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Jet impingement heat transfer from lobed nozzles

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ABSTRACT

The paper presents an experimental investigation of heat transfer obtained with impinging gas jets. Lobed nozzles are tested. The study parameters are the lobe geometry, the jet Reynolds number, Re, and the normalised standoff distance, z/D. The quantitative infrared thermography associated with the thermofoil technique is applied. At high Reynolds number ($Re \geq 15{,}000$)) and small normalised standoff ($z/D \leq 1$), the three-lobe nozzle affords performance better than the other nozzles. As the normalised standoff distance increases and exceeds $z/D = 7$, the 4-lobe yields better performance.

1. Introduction

Among heat transfer devices, impinging fluid jets are extensively exploited because of their ability to produce high local transport coefficients. The large heat transfer rate obtained with impinging streams, compared with classical boundary layer flows explains the popularity of this technique. In addition, impingement is often attractive for the designer, who can easily control the area and the distribution of thermal exchange. Impinging jet systems are present in many industrial and engineering processes where heat and/or mass transfer prevail. Typical examples are the annealing of metal and plastic belts, the tempering of glass sheets, the drying of paper and textiles, the cooling of turbine blades, the chemical vapour deposition, propulsion jet- to- flaps interaction in STOL aircraft and thermal anti-icing systems of wings.

The jet can be formed by round (SRN) or slot nozzles (SSN) depending on the application. Reviews on impinging jets have been the subject of numerous works [1–5]. Prior experimental works were carried out by Gardon and Cobonpue [6] who reported the heat transfer distribution for an impinging circular jet for nozzle-to-plate distances $z/D > 2$, for a single jet and an array of jets, also Gardon and Akfirat [7] studied the effect of turbulence on the heat transfer for a two dimensional impinging jet. The same authors, in a later work [8], studied the effect of multiple two-dimensional jets on the heat transfer distribution. Later, Hrycak [9] and Baughn and Shimizu [10] also carried out experimental works to evaluate heat transfer for a round jet using different methods to measure the surface temperature.

At low nozzle-to plate distances, Lytle and Webb [11] investigated the local heat transfer distribution of an impinging circular air jet. Lee et al. [12] analysed the effect of nozzle diameter of an impinging jet on heat transfer and fluid flow. More recently, Beitelmal et al. [13] studied 2D impinging jets and correlated heat transfer at the stagnation point, stagnation region and wall jet region. Hofmann et al. [14] performed an experimental study of the flow structure and heat transfer from a single impinging round jet. In 2007, O'Donovan and Murray [15,16] carried out a very interesting study of the mechanisms that influence the magnitude and location of secondary convective heat transfer peaks.

The effect of nozzle design on heat transfer for impinging air jets has been the subject of several works: Lee and Lee [17] specially emphasized the effect of nozzle edge configurations, Brignoni and Garimella [18] studied the effect of nozzle inlet chamfering on pressure drop and heat transfer characteristics in a confined impinging air jet, Lee and Lee [19] conducted an experimental work on the effect of nozzle aspect ratio on the local heat transfer characteristics of elliptic impinging jets, Zhao et al. [20] studied numerically the heat transfer performance of square, elliptic, and rectangular jets. More recently, Zhou and Lee [21] examined the

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Nomenclature

D	equivalent diameter (m^2)
h	heat transfer coefficient ($W/m^2 K$)
L	nozzle length
Nu	Nusselt number
Nu_o	stagnation Nusselt number
q_{cd}	foil conduction flux (W/m^2)
q_{cv}	convective flux (W/m^2)
q_l	heat losses flux (W/m^2)
q_J	Joule heating flux (W/m^2)
q_{rad}	radiation heat flux (W/m^2)
Re	Reynolds number
r	radial distance from the stagnation point (m)
T_{ref}	reference temperature (°C)
T_w	surface temperature (°C)
T_∞	free stream temperature of the fluid flow (°C)
z	nozzle plate spacing (m)

Greek symbols

ϵ_w	emissivity

Acronyms

IR	infrared
K–H	Kelvin–Helmholtz

heat transfer and fluid flow characteristics due to impinging air jets from a sharp-edged rectangular nozzle of aspect ratio of 4.0. In 2009, Gulati et al. [22] studied the influence of the shape of different nozzles on local heat transfer distribution.

Lobed nozzles have also received considerable attention. Many studies have been conducted to enhance mixing, such as the works of Tilman and Presz [23], Power et al. [24], Presz et al. [25], Hu et al. [26] or Smith et al. [27]. Research into the physics of mixing within these devices has been the subject of numerous works. Paterson [28] was the first to measure the velocity and turbulent characteristics of a lobed nozzle. Ukeiley et al. [29,30] and Glauser et al. [31] also characterized a planar lobed mixer flow hydrodynamically. Although many important results have been obtained through these investigations concentrated on discovering the underlying physics of the lobed mixing, however, as Oyakawa et al. [32] mentioned, few works have been carried out to study the convection coefficient associated with impinging lobed jets.

