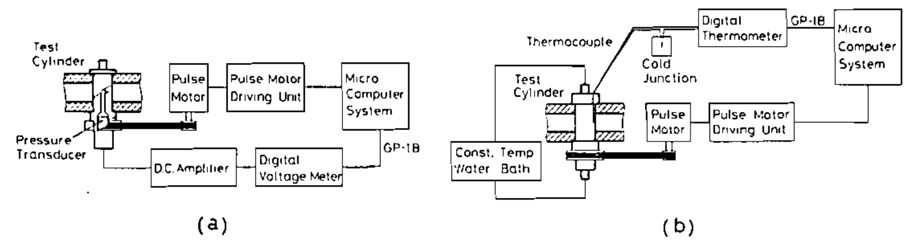


FIGURE 3 Block diagrams for pressure measurement (a) and for heat transfer measurement (b).

The sampling rate of pressure data was 1 kHz, and 128 data were sampled at each angle.

Block diagram of the measuring system of the local heat transfer is shown in Figure 3(b). For the local heat transfer measurement, a "totally-heated" cylinder (i.e. normally heated cylinder) or a partially-heated cylinder was rotated by a computer controlled stepping motor every 10 degrees, and the data of radial temperature gradient in the sensor were sampled 20 times at each angle. The local heat transfer rate was calculated from the radial temperature gradient, which was determined from the outputs of six thermocouples installed radially in the test cylinders. The thermocouples were connected to a digital multichannel thermometer and their outputs were processed by a computer via GP-IB bass system.

## EXPERIMENTAL RESULTS

### *Pressure Measurement*

The pressure coefficient and the drag and lift coefficients were calculated from the pressure distribution measured around the cylinder surface. In addition the Strouhal number was determined from the frequency spectrum of pressure fluctuation on the cylinder surface near the separation point.

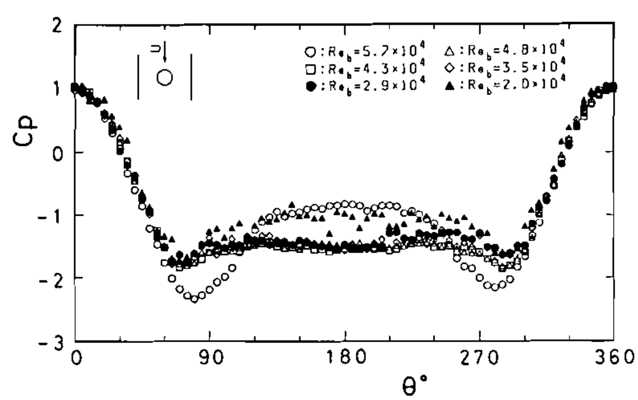


FIGURE 4 Pressure coefficient profiles of a center-set single cylinder.

Typical distributions of pressure coefficients of a cylinder set in the center of the conduit are shown in Figure 4 as a parameter of Reynolds number (Reb), which is based on the kinematic viscosity for the bulk temperature of water flow. In the figure the pressure coefficient profile is symmetrical.

### *Heat Transfer Measurement*

Figure 5 shows typical profiles of local Nusselt number around the test cylinder as a parameter of Reynolds number (Ref), which is based on the kinematic viscosity for the film temperature around the cylinder.

When a partially-heated cylinder was used as a test cylinder in the local heat transfer measurement, the cylinders was not isothermal and the surface was cooled to ambient temperature except near the heated sensor. In this case the thermal boundary layer around the cylinder surface does not develop from the front stagnation point of the cylinder and the profile of local Nusselt number around the cylinder becomes maximum at about $\theta = 50$ or 310 degrees in the relatively low Reynolds number region. In the relatively high Reynolds number region, the profile of local Nusselt number has its second peak at the side parts ($\theta = 110$–120 and 240–250 degrees) of the cylinder. Such a change in the profile of local Nusselt number is a typical phenomenon indicating the occurrence of the laminar to turbulent flow transition around the cylinder (e.g. Zukauskas, 1972).

### *Coefficient of Skin Friction*

An equation to calculate the coefficient of skin friction in a flow field with static pressure gradient was proposed by Brown as mentioned previously. In the present paper it is assumed that the Brown's equation is applicable to the flow field around a circular cylinder set in a water flow field.

