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Investigation of an impinging heated jet for a small nozzle-to-plate distance and high Reynolds number: An extensive experimental approach

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ABSTRACT

The present work aims at investigating a particular impinging jet configuration throughout a comprehensive experimental approach. A preheated air jet at 130 °C issues a fully developed circular pipe at Reynolds number 60,000 and discharges in the laboratory room to impinge a flat plate located 3 diameters downstream. The description of the velocity field and the complete Reynolds stress tensor is provided by stereoscopic particle image velocimetry (S-PIV) and Laser Doppler Velocimetry (LDV) measurements. For the first time, data are reported for the mean and fluctuating temperature of an impinging jet configuration with the help of cold-wire thermometry (CWT) measurements. The heat transfer distribution on the impinged plate is determined through an inverse method based on infrared thermography measurements on the rear face of the plate. The agreement between S-PIV and LDV measurements is shown excellent over the whole flow field. The measured Nusselt number distribution exhibits a secondary maximum at $r/D = 2$, as observed in previous experiments for short impinging distances. Flow dynamics is characterized through a spectral analysis of time-resolved measurements while flow topology features are identified through coherent structure detection based on S-PIV spatially-resolved instantaneous velocity fields. This analysis shows that the jet column mode, associated with a Strouhal number of 0.4, plays a key role in the primary structure dynamics.

1. Introduction

During the last 50 years, the impinging jet configuration has received considerable attention for two main reasons. Firstly, the high heat transfer rate experienced by the targeted surface explains its widespread use in industrial applications where thermal efficiency is of prior interest, such as in turbine blade cooling or aircraft leading edge heating for anti-icing purpose. Secondly, the flow characteristics of impinging jets have been proved complex to predict through numerical simulation [49,14] despite the geometric simplicity of the configuration. Hence, the impinging jet configuration is still a reference test case for turbulence modeling. In this context, the validation process requires accurate and well-documented experimental databases providing complete information about the flow field and heat transfer rates. The aim of the present study is to provide a joint description of both the velocity and temperature fields along with the heat transfer coefficient distribution of a little-studied impinging jet configuration. The experimental data provide both mean and fluctuating fields together with the flow topology and a spectral characterization.

1.1. State-of-the-art

The major reviews related to jet impingement are provided by Martin [31], Jambunathan et al. [24], Viskanta [46] and more recently Carlomagno and Ianiro [8]. From these reviews it was shown that the flow characteristics and the heat transfer distribution on the impinged plate are influenced by various parameters such as the jet Reynolds number, the impingement height, the confinement, the nozzle shape or the turbulence intensity at the nozzle exit. The impinging-jet flow is generally split into three zones that feature different characteristic behaviors: the free jet, the stagnation and the wall jet regions (Fig. 1).

The early contributions of Gardon and Akfirat [16] and Hoogendoorn [23] evidenced the importance of the jet turbulence in heat transfer processes. The jet turbulence principally depends on the jet exit conditions. As jet exit, most studies used either convergent nozzles, for which turbulence is only confined in thin boundary layers, or fully developed pipe flow. The dependence of the heat

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Nomenclature

Bi	Biot number (–)
C_p	plate specific heat capacity (kgm^2 s^{-2} K^{-1})
D	pipe diameter (m)
e	plate thickness (m)
Fo	Fourier number (–)
h	convective heat transfer coefficient (Wm^{-2} K^{-1})
H	impingement height (m)
k_f	fluid thermal conductivity (Wm^{-1} K^{-1})
k_p	plate thermal conductivity (Wm^{-1} K^{-1})
L	impinged plate length (m)
Nu_D	diameter-based Nusselt number (–)
Nu_L	plate length-based Nusselt number (–)
P	frequency-peak emergence criterion (–)
q_c	convective heat transfer (Wm^{-2})
R	pipe radius (m)
Ra_L	plate length-based Rayleigh number (–)
Re_D	diameter-based Reynolds number (–)
Re_τ	pipe friction Reynolds number (–)
St_D	diameter-based Strouhal number (–)
t	time (s)
T	temperature (°C)
T_f	film temperature (°C)
$T_{\mathrm{ref.}}$	reference temperature (°C)
T_{aw}	adiabatic wall temperature (°C)
T_e	ambient temperature (°C)
T_j	jet exit temperature (°C)
T_w	wall temperature (°C)
T_w^{rear}	rear-face wall temperature (°C)
u_x, u_r, u_θ	cylindrical velocity components (ms^{-1})
u_x, u_y, u_z	cartesian velocity components (ms^{-1})
u_τ	friction velocity (ms^{-1})
U_j	jet bulk velocity (ms^{-1})
U_m	jet centerline velocity (ms^{-1})
x, y, θ	cylindrical coordinates (m,m,rad)
x, y, z	cartesian coordinates (m,m,m)

