



The kinematics of boundary layer transition on a long circular cylinder impinged by a fully turbulent round jet

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ABSTRACT

We experimentally examine the impingement of a fully turbulent round jet (with diameter D_j) on a long circular cylinder (with diameter D) in the crossflow plane coinciding with the jet axis for $D/D_j = 2.5$ and $Re_{Dj} = 20,000$. Particular focus is placed on the kinematics of boundary layer transition that occurs and subsequently leads to a second thermal peak on the cylinder surface downstream of the primary thermal peak near the stagnation point when placed inside the jet's potential core. To this end, spectral analyses of wall shear stress data and time-resolved velocity data within both laminar and turbulent boundary layers have been performed. The present study demonstrates that the root mean square (rms) fluctuation of the stream-wise velocity component increases along both boundary layers due to the propagation of external perturbations from coherent structures that are shed from the jet exit, which incites the transition of the laminar boundary layer. The transition causes the local heat transfer elevation that interrupts the monotonic decrease from the primary thermal peak whereas it plays no direct part in forming the second thermal peak. Instead, the second thermal peak occurs at a delayed downstream azimuth angle from the transition where the rms velocity fluctuations of the boundary layer flow reach their peak at the dominant frequency, equivalent to that of the coherent structures of the jet.

1. Introduction

The heat transfer studies on the impingement of a round jet upon a circular cylinder have direct relevance to many engineering applications including furnace cooling [1,2], the cooling of extruded materials [3], and the internal cooling of gas turbine blades by blockage jets [4,5]. The following aspects have been previously considered: Reynolds number (Re_{Dj}), jet exit-to-cylinder spacing (H/D_j), and target cylinder-to-jet diameter ratio (D/D_j) on the overall heat transfer [6], stagnation point heat transfer [2,7–9], and circumferential and span-wise distributions of heat transfer for both constant temperature [7] and constant heat flux [1,2,8–10] conditions.

An example of the measured heat transfer distributions on the surface of a target cylinder placed inside the jet's potential core (e.g., $H/D_j = 2.0$) is shown in Fig. 1(a) [2] for $D/D_j = 2.5$ and $Re_{Dj} = 20,000$. Distinctive features in the circumferential heat transfer distribution on a circular cylinder whose diameter is greater than the round jet in Fig. 1(a) are summarized based on the work reported by Wang et al. [2] as:

- (a) a primary thermal peak near the stagnation point (i.e., $\alpha \sim 0^\circ$),
- (b) a local minimum in heat transfer roughly at $\alpha \sim 60^\circ$,
- (c) a second thermal peak at $\alpha = 70\text{--}80^\circ$.

Highest heat transfer occurs near the stagnation point ($\alpha \sim 0^\circ$) and declines away from the stagnation point ($0^\circ < \alpha < 60^\circ$) due to the thickening boundary layer [6,7]. However, the decline is interrupted by a local minimum $\alpha \sim 60^\circ$ and a second thermal peak forming between $\alpha = 70^\circ$ and $\alpha = 80^\circ$.

Similar features can be observed on a flat plate subjected to jet impingement as shown in Fig. 1(b) where the flat plate configuration may also conceptually be considered as a limiting case of a jet impinging on a circular cylinder with a large or infinite radius of curvature. When a fully turbulent round jet impinges on a flat plate at lower values of nozzle-to-plate spacing (e.g., $H/D_j < 6.0$), the observable second thermal peak coincides with a radial range roughly at $r/D_j = 2.0$ [11] where the second thermal peak at $70^\circ \leq \alpha \leq 80^\circ$ on a cylinder surface in Fig. 1(a) corresponds to $r/D_j \sim 1.7$ in Fig. 1(b). Here, a local maximum at $r/D_j = 0.5$ was reasoned to be the radial velocity acceleration in the deflection region followed by the radial spreading of the jet that reduces the radial velocity. Gardon and Akfirat [11] suggested that the second thermal peak at $r/D_j = 2.0$ on a flat plate is due to transition from laminar to turbulent boundary flow which remains the prevailing explanation for the second thermal peak in the radial range of $1.0 \leq r/D_j \leq 2.0$.

Unlike the univocal agreement on the cause of the observed second thermal peak on a flat plate, there has been dispute amongst previous studies for the cause of the second thermal peak on a circular cylinder.

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Nomenclature

A, B	empirical constants determined from linear regression of the data
C_f	skin friction coefficient defined in Eq. (5)
C_p	static pressure coefficient defined in Eq. (2)
D	diameter of the target cylinder (m)
D_j	diameter of the round jet (m)
E	voltage of the hot-film sensor (V)
f	frequency of coherent structures in the mixing layer (Hz)
H	nozzle-to-target cylinder spacing (m)
Nu_D	Nusselt number based on the target cylinder diameter
Re_{Dj}	jet Reynolds number based on the round jet diameter defined in Eq. (1)
P_u	power spectrum of velocity fluctuations (u')
r	radial coordinate of the round jet with its origin at the jet axis