The pressure coefficient of a cylinder was measured by a test cylinder with a

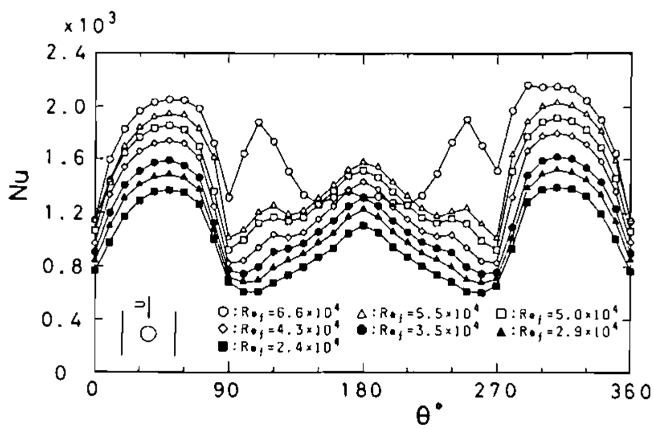


FIGURE 5 Profiles of local Nusselt number of a center-set partially-heated cylinder ($L/0.4$ mm).

pressure transducer and the local Nusselt number was measured by a partially-heated cylinder with a thin local heat transfer sensor, as described in the previous section. Their results have been used to calculate the distribution of the coefficient of skin friction around a cylinder in present water flow field. The equation used for the calculation is as follows;

$$To = \frac{19}{10} \cdot \frac{1}{L^2}\left(\frac{\mu^2}{\rho Pr} Nu^3 - \frac{\mu_{st}^2}{\rho_{st} Pr_{st}} Nu_{st}^3\right) - \frac{5}{18} \cdot L \cdot \frac{dP}{dX} \cdot \frac{1}{Nu} \tag{1}$$

Three typical distributions of the coefficient of skin friction around a cylinder and the distributions of the pressure coefficient and of the local Nusselt number are shown in Figure 6, as a parameter of Reynolds number (Reb). From the results, it is clear that the distribution of skin friction around a cylinder can be approximately simulated by the local Nusselt number distribution measured by the present partially-heated cylinder.

These results were compared with the ones obtained from an approximate theory of boundary layer around a circular cylinder. As present flow field around a cylinder was affected by the blockage effect in the conduit and Hiwada *et al.* (1976) proposed an empirical equation for the tangential flow velocity just outside of boundary layer of a circular cylinder under the blockage condition, the following equation was used;

$$\begin{aligned} \frac{U_\theta}{U} &= 3.58A_1\left(\frac{X}{d}\right) - 2.45A_2\left(\frac{X}{d}\right)^3 - 1.22A_3\left(\frac{X}{d}\right)^5 \\ A_1 &= 1.0 + 1.03(d/L)^2 \\ A_2 &= 1.0 - 0.58(d/L)^2 \\ A_3 &= 1.0 - 0.25(d/L)^2 \end{aligned} \tag{2}$$

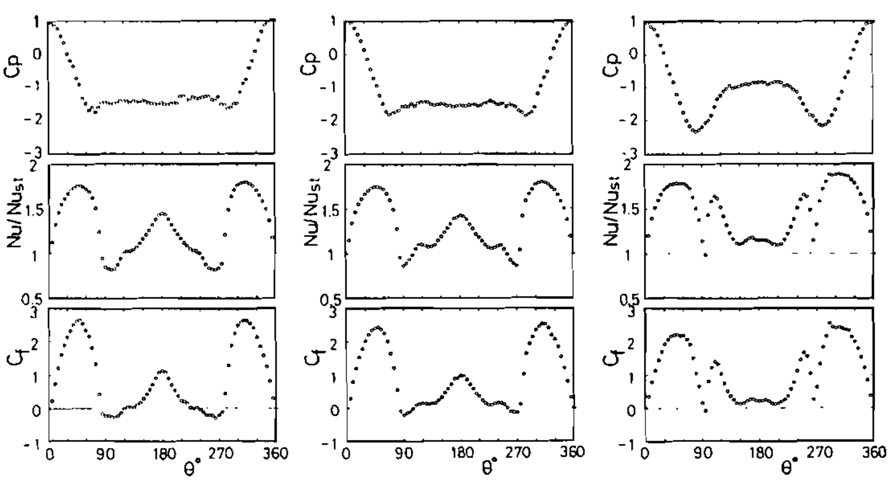


FIGURE 6 Profiles of pressure coefficient, local Nusselt number and skin friction coefficient of a single cylinder. (a) Reb = $2.9 \times 10^4$, (b) Reb = $4.3 \times 10^4$, (c) Reb = $5.7 \times 10^4$.

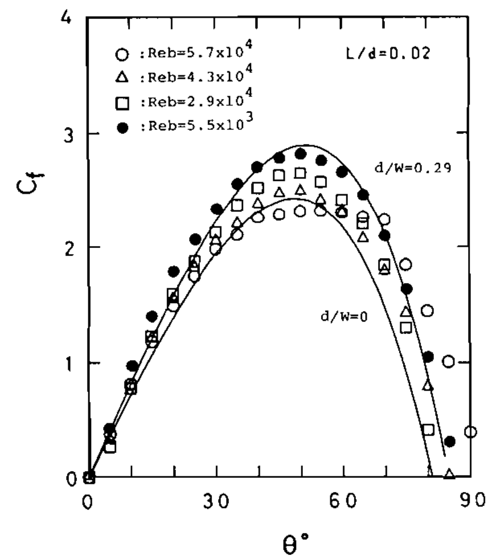


FIGURE 7 Skin friction coefficient at the front half of a cylinder.

