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A comparative study of single-/two-jet crossflow heat transfer on a circular cylinder

X.L. Wang [a], J.H. Lee [b], T.J. Lu [a], S.J. Song [b], T. Kim [c,*]

[a] *State Key Laboratory for Mechanical Structure Strength and Vibration, Xi'an Jiaotong University, Xi'an 710049, China*
[b] *School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, South Korea*
[c] *School of Mechanical Engineering, University of the Witwatersrand, Wits 2050, Johannesburg, South Africa*

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ABSTRACT

This study presents thermo-fluidic characteristics on a circular cylinder subject to the impingement of single-/two-counter jets in crossflow. For a fixed circular jet diameter (D_j), the diameter of a target cylinder (D) varies, $D/D_j = 2.5$, 5.0, and 10.0. Two separate scenarios are considered and compared; at a fixed jet Reynolds number, $\mathrm{Re}_j = 20{,}000$ and at a fixed total mass flow rate. Results demonstrate that laminar to turbulent transition occurs on a fore cylinder surface which contributes significantly to overall heat transfer. However, it occurs only if the target cylinder is positioned inside the potential core of each jet and only if enough spacing (T) between the jets which is determined by the diameter ratio (D/D_j) as $T = \pi D/2$, is ensured. With small spacing, a reverse flow region formed between the jets ($=\pi D/4$) suppresses the occurrence of the transition. For a fixed jet Reynolds number, the added second jet improves local heat transfer only on the rear cylinder surface whereas the fore cylinder surface is essentially unaffected by the second jet. For a fixed total flow rate, the single impinging jet removes substantially more heat than that achievable by the two-counter jets in the present D/D_j ranges.

1. Introduction

Thermo-fluidic characteristics of jets impinging on a flat plate for cooling or heating have long been studied due to its superior heat transfer performance compared to other convective heat transfer schemes. Consequently, a multitude of studies have been conducted [1–4]. It has been established that with a single impinging jet, the overall and local heat transfer on a flat plate depends strongly on many parameters including a jet exit-to-flat plate distance (termed an "impinging distance") [1,3]. The highest heat transfer on a flat plate typically occurs at the stagnation point coinciding with the jet axis at low Reynolds number ranges and low turbulence levels [5,6]. Depending on the impinging distance relative to the potential core of jet flow, either two peaks of local heat transfer (the primary peak at the stagnation point and a second peak off from the stagnation point) or a single peak (only the primary peak at the stagnation point) exist.

In certain applications, the radius of a target surface is finite compared to the infinite radius of a flat plate. The cooling of a circular furnace containing the melt of metal slurry with gaseous pores during the closed-cell foaming process (e.g., via the direct foaming method) [7,8] (Fig. 1) can be an example. In this particular application, many parameters affect the quality of final foam products including those associated with the cooling. A literature survey reveals that previous studies on crossflow multiple jets impinging on a circular cylinder emitting constant heat flux are scares.

Two separate configurations may serve as references to this particular configuration (or application): (i) heat removal from a circular cylinder by an impinging jet and (ii) multiple jets impinging on a flat plate. Some major findings on each reference are separately summarized as follows.

Observations made on circumferential heat transfer characteristics on a circular cylinder (or a convex surface) impinged by single impinging jet [9–17] are: (a) when positioned close to the jet exit (i.e., inside the jet's potential core), a second peak, in addition to a primary peak at the stagnation point, forms; (b) a second peak disappears when positioned relatively far away from the jet exit along the jet axis; (c) flow separation causes a local heat transfer minimum on "small" target cylinders (smaller than the jet diameter) whilst transition from laminar to turbulent flow causes a second peak on "large" target cylinders (larger than the jet diameter), and (d) the overall heat transfer rate decreases as

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[*] Corresponding author. Tel.: +27 11 717 7359.
E-mail address: tong.kim@wits.ac.za (T. Kim).

