International Journal of Thermal Sciences 78 (2014) 1–8

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Heat transfer of a circular impinging jet on a circular cylinder in crossflow

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

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

ARTICLE INFO

Article history:
Received 14 April 2013
Received in revised form
5 November 2013
Accepted 5 November 2013
Available online 18 December 2013

Keywords:
Circular cylinder
Circumferential heat transfer
Impinging circular jet
Flow separation
Transition

ABSTRACT

Local heat transfer characteristics on a circular cylinder subject to a circular impinging jet in crossflow are studied experimentally at a fixed jet Reynolds number of $Re_j = 20{,}000$. Three cylinder-to-jet diameter ratios, $D/D_j = 0.5$, 2.0, and 5.0 are selected for a fixed jet diameter D_j. As reference, heat removal from a flat plate (having $D/D_j = \infty$) by the same circular impinging jet is also measured. Results reveal that local surface heat transfer characteristics are governed separately by the mechanisms for two limiting configurations. Smaller cylinders (than the circular jet diameter e.g., $D/D_j \leq 0.5$) behave as if immersed in uniform free-stream – flow separation causes the local minimum heat transfer. Larger cylinders (than the circular jet diameter e.g., $D/D_j \geq 2.0$) follow the local heat transfer characteristics observable on a flat plate subject to a circular impinging jet – laminar to turbulent flow transition induces local heat transfer peaks.

1. Introduction

Impinging jet cooling (or heating) has long been studied due to its superior heat transfer capability to other convective heat transfer schemes. A circular impinging jet on a flat plate serves as a fundamental configuration amongst others. Consequently, a multitude of studies have been devoted to this configuration [1–5]. Some of the conclusions drawn are summarized as: (a) the highest heat transfer on a flat plate typically occurs at the stagnation point whose magnitude varies with jet exit-to-flat plate spacing (or referred to an impinging distance) at low turbulence levels [4] and low Reynolds numbers [6] and (b) depending on the impinging distance relative to the potential core of jet flow, either two peaks of local heat transfer (a primary peak at the stagnation point and a second peak off from the stagnation point) or a single peak (only a primary peak at the stagnation point) exists.

In some engineering applications, a target surface has a finite radius (e.g., circular cylinders and convex surfaces)) such as 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] (see Fig. 1). In this particular application, many parameters are known to affect the quality of final foam products including those associated with the furnace cooling. The circular furnace experiences two distinctive upstream flow conditions (depending on its relative location to the potential core of cooling jet flow): uniform-like (inside the potential core) and shear (outside the potential core) flows. Furthermore, a diameter ratio between the cooling jets and the circular furnace may also play an important role in the local thermal flow characteristics on the furnace surface, which differentiates the present configuration from impinging circular jets on a flat plate.

Gau and Chung [9] who investigated the heat transfer characteristics of semi-cylindrical convex surfaces (with a diameter of D) subject to slot jet cooling with a slot width of b, observed that decreasing the ratio of D/b enhances heat transfer at the stagnation point, arguing that the increased counter-rotating vortex size is responsible. Cornaro et al. [10] conducted heat transfer experiments on jet impingement cooling on convex semi-cylindrical surfaces and observed that the stagnation Nusselt number increases with decreasing D/D_j. Lee et al. [11] examined local heat transfer on convex surfaces subject to a round impinging jet and reported that the stagnation Nusselt number increases with decreasing D/D_j.

Experimental results contradicting those discussed above have also been reported by Sparrow et al. [12] who used a naphthalene mass transfer technique to measure mass transfer coefficients on a

* Corresponding author. Tel.: +27 11 717 7359.
E-mail address: tongbeum@gmail.com (T. Kim).

1290-0729/$ – see front matter © 2013 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.ijthermalsci.2013.11.005

Nomenclature

C_p	static pressure coefficient defined in Eq. (2)
D	target circular cylinder diameter, m
D_j	circular jet diameter, m
h	convection heat transfer coefficient, W/(m^2 K)
k_f	thermal conductivity of air, W/(m K)
Nu	Nusselt number based on a jet diameter defined in Eq. (3)
p_e	static pressure measured at a jet exit ($z = 0$), Pa
$p(\alpha)$	pressure measured at an arbitrary azimuth angle (α), Pa
Pr	Prandtl number
r	radial coordinate
Re_j	Reynolds number based on a jet diameter defined in Eq. (1)
s	a lateral distance from the stagnation point of a target cylinder along the S-axis, m; inflection point
S	coordinate along the circumference of a cylinder
T_j	jet temperature measured at a jet exit, K
T_s	local temperature measured on a circular cylinder, K
w	axial velocity component of 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
z	a distance along a jet axis from a jet exit to a stagnation point on a cylinder, m
Z	axial coordinate coinciding with a jet axis
Z'	coordinate coinciding with a target cylinder axis
α	an azimuth angle measured from the stagnation point of a cylinder, degree
ρ	density of air, kg/m^3
μ	viscosity of air, kg/(m s)

circular cylinder subject to a circular impinging jet. Both the stagnation point and circumferential distributions on a cylinder surface were measured. The stagnation mass transfer was increased with increasing D/D_j at a fixed impinging distance and jet Reynolds number. Tawfek [13] investigated circumferential and axial heat transfer distributions on an isothermal circular cylinder subject to a round impinging jet. The results showed that the increased cylinder diameter enhances the stagnation heat transfer. Singh [14] experimentally and numerically investigated a circular air impinging jet on a cylinder. It was observed that the stagnation heat transfer increases as the diameter ratio D/D_j increases, as opposed to the findings reported in Refs. [9–11], as summarized in Table 1.

