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Turbulence intensity effects on heat transfer and fluid-flow for a circular cylinder in crossflow

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ABSTRACT

The intrinsically unsteady heat transfer on the surface of a cylinder in crossflow has been investigated in detail by numerical simulation as a function of the freestream turbulence intensity and the Reynolds number. After a brief startup transient, a periodic steady state is established at all circumferential locations. The resulting timewise fluctuations were seen to be of different phase depending on where on the circumference they occur. On one side of the cylinder, maxima occurred at the same moment in time as minima occurred on the other side. This finding and comparisons of the magnitudes of the local heat transfer coefficients showed that side-to-side symmetry does not prevail in the presence of the unsteadiness. The fluctuation frequencies were found to be virtually uniform over the entire circumference of the cylinder and varied only slightly with the Reynolds number and the turbulence intensity. The full slate of results included: (a) timewise and circumferential variations of the local heat transfer coefficient, (b) timewise variations of the all-angle spatial-averaged heat transfer coefficient, (c) spatial variations of the timewise-averaged heat transfer coefficient, (d) spatial- and timewise-averaged heat transfer coefficients as a function of turbulence intensity and Reynolds number, (e) timewise fluctuation frequencies, (f) comparisons with the experimental literature, and (g) effect of the selected turbulence model. As expected, the magnitude of the heat transfer coefficient increases as the turbulence intensity increases.

1. Introduction

The effect of freestream turbulence on the fluid flow and heat transfer for a cylinder in crossflow has attracted considerable interest over the past 75 years; for example, [1,2] are representative of the earlier work. It is convenient to classify the relevant literature into experimental and analytical work. By far, the amount of experiment work has considerably exceeded that by analysis. Since the outcomes of both the experimental and the analytical work are highly varied and do not lead to definitive conclusions, only a chronological overview is sufficient. In the literature survey that follows, attention will be focused on the effects of free stream turbulence on heat transfer for the cylinder in crossflow. That focus precludes the extensive literature on steady-state heat transfer for that geometry. The latter literature, while of interest in its own right, is peripheral to the goals of the present investigation. There is also a significant literature on crossflow about shapes that are not circular, but here again that work does that contribute to the present investigation. Here, broad-ranging numerical simulations utilizing a carefully validated turbulence model were employed to provide definitive results for the effects of free stream turbulence on the local, time-varying heat transfer for the cylinder in crossflow.

In [3], in the early 1970s, experiments at a fixed Reynolds number of 19,000 were performed with a variation of turbulence intensity from 2.5% to 16%. The results for the time- and area-average Nusselt number were correlated by the means of the parameter $TuRe^{1/2}$, where Tu is the turbulence intensity and Re is the cylinder Reynolds number. Somewhat later, in 1977, Zukauskas and coworkers [4] reported extensive data for cylinder Reynolds numbers between 10^5 and 10^6, thereby traversing the critical regime. Four different values of turbulence intensity were investigated: 1.2, 2.7, 7, and 15%. The heat transfer results, all for which corresponded to temporal and spatial averages, were correlated by the parameter $Tu^{0.2}Re^{0.6}$.

In 1995, experiments were reported in [5] in which the turbulence intensity was varied from 1.5 to 40% for Reynolds numbers up to about 40,000. In the final correlation, the average Nusselt number depended on $TuRe^{1/2}$. The experiments performed by Peyrin and Kondjoyan [6] in 2002 were based on a fixed velocity and a fixed value of the turbulence intensity as the turbulence length scale was varied by a factor of two. No effect on the average heat transfer coefficient was observed. More recently, in 2007,

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Nomenclature

A	SST model constant
c_p	specific heat at constant pressure
D	cylinder diameter
F_1, F_2	blending functions in the SST model
f	fluctuation frequency
$h(\theta,t)$	local, time-varying heat transfer coefficient
$\bar{h}(\theta)$	local, time-averaged heat transfer coefficient
h	spatial- and time-averaged heat transfer coefficient
k	molecular thermal conductivity
k_{turb}	turbulent thermal conductivity
$\underline{Nu}(\theta,t)$	local, time-varying Nusselt number
$\overline{Nu}\ (\theta)$	local, time-averaged Nusselt number
Nu	spatial- and time-averaged Nusselt number
p	pressure
P_k	production term for the turbulent kinetic energy
Pr_{turb}	turbulent Prandtl number
q,q_w	local heat flux
Re	Reynolds number
S	absolute value of the shear strain rate
St	Strouhal number
t	time
T	temperature
T_w	wall temperature
T_∞	freestream fluid temperature
Tu	freestream turbulence intensity
u_i	velocity component in the i-direction
U	freestream velocity
x_i	Cartesian coordinate
α	SST model constant
β_1, β_2	SST model constants
ε	turbulence dissipation
θ	cylindrical coordinate angle
κ	turbulent kinetic energy
μ	molecular or dynamic viscosity
μ_{turb}	turbulent viscosity
ν	kinematic viscosity
ρ	fluid density
σ	SST diffusion coefficient
ω	specific rate of turbulence dissipation