St	Strouhal number for coherent structures in the mixing layer defined in Eq. (7)
u_{rms}	root-mean-square (rms) of velocity fluctuations defined in Eq. (6) (m/s)
W	time window (s)
w_e	centreline velocity at the jet exit (m/s)
y	coordinate normal to the surface of the target cylinder at an arbitrary azimuth angle, α
z	coordinate coinciding with the round jet axis
z'	coordinate along the span of the target cylinder
α	azimuth angle having its origin at the stagnation point (degree)
γ	intermittency
μ	dynamic viscosity of air (kg/(ms))
ρ	density of air (kg/m ³)
τ_w	wall-shear stress defined in Eq. (3) (N/m ²)

Some studies claimed boundary layer separation preceding the second thermal peak [12–14] while others refuted the location of separation [8,9,15–17], suggesting boundary layer transition as the cause [2]. According to Schuh and Persson [15], if the target cylinder is smaller

than the jet (i.e., $D/D_j < 1.0$) and is positioned within the jet's potential core, the pressure distribution does not differ qualitatively but only quantitatively from that immersed in a uniform free-stream. Recent experimental evidence reported by Wang et al. [2] shows that with the target cylinder-to-round jet diameter ratio (D/D_j) of 0.5, there is a local minimum in heat transfer associated with flow separation, which is similar behaviour to a cylinder immersed in a uniform free-stream whereas for $D/D_j = 2.5$, the impinging jet on the target cylinder behaves similarly to that qualitatively on a flat plate with a second thermal peak caused by transition that is supported by shear stress data.

It has been agreed that if the target cylinder is bigger than the jet (i.e., $D/D_j > 1.0$), transition leads to (or causes) the observed second thermal peak on the cylinder surface, in addition to the primary peak in heat transfer near the stagnation point. However, there are still questions concerning the formation of the second thermal peak that remain open as:

- How is transition initiated and how does it progress along the surface of the target cylinder?
- How does transition kinematically lead to the second thermal peak?

Therefore, this study squarely addresses these questions. To this end, a series of experiments using a single component hot-wire anemometer and a hot-film shear stress sensor have been conducted on a circular cylinder which is subjected to a fully turbulent round jet at $Re_{Dj} = 20,000$ with the nozzle-to-target cylinder's leading edge spacing fixed at $H/D_j = 2.0$. Here, the round jet (with diameter of D_j) is smaller than the target cylinder (with diameter of D) i.e., a ratio of $D/D_j = 2.5$ which has been fixed for the entire study. Prior to experiments, the present round jet that is fully turbulent has been characterized especially for the length of the potential core to be $H/D_j = 5.0$.

2. Experimental details

2.1. Test rig

A purpose-built test facility (Fig. 2) has been used to investigate transition that takes place leading to the second thermal peak at a certain downstream location from the stagnation point. Air supply from a small-scale wind tunnel, featuring a 22-kW centrifugal blower with a maximum volumetric flowrate of 80 m³/min and a free-stream turbulence intensity of 0.5% (measured by a single component hot-wire anemometer), passes through flexible tubing to the test bench which includes a conical small-angle diffuser followed by a settling chamber with honeycomb flow straighteners and a contraction that terminates with a round jet nozzle ($D_j = 25$ mm).

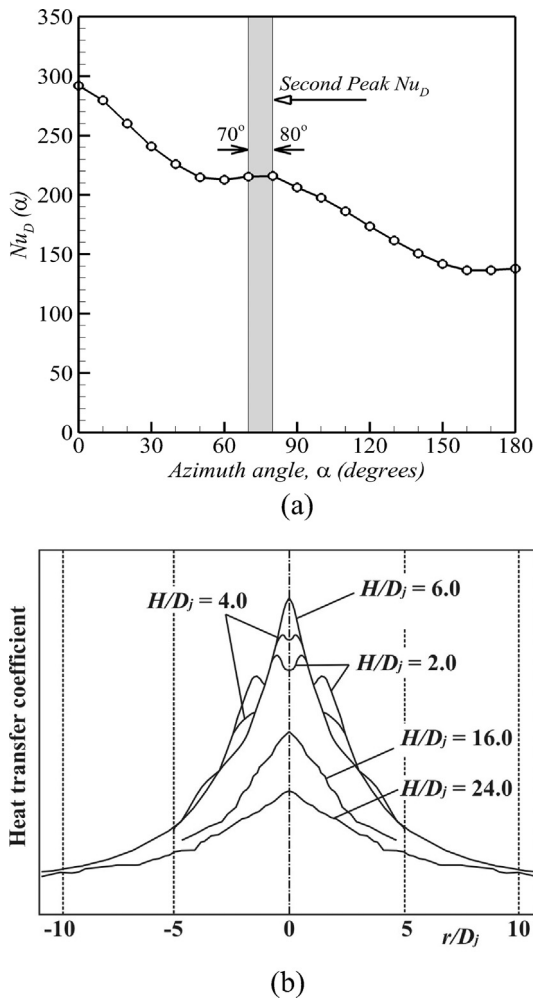


Fig. 1. Local heat transfer distributions resulted from round jet impingement. (a) On a circular cylinder ($D/D_j = 2.5$ for $Re_{Dj} = 20,000$) in the crossflow plane inside the potential core ($H/D_j = 2.0$) [2], (b) on a flat plate for $Re_{Dj} = 20,000$ with varying a dimensionless distance between the jet exit and the target flat plate (H/D) [11].

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