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Local heat transfer due to several configurations of circular air jets impinging on a flat plate with and without semi-confinement

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Abstract

A technique based on infrared thermography is used to determine the convective heat transfer on a flat plate on which either a single circular air jet or a row of jets impinged. The flat plate is heated using the thin-foil technique, which enables one to impose different convective heat fluxes. For each flux, a temperature distribution is recorded using a thermographic camera. After that, local heat transfers and local adiabatic temperatures are determined by means of a linear regression method. Parameters that are made to vary include jet injection temperature, the Reynolds number, spacing between adjacent jet, and the distance between the flat plate and jets orifices. In each case, two configurations are investigated: one with and the other without semi-confinement. Results show the independence of heat transfer coefficients and effectiveness from the jet injection temperature within the range studied. The influence of confinement on heat transfer coefficient is weak, but it has a great impact on effectiveness.

Keywords: Impingement; Jets; Thermography; Nusselt number

1. Introduction

Due to its ability to enhance heat transfer, jet impingement is used in a wide range of applications in order to cool, heat or dry surfaces. These applications include glass production, drying of textile and papers, annealing of metals, and cooling of electronic components. Impinging jets are also used in the cooling of particular regions of turbojets such as turbine blades and walls of combustion chambers.

In many of these applications, jet temperature is different from that of the environment in which is issuing. In that case, entrainment of the surrounding fluid into the jet can greatly affect jet temperature and consequently heat transfer from the impingement surface to the jet. Several parameters can affect this entrainment such as the number of jets and the semi-confinement.

Numerous experimental investigations have been performed on flow and heat transfer of jets impinging on flat plate and Jambunathan et al. [1], and Viskanta [2] carried out extensive literature surveys on jet impingement and the influence of different parameters.

But few studies have taken into account the effect of thermal entrainment on heat transfer to impinging jets. Striegl and Diller [3,4] measured heat transfer of up to two slot jets injected into a surrounding fluid whose temperature varied between injection temperature and plate temperature. Other researchers used the adiabatic temperature as a reference to calculate heat transfer coefficients. So, in the case of a single jet, Hollworth and Wilson [5] noticed that for $H/D \geqslant 5$, profiles of dimensionless adiabatic temperature did not depend on Reynolds number and jet-to-plate spacing. With the same apparatus, Hollworth and Gero [6] concluded that if adiabatic temperature is taken as the reference temperature, Nusselt number values are independent from $(T_j - T_\infty)$. Goldstein et al. [7] also used an adimensioned

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Nomenclature

D	jet diameter	m
e	impingement plate thickness	m
H	jet exit to impingement plate distance	m
h	heat transfer coefficient on front side	$W \cdot m^{-2} \cdot K^{-1}$
h_r	heat transfer coefficient on rear side	$W \cdot m^{-2} \cdot K^{-1}$
Nu	Nusselt number, $= hD/\lambda_{air}$	
P	jet center to center spacing	m
r^2	correlation coefficient of linear regression	
Re	Reynolds number, $= \rho V D/\mu$	
T_{aw}	adiabatic wall temperature	K
T_{inj}	injection wall temperature	K
$T_{w,f}$	front wall temperature	K
$T_{w,r}$	rear wall temperature	K
T_∞	ambient temperature	K
V_{inj}	injection velocity	$m \cdot s^{-1}$
X	streamwise coordinate from the center of the jet row	m
Y	spanwise coordinate from the central jet of the row	m
Z	coordinate from the impingement plate	m

Greek symbols

ε_{inj}	injection wall emissivity	
ε_w	impingement wall emissivity	
η	effectiveness, $= (T_{aw} - T_\infty)/(T_j - T_\infty)$	
λ_{air}	air thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
λ_w	wall thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
μ	dynamic viscosity	$Ns \cdot m^{-2}$
ρ_{air}	air density	$kg \cdot m^{-3}$
σ	Stefan–Boltzmann constant, $= 5.67 \times 10^{-8}$	$W \cdot m^{-2} \cdot K^{-4}$
$\varphi_{co,f}$	convective heat flux density on the front side	$W \cdot m^{-2}$
$\varphi_{co,r}$	convective heat flux density on the rear side	$W \cdot m^{-2}$
φ_{elec}	electrical flux density dissipated by Joule effect	$W \cdot m^{-2}$
$\varphi_{ra,f}$	radiative heat flux density on the front side	$W \cdot m^{-2}$
$\varphi_{ra,r}$	radiative heat flux density on the rear side	$W \cdot m^{-2}$

adiabatic temperature: the effectiveness. They showed that it was independent from the Reynolds number and $(T_j - T_\infty)$. Effectiveness decreased with the increasing of jet-to-plate spacing. Baughn et al. [8] used crystal liquid technique and confirmed the results of Goldstein.

Studies concerning a single row of jets are no more numerous than those investigating entrainment effect. Carcasci [9] used a visualisation smoke technique to study the flow of a row of air jets. A series of vortexes and adverse vortexes was observed at the meeting points of the jets. Gardon and Akfirat [10] studied local heat transfer and pressure of a row of slot jets on a flat plate. They pointed out an elevation of heat transfer midway between the jets impingement points. This elevation was visible only for small nozzle-to-plate spacing ($H/D < 6$). For large nozzle-to-plate spacing, loss of the identity of the jets was recorded. Koopman and Sparrow [11] used a naphthalene sublimation technique to measure local Sherwood numbers that can be converted to Nusselt number by employing the heat-mass analogy. Their study involved a row of four jets. Goldstein and Timmers [12] measured heat transfer distribution of a row of three jets on a flat plate using a liquid crystal method. Employing the transient liquid crystal technique, Yan and Saniei [13] investigated heat transfer of a pair of impinging jets and particularly the influence of the jet-to-jet spacing on local heat transfer. In all these studies, jet injection temperature was the same as ambient temperature. The only experimental investigation that dealt with the problem of a row of circular air jets with injection temperature different from the ambient one is that of Goldstein and Seol [14]. Nevertheless, the difference in temperature was weak (less than 20 degrees). Effectiveness was measured by heating the jet flow without heating the plate. The study confirmed that effectiveness is independent from the Reynolds number and $(T_j - T_\infty)$, but dependent on jet-to-plate spacing and of the jet-to-jet distance.

The effect of semi-confinement has been investigated by Obot et al. [19]. They concluded that semi-confinement reduces heat exchanges particularly, with small jet-to-plate spacing. Using Laser Doppler anemometry and liquid crystal, Ashforth-Frost and Jambunathan [20] reported that semi-confinement extends the potential core of a jet and reduces its stagnation point heat transfer.

This study presents an experimental investigation of thermal entrainment with either a single jet or a row of jets. All jets are circular air ones. The jet exit diameter is 10 mm. The range of the different parameters is:

- $H/D = 2$; 5;
- $P/D = 4$ (7 jets); 8 (3 jets);
- $Re = 23\,000$;
- $0 \leqslant X/D \leqslant 7$;
- $20\,°C \leqslant T_j \leqslant 60\,°C$;
- $20\,°C \leqslant T_\infty \leqslant 25\,°C$.

The effect of semi-confinement on impingement heat transfer has also been investigated.