Greek symbols

α	plate thermal diffusivity (m^2 s^{-1})
β	coefficient of thermal expansion (K^{-1})
Δt	time step (s)
ΔT	jet to ambiant temperature difference (°C)
Δx	spatial discretization in plate thickness (m)
η	effectiveness (–)
ν	kinematic viscosity (m^2 s^{-1})
ρ_p	impinged plate density (kgm^{-3})

Other symbols

$\langle\rangle$	ensemble-averaged quantity
$'$	fluctuating part
RMS	root-mean-square

transfer on the Reynolds number Re_D and the nozzle-to-plate spacing H/D was thoroughly investigated through the experiments Lytle andWebb [29], Hofmann et al. [22], Katti and Prabhu [26], Lee and Lee [28] that followed the pioneering work of Baughn and Shimizu [2]. The considered jet Reynolds number range was $5000 < \mathrm{Re}_D < 150,000$ and the nozzle-to-plate spacing H/D varied between 0.25 and 10. The heat transfer coefficient was shown to present a maximum at the stagnation point, the level of which depends on H/D. The optimal heat transfer coefficient was reached for $H/D = 6$, which appears to coincide with the potential core length of the jet [16]. For low nozzle-to-plate distances $H/D < 4$, the radial distribution of heat transfer coefficient was shown to exhibit a secondary peak [2]. Its location, which varies from $r/D = 1.2$ to $r/D = 2.1$, and intensity both depend on the Reynolds number and the nozzle-to-plate distance. Several explanations for its appearance were proposed. The today most accepted interpretation relates the secondary maximum to the interaction of primary vortices, originated from the jet shear layer, with the impingement plate. This hypothesis is supported by the recent numerical simulations of Hadžiabdić and Hanjalić [20] and Dairay et al. [12] and the experiments of O'Donovan and Murray [36] through simultaneous acquisition of heat transfer and velocity.

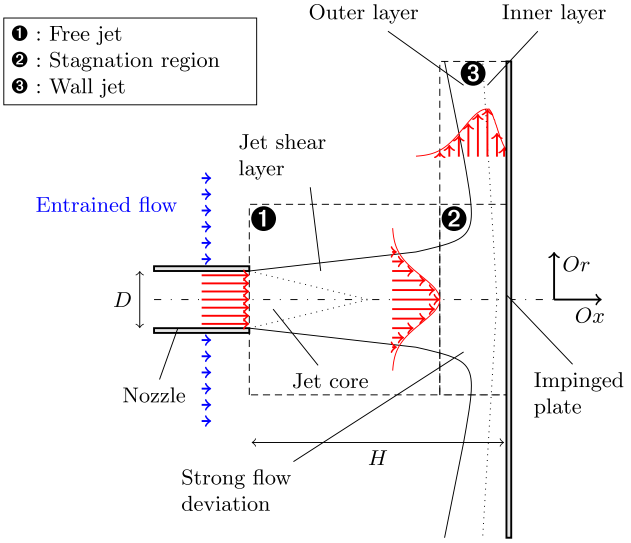

Fig. 1. Schematic description of a round jet impinging on a flat plate.

The mean and fluctuating properties of the flow field were first addressed by [10] through hot-wire anemometry measurements (HWA) for a jet which issues a fully developed long pipe at $\mathrm{Re}_D = 23,000$ and 70,000, for H/D ranging from 2 to 10. The experiments of Nishino et al. [35], which were based on particle tracking velocimetry, provided important information about turbulence statistics in the stagnation region such as regions of negative production of turbulent kinetic energy. Guerra et al. [19] performed both HWA and thermocouple measurements of the mean temperature over a heated plate for $H/D = 2$ and $\mathrm{Re}_D = 35,000$. Geers [17] carried out both LDV and PIV measurements on Cooper's configuration. This configuration was again investigated by Tummers et al. [43] through LDV measurements which were specifically tuned for near-wall exploration.

In the last decade, the improvement in the PIV capabilities led to numerous investigations which focused on the impinging jet flow topology [21,39]. Time-resolved tomographic PIV was applied on low-Reynolds number ($\mathrm{Re}_D < 5,000$) impinging jet at short impinging distances by Violato et al. [45] and Sodjavi et al. [40]. These studies revealed the three dimensional large scale turbulent structures generated in the free jet and their subsequent interaction with the plate, leading to creation of counter-rotating secondary vortices in the near wall region. This interaction, often referred to as unsteady separation, was first introduced by Didden