Technical Notes

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Heat Transfer on a Stationary Test Cylinder with Wake Generators

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Introduction

IN modern gas turbines, one of the most critical heat transfer regions on a turbine blade is near the blunt leading edge, where there is a stagnation point with a thin boundary layer, which leads to high heat transfer. By obtaining a semi-analytical solution, Frossling[1] provided the Frossling factor, $Nu/\sqrt{Re}$, as a function of the angular position from the stagnation point. The correlation was valid on the front surface of a cylinder with $\theta \leq 60$ deg in a laminar flow region. Churchill and Bernstein[2] studied the heat transfer of forced convection in a crossflow over a circular cylinder. They proposed correlation of experimental heat transfer data on a cylinder under both constant heat flux and constant wall temperature boundary conditions. Simoneau et al.[3] investigated the effect of an upstream rotor on the heat transfer on a circular cylinder. They found that doubling the rotor–stator distance had only a small effect on both turbulence and Nusselt number. O'Brien[4] explored both time-averaged (steady-state) and time-resolved (instantaneous) effects of wake passing on the heat transfer in the stagnation region of a cylinder. He reported that the time-averaged heat transfer were asymmetric with respect to the stagnation line. Han et al.[5] investigated the influence of unsteady wake on the heat transfer coefficient of a gas turbine blade.

Funazaki[6] measured the time-averaged heat transfer distributions around the leading edge of a blunt body that was under the influence of incoming periodic wakes. He found that the wakes passing over the leading edge cause a significant increase in heat transfer before flow separation. Park et al.[7] used a digital particle image velocimetry/thermometry (DPIV/T) technique to measure the velocity and temperature distribution of the wake on a heated circular cylinder. They demonstrated that DPIV/T could be a viable method to measure velocity and temperature accurately in turbulent flows.

In the present experimental study, a test cylinder is submerged in the wake of an upstream array of cylinders (rods) of smaller diameter than that of the test cylinder. The influence of the wakes on the heat transfer over the test cylinder is investigated by varying the freestream Reynolds number, the number of upstream rods n, and the adjustable shift angle between the rods and the test cylinder, ϕ. The latter two parameters, n and ϕ, which have been seldom investigated in the literature, reveal some interesting findings.

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Experimental Apparatus and Procedure

The experimental apparatus consists of two major parts: One is the annular-type wind tunnel and the other is the test section. The details of the apparatus are described as follows.

Annular-Type Wind Tunnel

It is an open-loop suction-type low-speed wind tunnel with an annular airflow. The airstream is drawn into the test section through an annular space between a ring-shaped Plexiglas® bell mouth and a hemispherical cone. The diameters of the bell mouth are 150 and 90 cm, corresponding to the beginning and central positions. The flow velocity is measured by using a Flow Master sensor, which is located 0.5 cm in front of the test cylinder.

Test Section

The test cylinder, which is made of high-quality bakelite with a thickness of 0.6 cm, is 9.0 cm in diameter and 14.0 cm in height. To serve as a heater, an enameled wire needs to be coiled on the outer surface of the test cylinder. Electrical power needed for the enameled-wire heater is supplied through a power slip ring, which is mounted at the end of the hollow shaft. The thermal boundary condition of uniform heat flux can be achieved. There are 10 T-type thermocouples placed at unequal distances around the circumference at midspan. The distance between the leading edge of the test cylinder and the centerline of the wake-generating cylinder is 9 cm for all tests. Three annular-type wake generators with 18, 36, and 72 round rods evenly spaced along the circumference are tested. The diameter and length of the rod are 0.8 and 13.5 cm, respectively. The range of adjustable shift angle between the rods and the test cylinder, ϕ, is 0, 2.5, 5.0, 7.5, and 10 deg for 18 rods, 0, 2.5, and 5.0 deg for 36 rods, and 0 and 2.5 deg for 72 rods, respectively. The turbulence intensity is measured at 8.5 cm behind the rods of the

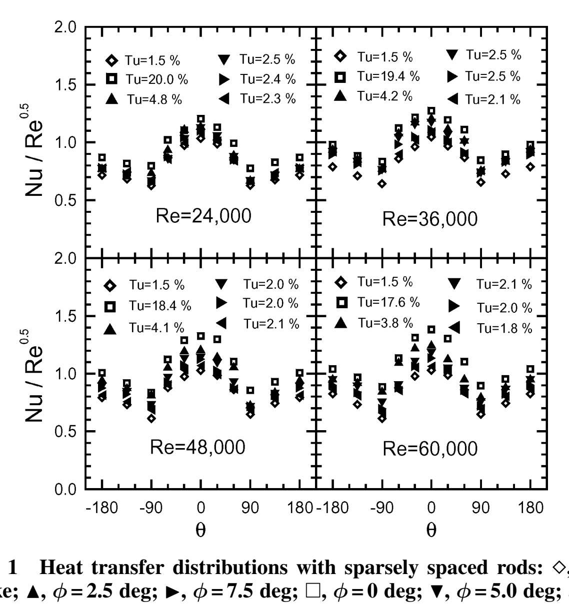

Fig. 1 Heat transfer distributions with sparsely spaced rods: ◇, no wake; ▲, $\phi = 2.5$ deg; ►, $\phi = 7.5$ deg; □, $\phi = 0$ deg; ▼, $\phi = 5.0$ deg; and ◄, $\phi = 10.0$ deg.