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Nomenclature

C_f	skin friction coefficient defined in Eq. (10)
C_p	static pressure coefficient defined in Eq. (5)
D	target circular cylinder diameter, m
D_j	circular jet diameter, m
E	voltage from hot-film sensor, V
g	gravitational acceleration, m/s^2
Gr	Grashof number based on cylinder diameter, $Gr = g\beta(T_s - T_j)D^3/\nu^2$
h	convection heat transfer coefficient, W/(m^2 K)
k_f	thermal conductivity of air, W/(m K)
n	the number of jets
Nu	Nusselt number based on a jet diameter defined in Eq. (6)
$p(\alpha)$	static pressure measured at an arbitrary azimuth angle, Pa
p_e	static pressure measured at a jet exit, Pa
q''	heat flux, W/m^2
$\dot{m}$	mass flow rate, kg/s
r	radial coordinate
Re_j	Reynolds number based on a jet diameter defined in Eq. (4)
Ri	Richardson number in Eq. (8)
s	lateral distance from a stagnation point, m
S	cylinder span, m
T	jet-to-jet spacing (=$\pi D/n$), m
T_j	jet temperature measured at a jet exit, K
$T_s(\alpha)$	local temperature measured on a cylinder surface, K
w	axial velocity component of jet flow discharged from a circular jet, m/s
w_e	jet exit velocity at $r = 0$ and $z = 0$, m/s
w_0	centerline (axial) velocity at $r = 0$, m/s
y	coordinate normal to a cylinder surface
z	coordinate coinciding with a jet axis
α	azimuth angle measured from a stagnation point, °
β	thermal expansion coefficient
ρ	density of air, kg/m^3
μ	dynamic viscosity of air, kg/(m s)
ν	kinematic viscosity of air, m^2/s
τ_w	wall shear stress, N/m^2

the impinging distance increases for fixed Reynolds numbers. It has also been reported that a diameter ratio (D/D_j) plays an important role in determining overall heat removal performance: a higher overall heat transfer on a smaller diameter ratio is obtained for a given jet Reynolds number and fixed impinging distance [9–10,14].

For multiple jets impinging on a flat plate, if spacing between neighboring jets and an impinging distance are small, the interference between jets is strong. A region called "a reverse flow region" is formed where counter-flowing streams from the jets meet (on the symmetric axis in Fig. 1). This region lowers the overall rate of heat transfer if the jet flow is confined [18,19] whereas its adverse effect is observed if the jet flow is unconfined [20]. The jet flow leaving the stagnation point formed by each jet experiences initially a favorable pressure gradient but followed by an adverse pressure gradient in a "wall jet region" [21]. With small spacing between the jets, this adverse pressure gradient may be strengthened due to a relatively high pressure existing in the reverse flow region [22]. As a result, laminar to turbulent transition on the flat plate tends to be suppressed.

In the present configuration, jet-to-jet spacing (T) is determined by the number of jets (n) equi-azimuthally distributed over the circumference of a cylinder diameter (D) as $T = \pi D/n$. Since two-counter jets are considered, the two jets are azimuthally positioned at $\alpha = 0°$ and $180°$ around the cylinder. The following specific issues aim to be addressed.

(i) how jet-to-jet spacing (with two-counter jets, $n = 2$) which is varied with the diameter ratio D/D_j alters local heat transfer characteristics caused by laminar to turbulent transition and a reverse flow region,

(ii) how these two distinctive features are influenced by the relative position to the potential core of the jet flow, and

(iii) for a given total flow rate, a single circular jet or two-counter jets is more effective in terms of overall heat removal from a cylinder.

To this end, the present study experimentally considers two separate configurations: a target cylinder emitting heat which is cooled by (i) a single jet and (ii) two-counter jets for both a fixed jet Reynolds number and a fixed total mass flow rate. The circular jets are positioned at two distinctive impinging distances from a target cylinder – inside/outside the potential core of the jet flow.

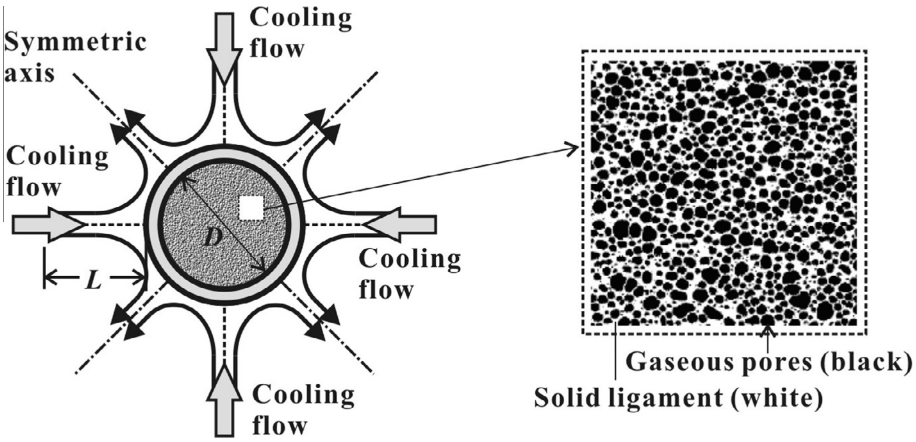

Fig. 1. Schematic of furnace cooling by multiple impinging jets on to a cylindrical furnace containing metal melt with closed-cells.