In the region between 0 and 90 degrees, the skin friction coefficient was calculated by the equation of an approximate theory of boundary layer described above. The results are shown in Figure 7. The data obtained from the present experiment by the partially-heated cylinder ($L = 0.4$ mm) are added in the figure. One of the solid lines indicated in the figure shows the result without blockage effect ($d/W = 0$) and the other line does the result under the blockage effect condition ($d/W = 0.29$), which corresponds to the present experiment.

The results measured in the present experiment are approximately between the two calculation results. Therefore, we can say that the distribution of skin friction coefficient in a water flow field can be calculated from both distributions of the local Nusselt number measured by a partially-heated cylinder and of the pressure coefficient measured by a cylinder for pressure measurement.

### *Separation Angle*

In order to measure the separation angle around a cylinder in a conduit, another circular cylinder was manufactured for the flow visualization by a dye-injection technique. It had a small hole on its surface corresponding to the mid-horizontal plane in the conduit. Methylene blue solution in water was ejected through the hole into the water flow field around the cylinder and the separation angles were determined by the method proposed by Son and Hanratty. The results are shown in Figure 8 with filled circles.

As a method to determine the separation angle from the skin friction profile, the zero-crossing points or the minimum points were read on the distribution diagram of skin friction coefficient, and the angular coordinates of their points

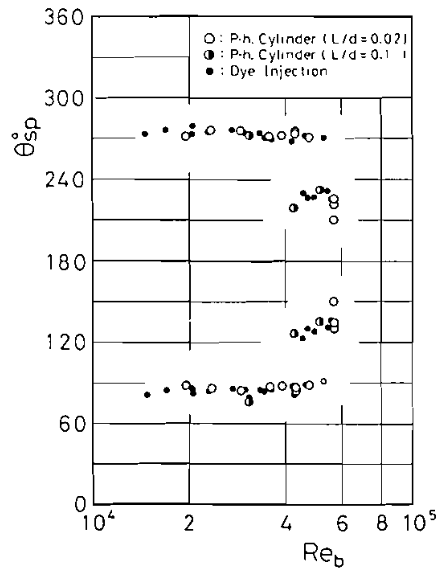


FIGURE 8 Comparison of the determined separation angles by a partially-heated cylinder with the measured ones by dye-injection.

were regarded as the angle corresponding to the separation of the boundary layer around the cylinder. Their values are indicated with open circles in Figure 8.

The separation angles determined by another partially-heated cylinder ($L = 2.0$ mm) are also indicated in Figure 8 with half-filled circles. These results have rather good agreement. Therefore, the separation angle of boundary layer around a cylinder can be determined by the distribution measurement of local Nusselt number of a partially-heated cylinder in a water flow field.

## CONCLUSIONS

In this study, firstly the flow characteristics of a single cylinder in a water flow field were examined by measuring the pressure distributions and the local heat transfer profiles around the test cylinder. Secondly, the coefficient of skin friction of a cylinder was calculated and the separation angles were determined. The main results obtained are summarized as follows;

(1) When both the local Nusselt number and the pressure coefficient of a cylinder were measured by a partially-heated cylinder and a cylinder with a pressure transducer, the coefficient of skin friction of the cylinder in a water flow field can be successfully calculated by means of Brown's equation.

(2) From the heat transfer characteristics measured by a partially-heated cylinder, the separation angle around a circular cylinder can be determined. The result was ascertained by a flow visualization technique of dye-injection.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

| | |
|---|---|
| $Cf$ | coefficient of skin friction |
| $d$ | diameter of cylinder |
| $L$ | thickness of local pressure sensor |
| $Nu$ | local Nusselt number |
| $P$ | pressure |
| $Pr$ | Prandtl number |
| $Reb$ | Reynolds number based on main flow temperature |
| $Ref$ | Reynolds number based on film temperature around cylinder |
| $To$ | skin friction |
| $U$ | flow velocity |
| $U_\theta$ | tangential velocity component at the outer boundary layer region around cylinder |
| $X$ | coordinate along the cylinder surface from front stagnation point |
| $\rho$ | density |
| $\nu$ | kinematic viscosity of water |
| $\theta$ | angular coordinate measured counter-clockwise from the direction of main flow |
| $\theta sp$ | separation angle |
| | Subscript |
| $st$ | values at front stagnation point |

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