In 1998, Oyakawa et al. [32] investigated how the impingement heat transfer characteristics are affected by the separations between the nozzle exit-to-plate when the jet issuing from a cross-shaped nozzle impinges on the target plate, Furthermore, they reported how the phenomenon of axis switching was also reflected on the flow and heat transfer on the target plate.

This paper presents an experimental characterization of lobed geometries to study the local heat transfer distribution in normally impinging gas jets for Reynolds numbers from 10,000 to 50,000 and non-dimensional jet-to-plate spacing (z/D) from 1 to 12. The quantitative infrared thermography associated with the thermofoil technique is applied. Local and average Nusselt numbers on the impinged surface are presented for the two nozzle configurations investigated and compared with a circular configuration and previous authors' works.

2. Experimental facility

Fig. 1 sketches the experimental test set-up. A jet is produced by blowing air by means of a compressor through a settling chamber ending with a converging section followed by a nozzle of short aspect ratio ($L/D = 4.5$). The detailed description of the setup can be found in [33].

Two lobed pipes were designed with an equivalent diameter of 20 mm and a circular pipe with the same diameter was also built for comparison purposes. The design in detail of the different types of nozzle tested is shown in Fig. 2. The first lobed geometry has three lobes and the second one has four lobes.

The jet is oriented perpendicularly to the target, which consists of a flat plate uniformly heated by Joule effect. It is made of a thin copper foil, 40 μm thick. The foil is chemically treated to produce a double spiral circuit, 1 mm wide with grooves of 1 or 2 mm, fixed on an epoxy sheet, less than 1 mm thick and with diameter of 0.3 m. The resistance circuits are connected to an electrical generator monitored by an ammeter and voltmeter. The infrared radiometer is a Thermocam SC3000 with an announced NETD of 0.03 °C at 30 °C. The camera scans the rear face of the foil, which is coated with a black paint of emissivity $\epsilon_w = 0.96$ to improve the

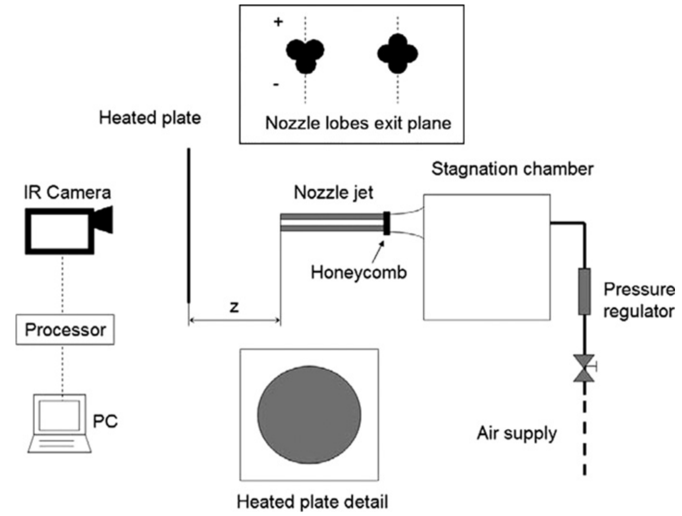

Fig. 1. Schematic of the impinging jet facility.

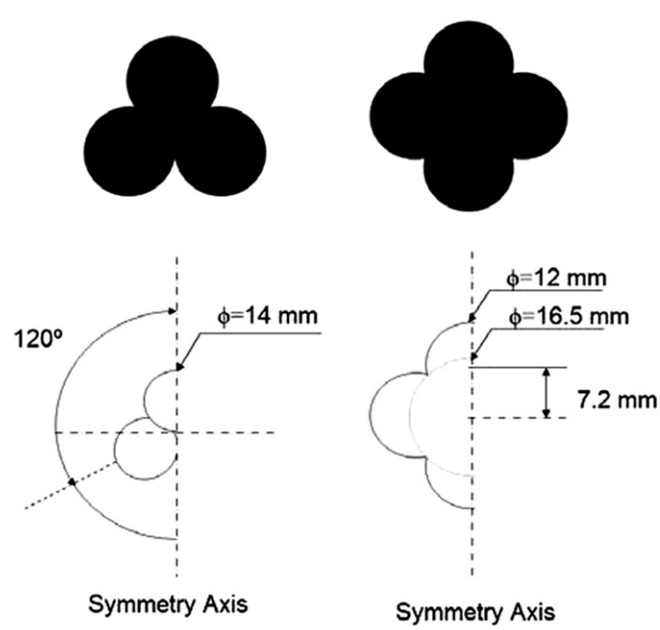

Fig. 2. Geometric details of the lobed geometries.