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Evidence of flow vortex signatures on wall fluctuating temperature using unsteady infrared thermography for an acoustically forced impinging jet

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ABSTRACT

Infrared thermography is used to investigate unsteady wall temperature in the configuration of a round jet impinging orthogonally on a uniform flux heated plate. The Reynolds number is 28,000 and the orifice to plate distance is $H/D = 3$. The flow can be forced using a loudspeaker located on the top of the injection module. Two forcing Strouhal numbers are then studied, $\mathrm{St}_{\mathrm{LS}} = 0.26$ and 0.79. The unprocessed results reveal a first propagation mode of the fluctuating temperatures along the impingement plate. It does not depend on the forcing and is characterized by very low frequencies and corresponds to the propagation of warm and cold bubbles in privileged azimuthal directions. Their amplitudes reach 0.5K. Using processing tools such as phase averaging or high-pass filtering, another propagation mode is revealed: the radial spread of cold and warm fronts, linked to the convection of vortices along the impingement plate. Indeed, their characteristic frequencies and convection velocities correspond to those of the vortices along the plate and the amplitudes reach 0.1K.

1. Introduction

Due to its high heat transfer rate, jet impingement is used in a wide range of applications where extensive cooling or heating is necessary. These applications include glass production, anti-icing systems, cooling of turbojet engine walls or electronics. Consequently, impinging jet flow structure and heat transfer have been studied extensively both experimentally and numerically. Martin (1977), Downs and James (1987), Jambunathan et al. (1992), Viskanta (1993) or, more recently, Zuckerman and Lior (2006) carried out extensive literature surveys on jet flow and heat transfer and the influence of different parameters.

All these studies led to the jet flow division into three zones. The first one, the free jet corresponds to flow before the impingement. It can be divided into two parts: the potential core surrounded by the shear layer. In the potential core, the mean velocity and temperature are still the same as at the nozzle exit. On the contrary, the shear layer is intrinsically unstable. The jet flow's second zone is the stagnation zone where the jet flow is turned radially outward. Finally, away from the impinging point, there is the third jet flow zone called wall jet as the jet becomes similar to a wall flow. In this zone, velocity decreases.

One of the most notable structures of the impinging jet flow are the shear layer vortices. In fact, waves appear near the nozzle lip and their growth leads to the forming of roll-up vortices. Crow and Champagne (1971) have shown that the frequency of those vortices is $\mathrm{St} = fD/u_0 = 0.3$. In the stagnation zone, shear layer vortices are deflected and roll along the impingement plate. Their mean distance to the impingement plate depends on jet-to-plate distance (Roux et al., 2011): for a small jet-to-plate distance, they come closer to the plate. For a low Reynolds number jet, Popiel and Trass (1991) have visualized secondary vortex structures in the zone where vortices are close to the wall ($r/D \approx 2$).

High jet impingement heat transfer is the consequence of such flow field and, in particular, of the interaction of vortices with the wall.

First of all, the main heat transfer influence parameters are the injection Reynolds number Re (Goldstein et al., 1986) and dimensionless injection-to-plate distance H/D. Heat transfer globally increases with the Reynolds number, whereas the influence of H/D is much more complex. Two different types of H/D can be

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Nomenclature

A	amplitude of the velocity excitation (–)
D	jet nozzle diameter (m)
f	frequency (Hz)
f_{LS}	excitation frequency (Hz)
f_{char}	characteristic frequency (Hz)
H	orifice-to-plate distance (m)
Nu	Nusselt number (–)
N_{φ}	number of samples having the phase φ in a periodic signal (–)
Q	mass flow ($\mathrm{kg\,s^{-1}}$)
r	radial coordinate (m)
Re	Reynolds number (–)
s	Curvilinear abscissa following vortices trajectory (m)
St	Strouhal number (–)
t	time (s)
t_{φ}	time at phase φ in a periodic signal (s)
T	temperature (K)
$\overline{T}$	time averaged temperature (K)
$\langle T \rangle$	phase averaged temperature (K)
$\langle \check{T} \rangle$	azimuthal average of $\langle T \rangle$ (K)
T'	fluctuating temperature (K)
$\widehat{T}$	high pass filtered temperature (K)
$\check{T}$	azimuthal average of $\widehat{T}$ (K)
T_{ad}	adiabatic wall temperature (K)
T_{amb}	ambient temperature (K)
$\bar{u}$	time averaged velocity ($\mathrm{m\,s^{-1}}$)
u_0	nozzle outlet velocity ($\mathrm{m\,s^{-1}}$)
u_z	axial velocity ($\mathrm{m\,s^{-1}}$)
x, y	Cartesian coordinate system on the impingement plate (m)
z	axial coordinate (m)
λ_{air}	air thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
φ	phase of a periodic signal (–)
φ_{co}	convective heat flux density on the front side ($\mathrm{W\,m^{-2}}$)
ρ	air density ($\mathrm{kg\,m^{-3}}$)
ω	pulsation ($\mathrm{s^{-1}}$)
Ω	average vorticity ($\mathrm{s^{-1}}$)

defined: high ($H/D > 5$) and low ($H/D < 5$), depending on the jet potential core length.