Thus far, observations made on circumferential heat transfer characteristics on a circular cylinder (or a convex surface) impinged by a circular single jet are: (a) when positioned close to the jet exit, a second peak, in addition to a primary peak at the stagnation point, forms and (b) a second peak disappears when positioned relatively far away from the jet exit along the jet axis [9–13]. Despite numerous efforts including those discussed above, some thermo-

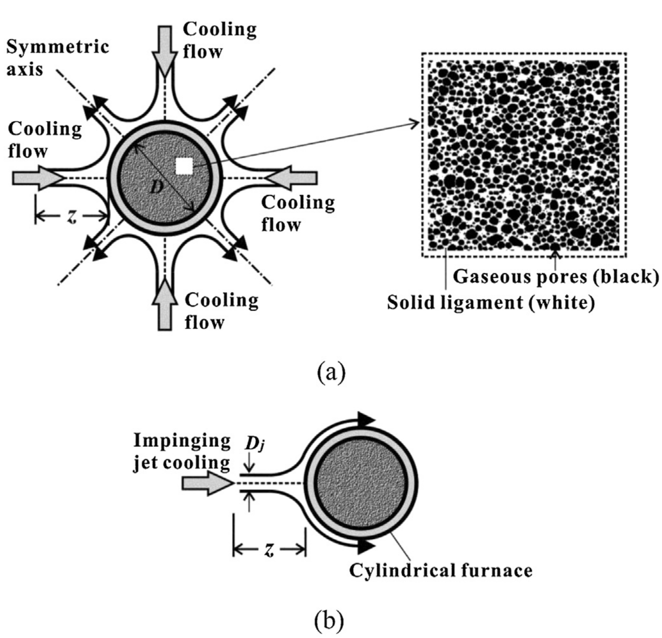

Fig. 1. Schematic of furnace cooling: (a) multiple impinging jet cooling of a cylindrical furnace containing metal melt with closed-cell pores; (b) single impinging jet cooling as a simplified configuration of (a).

physics has not been fully understood regarding local heat transfer at the stagnation point and along the circumference of a circular cylinder (or convex surface) subject to a circular impinging jet. Specific issues to be squarely addressed are:

(a) how a target cylinder-to-jet diameter ratio affects the dependence of the stagnation heat transfer on an impinging distance, and
(b) how the presence of the potential core of a circular jet (i.e., its relative location to the impinging distance) alters local heat transfer characteristics on a cylinder surface.

2. Experimental details

2.1. Test rig and instrumentation

A series of experiments on a circular cylinder of diameter D positioned at two distinctive locations (inside and outside the potential core of jet flow) have been conducted for a fixed jet Reynolds number of $Re_j = 20{,}000$. As reference, the circular jet removing heat from a flat plate (i.e., $D = \infty$) is also considered. Three selected cylinder diameters $D/D_j = 0.5$, 2.0, and 5.0 are tested for a fixed D_j in addition to the flat plate (Fig. 2). Detailed dimensions are listed in Table 2. Static pressure and heat transfer coefficients along the circumference of each cylinder are measured. Prior to pressure and heat transfer measurements, the potential core length of the present circular jet flow is measured.

Fig. 3 shows a schematic of the present test facility. Air at ambient conditions drawn by a centrifugal fan is discharged from a circular jet nozzle with a fixed inner diameter of $D_j = 30$ mm. The mass flow rate measured by an orifice plate is adjusted to fix the jet Reynolds number Re_j (Eq. (1)) at 20,000. An acrylic (target) circular cylinder ($k_s \sim 0.02$ W/mK) is mounted on a linear traverse system to vary the impinging distance systematically.

To quantify the potential core length, the centerline velocity of the jet flow is measured using a Pitot tube which is mounted on an automated linear traverse system along the Z-axis. Pressure readings from the stagnation and static tappings are recorded by a differential pressure transducer (DSA™, Scanivalve Inc.). To obtain the circumferential variation of static pressure on the cylinder surface, a static pressure tapping (inner diameter of 0.5 mm) is drilled into the cylinder surface and the cylinder is rotated in a 2.5° increment to cover the circumferential range from $\alpha = 0°$ (stagnation point) to $\alpha = 180°$.