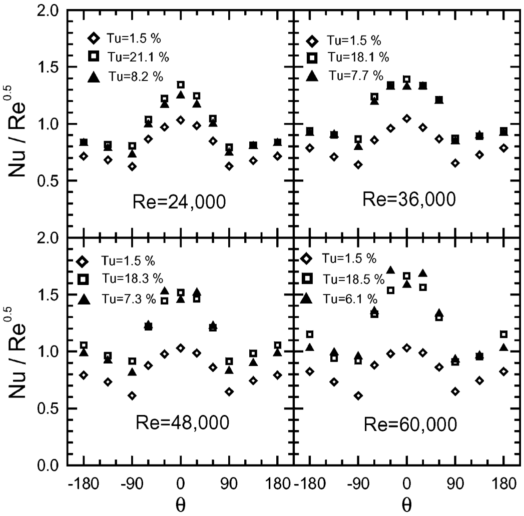

Fig. 2 Heat transfer distributions with the densely spaced rods: ◇, no wake; ▲, $\phi = 2.5$ deg; and □, $\phi = 0$ deg.

wake generators. The rms value of the data is measured for 5 min. The Reynolds number is changed from 2.4×10^4 to 6×10^4.

Results and Discussion

The heat transfer results with various ϕ and Reynolds number are shown in Figs. 1 and 2 for 18 rods (sparsely spaced rods) and 72 rods (densely spaced rods), respectively. The case without the wake generator is indicated as no wake. At $\phi = 0$ deg, because the upstream rods impact directly on the test cylinder, the turbulence intensity and Nusselt number are higher than those at the other shift angles. The shift angle is adjusted from the right to the left when it is viewed from upstream to downstream. The adjustment of the shift angle leads to different distances between the shifted rod and the test cylinder. Therefore, the distance at the left-hand side of the test cylinder is slightly smaller than that at the right of the test cylinder. This effect enables the heat transfer at the left to be usually higher than that at the right, especially under high Reynolds numbers. An increase in Reynolds number evidently also tends to increase the heat transfer everywhere on the test cylinder. However, with the increase in the Reynolds number, the Frossling factor appears to be weakly enhanced in the entire test cylinder region. The stagnation point Frossling factor for $\phi = 0$ deg is about 15∼30% higher than that without the wake generator ($Tu = 1.5\%$) as shown in Fig. 1. This is obviously a significant increase of the leading edge heat transfer.

Figure 2 shows the wake-affected heat transfer with various ϕ for densely spaced rods. Because of the compact arrangement of wake generator, the vortex shedding created by upstream adjacent rods may be superimposed. It increases the magnitude of wake fluctuation and turbulence intensity. Because of wake merging, the augmentation of Tu in Fig. 2 is nearly two times of that in Fig. 1 for $\phi = 2.5$ deg. This increase in Tu indicates an increase of heat transfer coefficient with an increasing number of rods in Figs. 1 and 2 for $\phi = 2.5$ deg. The wake interaction is more pronounced and complex in densely spaced rods. Therefore, for the shift angles of 2.5 and 0 deg, the heat transfer distribution shows a greater contrast with the case without the wake generator. It is sharply increased in the leading edge of the test cylinder.

Figure 2 also shows the increase of the Frossling factor with the increase of Reynolds number in the wake-induced cases. This is because the higher Reynolds number creates a faster moving vortex shedding and produces a thinner boundary layer on the test cylinder surface. This enhances heat transfer. The level of heat transfer improvement with wake effect is about 35∼70% higher than that in the case without wake effect. Moreover, the effect of wake merging influences the neighborhood of the stagnation point.

Summary

The effects of unsteady wake on convective heat transfer around a test cylinder are presented. Because of the merging of the wakes caused by neighboring rods, wake interaction is stronger and more complex in a dense configuration of the wake generator. Therefore, the heat transfer with a wake compared with that without a wake is sharply increased in the whole leading edge area of the test cylinder. Because the unsteady wake impacts directly on the test cylinder, the turbulence intensity at zero shift angle between the rods and the test cylinder is higher than that at other shift angles. Therefore, the Nusselt number at zero shift angle is also higher than that at other shift angles.

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