For high injection-to-plate distances, heat transfer reaches its maximum at the impinging point and then decreases (Baughn and Shimizu, 1989).

For a small jet-to-plate distance, heat transfer has a similar variation except from two local maximum. The first maximum is localized close to the impinging point of the jet shear layer ($r/D \approx 0.5$) and consequently the heat transfer global maximum is no higher at the impinging point. It is not noticed in all studies: in experiments by Baughn and Shimizu (1989) or Fénot et al. (2005) this maximum is not present. Several explanations have been suggested (Lytle and Webb, 1994; Roux et al., 2011) but the most plausible is the influence of the injection: for a contraction nozzle, the local maximum is visible whereas for a long tube injection, the heat transfer maximum is at the impinging point. This is probably due to injection velocity profile which is flat for the contraction nozzle, whereas for the long injection nozzle, the velocity reaches its maximum at the center of the jet. Also, for low injection-to-plate distance and high injection Reynolds number, a second maximum can occur. It is recorded by many authors (Baughn and Shimizu, 1989; Roux et al., 2011; O'Donovan and Murray, 2007a). The position of this secondary maximum depends on the study but is always close to $r/D = 2$. The explanation for this Nusselt number peak is relatively controversial. Gardon and Akfirat (1966) associated this second Nusselt number maximum with the transition from a laminar to a turbulent boundary layer. Goldstein et al. (1986) recorded an adiabatic wall temperature minimum for the same r/D and proposed to link the peak with it. Hadziabdic and Hanjalic (2008) took note of separation bubbles due to interaction of shear layer vortices with the impingement wall. They imputed to these bubbles the Nusselt number minimum situated at $r/D \approx 1.6$ and to the destruction of these bubbles the maximum Nusselt number at $r/D = 2$.

So, vortices are transiently convected along the shear layer and the wall jet flow. Those transient structures seem to induce steady state heat transfer enhancement. But it is not clear if this mean heat transfer enhancement is due to thermal fluctuations or if the link between transient flow structures is more complex. Unfortunately, transient heat transfer studies are relatively few in particular concerning jet impingement. O'Donovan and Murray (2007b) have studied both mean and fluctuating Nusselt numbers for a jet impinging on a plate with an imposed uniform temperature. They notice an increase of RMS Nusselt number at the impinging point for high injection-to-plate spacing ($H/D = 6$) and around $r/D = 1.8$ (position of the second local heat transfer maximum) for small one ($H/D = 3$). Moreover, they compared the heat transfer spectra to velocity spectra measured by LDV (3 mm away from the plate). They show that axial velocity fluctuations exhibit higher coherence with heat transfer signal particularly for $r/D = 1$. Unfortunately, the LDV technique limits their study to a small number of discrete measurement point. Another wall temperature temporal measurement study has been done by Narayanan and Patil (2007) on an unperturbed slot jet impinging on a uniform heat flux density plate, using infrared thermography. The jet Reynolds number is 22500. A proper orthogonal decomposition (POD) analysis was performed on the data set, which enables to identify the number of dominant modes of variability in the fluctuating temperature time series. The authors show that low orifice-to-plate distances ($H/D = 0.5$) result in high temperature fluctuations at the location of the secondary peak. These fluctuations can then be estimated using only two POD modes in the reconstruction.

As the heat transfer characteristics seem to be linked to the shear layer vortices, several authors tried to control these vortices in order to optimize and better understand heat transfer on an impinging round jet (Sheriff and Zumbrunnen, 1994; Mladin and Zumbrunnen, 2000; Gau et al., 1997). Liu and Sullivan (1996) showed that perturbations at St = 0.86 and 1.59 lead to different heat transfer evolution. Hwang et al. (2001) and Hwang and Cho (2003) studied the influence of different forcing parameters, such as forcing Strouhal number (from 1.2 to 4), vortex control method (main jet or shear layer excitation) or velocity ratio.

In the present study, the configuration is a round jet impinging normally on a flat heated plate. The flow can be forced using a loudspeaker, which enables to amplify some frequencies in the turbulence spectrum, that is to say to intensify vortices corresponding to these frequencies. The wall temperature fluctuations are then measured using infrared thermography. Post-processing tools such as phase averaging or high-pass filtering are used to educe and analyze the effect of vortices passing along the wall on wall temperature fluctuations.