experiments were carried out in Ref. [7] for a fixed Reynolds number at which the turbulence intensity was varied at a fixed value of the length scale, and the length scale was varied for a fixed value of the turbulence intensity. For the fixed length scale experiments, the heat transfer increased with increasing turbulence intensity, while for a fixed intensity value $Tu = 6.9\%$, the heat transfer decreased with increasing turbulence length scale.

The foregoing literature review confirms the rather dispersed nature of the experimental information that is available for the cylinder in crossflow. For the most part, the flow was considered to be steady or quasi-steady, and the turbulence length scale was regarded as a minor variable.

The analytical work relating to the effects of freestream turbulence is generally approximate and based on simplifying assumptions so that a broad overview is sufficient. In 1966, Smith and Kuethe [8] performed an analysis of the flow at the stagnation point of a cylinder in crossflow. The eddy viscosity was assumed to be proportional to the turbulence in the freestream, the proportionality constant being determined from experimental data. The governing equations were the boundary layer equations for incompressible flow near the stagnation point. In 1979, Sunden [9] analytically investigated the effects of freestream turbulence and turbulence length scale on skin friction and heat transfer. The analysis was confined to the steady state and to phenomena that take place upstream of angular positions that are 60–70° from the forward stagnation point, thereby ignoring the wake region of the cylinder.

In 1982, Gorla and co-workers [10] used a boundary layer model to study turbulence effects in the steady state, with a major emphasis on the stagnation point. The solution approach was the approximate local similarity method, and irrotational-potential-inviscid flow was assumed for the freestream. The eddy diffusivity model was adjusted to achieve agreement with the experimental data. For a given length scale, the Nusselt number was found to increase with increasing value of $TuRe^{1/2}$. The Zukauskas group [11] used a very simple model for the thermal boundary layer to predict the variation of the steady-state heat transfer coefficient as a function of angular position for Re values ranging from 5.5×10^4 to 2.03×10^6 and for $Tu = 1.5\%$ without any concern for the length scale.

The goals of the present investigation are broader than those identified in the foregoing literature survey. The major difference is the emphasis here on the innately unsteady nature of the local heat transfer coefficient. New patterns of timewise variation are explored including both spatially local and spatially averaged results. Post processing enabled the range of outcomes to include the more familiar steady-local and steady-spatial-averaged results. The dependence of these results on the magnitudes of the Reynolds number and the turbulence intensity is highlighted. Also investigated were the response of the results to the selected turbulence model and to the thermal boundary conditions.

2. Modeling and numerical simulations

The physical situation to be investigated by numerical simulation is depicted in an elevation view in Fig. 1. As seen there, a circular cylinder situated in a large rectangular solution domain is positioned in crossflow in a uniform upstream freestream. The turbulence intensity of the freestream flow is a major independent variable of the work, with the Reynolds number being a second independent variable. Heat transfer is the major focus of the investigation, and a broad range of heat transfer results are presented and elucidated by discussion.

As seen in Fig. 1, the upstream boundary of the domain is situated 10 cylinder diameters ahead of the forward stagnation point, and the 50-diameters downstream extension of the domain was chosen to be large enough to enable wake effects to be properly dealt with. The lateral extension of the solution domain was 15 diameters at either side of the cylinder. The range of considered Reynolds numbers extended from 10,000 to 50,000, where $Re = \rho UD/\mu$, and the turbulence intensity Tu at the inlet of the solution domain varied over the range 1, 5, and 10%.

Two thermal boundary conditions at the cylinder surface were investigated: (a) uniform wall temperature and (b) uniform wall heat flux. The freestream temperature at the upstream boundary of the solution domain was specified as being uniform across the span of the boundary. Also uniform across that boundary are the assigned values of the freestream turbulence and the velocity normal to the boundary, the latter of which results in the Reynolds numbers that were mentioned earlier. The two lateral boundaries