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An experimental study of a turbulent jet impinging on a flat surface

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ABSTRACT

The flow characteristics of an isothermal turbulent jet impinging normally on a flat plate was studied experimentally using hot-wire anemometry. The air jet discharged from a round pipe with an inner diameter D and the distance between the pipe exit and the flat impingement plate was 9D. The Reynolds number, based on the jet centerline velocity at pipe exit and the pipe inner diameter, was 10,338. Measurements were performed in the free- and wall-jets, mean velocity, RMS, Reynolds shear stress, higher-order moments of velocity fluctuations, dissipation spectrum as well as spatial characteristic scale results being presented. Moreover, a multiscale analysis method based on wavelet transform was applied to gain deeper insight into the multiscale turbulent structures and to extract the most essential scales governing the development of the turbulent flow structures of the impinging jet. The experimental results show that the normal velocity fluctuations have the greatest skewness and the highest intermittency in the mixing region and this characteristic is more prominent downstream the pipe exit. The radial velocity fluctuations at a small distance from the flat surface trend towards Gaussian values far away the jet centerline. The strongest dissipation structures grows with larger scales and lower frequencies far away from the pipe exit, and the frequency range of the dissipation structures is reduced far away from the jet centerline together with the spatial distribution of the dissipation structures expanding with larger scales and lower frequencies. The scales in the center of the mixing region have the most energy, from which the scales belonging to the inertial range have a trend to shift to the larger scales with the increasing radial traverse, thus the scales of the coherent structures belonging to the dissipation region get more as well as larger. The scales belonging to the inertial range in the wall-jet region tend to the larger scales with the increasing normal traverse.

1. Introduction

Impinging jets have received considerable attention over the past few decades. They are used in a wide variety of industrial applications due to their inherent high heat transfer rate, including tempering of glass plate, annealing of metal sheets, drying of textile and paper products, and cooling of heated components in gas turbine engines and electronic instruments, which are also employed in mass transfer applications, such as mine ventilation, tunneling operations, paint spraying and cavitation drilling. Furthermore, they are relevant to vertical/short-takeoff-and-landing (V/STOL) aircrafts that take off or land with little or no forward momentum. Impinging jets also present an important test case for the development and validation of mathematical models of turbulent flow from a turbulence modeling perspective.

Numerous studies of jet impingement have been reported, and comprehensive reviews are available in the literature [1–5]. This simple but generic flow can be characterized as the combination of three distinct regions: free-jet region, impingement region and wall-jet region. More than two decades ago, Cooper et al. [6] studied the turbulent flow field of a single jet impinging orthogonally on a large planar surface. Data for the mean velocity profile in the vicinity of the surface and also for the three Reynolds stress components were presented. The results obtained were referred to in the companion paper by Craft et al. [7] to assess and examine the performance of four different turbulence models: the κ–ε model and three-second order moment closures. Kim [8] investigated the flow and heat transfer characteristics of a heated axisymmetric round jet impinging on a normal plate, and the first stage of his study described the flow field of three-dimensional mean flow and turbulent flow quantities in free-jet, stagnation and wall-jet regions, and the second stage presented the convective heat transfer coefficient distributions on the impingement plate. More recently, Tummers et al. [9] reported on detailed measurements

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Nomenclature

C_i	constants in the polynomial equation of calibration curve
D	inner diameter of jet pipe
$D_{11}(\kappa_1)$	dissipation spectrum
E_b	probe bridge voltage
$E(f)$, $E_{jj}(\kappa_1)$, $E_{11}(\kappa_1)$	energy spectrum
f	frequency
H	distance between pipe exit and impingement plate
L	integral lengthscale
$R_{jj}(\tau)$	autocorrelation function
u	normal velocity fluctuation
u_{rms}	root mean square of normal velocity fluctuation
u_η	Kolmogorov velocity scale
U	normal mean velocity
U_c	local centerline mean velocity
U_{ec}	jet centerline mean velocity at pipe exit
U_{prb}	velocity across the probe
υ	radial fluctuating velocity
υ_{rms}	root mean square of radial velocity fluctuation
V	radial mean velocity
x	radial distance from jet centerline
y	normal distance from impinging plate
ε	dissipation rate of turbulent kinetic energy
κ_1	wave number
λ	Taylor microscale
ν	kinematic viscosity
η	Kolmogorov lengthscale
τ	time interval
$\langle\ \rangle$	mean time average

of the turbulent flow in the stagnation region of a single round jet impinging on a flat plate. The mean velocity components and Reynolds stresses were determined by using a two-component LDA. Moreover, a modified one-component LDA was used to perform near wall measurements and PIV measurements were taken to study instantaneous reversals in the near wall region. Loureiro and Silva Freire [10] employed LDA to characterize the mean and turbulent fields including the wall shear stress, and investigated the influence of some governing parameters on the near wall characteristics of a confined circular jet impinging over a smooth flat plate. The wall shear stress and the vortex dynamics in a circular impinging jet for Reynolds numbers of 1260 and 2450 are studied by El Hassan et al. [11]. The wall shear stress is obtained at different radial locations from the stagnation point using the polarographic method and the velocity field is given from the TR-PIV technique in both the free jet region and near the wall in the impinging region. The distribution of the momentum thickness is also inspected from the jet exit toward the impinged wall. The flow characteristics of a single jet impinging on a protrusioned surface were investigated using PIV and numerical simulation by Zhang et al. [12], and the heat transfer characteristics were explored on the basis of the numerical results. Ozmen [13] investigated the effects of Reynolds number, nozzle-to-plate spacing and jet-to-jet spacing on the flow structure characteristics of confined twin jets issuing from the lower surface and impinging normally on the upper surface. Measurements were performed using PIV, flow visualization using fluorescent dye and infrared thermography by Kim and Giovannini [14] to study a turbulent axisymmetric air jet impinging on a square cylinder mounted on a flat plate, and turbulence statistics and flow's topology were investigated. Shim et al. [15] carried out the velocity field measurements by using PIV and studied the structural characteristics of an impinging jet on a circular cylinder for two different nozzle height at the same jet Reynolds number. Electrodiffusion and particle image velocimetry (PIV) measurements were made to compare the flow dynamics and mass transfer by Meslem et al. [16] in impinging circular jet issuing respectively from a convergent nozzle and a square-edged orifice nozzle with the same exit diameter at a low Reynolds number of 1360 based on nozzle diameter and exit bulk velocity. Katti [17] studied the effect of jet-to-plate spacing and low Reynolds number on the local heat transfer distribution to normally impinging submerged circular air jet on a smooth and flat surface and the local heat transfer characteristics are obtained using thermal images from infrared thermal imaging technique. It was observed that at lower Reynolds numbers, the effect of jet to plate distances covered during the study on the stagnation point Nusselt numbers is minimal. At all jet to plate distances, the stagnation point Nusselt numbers decrease monotonically with the maximum occurring at a nozzle-to-plate space of 0.5*d* as opposed to the stagnation point Nusselt numbers at high Reynolds numbers which occur around a nozzle-to-plate space of 6*d*. The heat transfer to an obliquely impinging air jet was investigated by O'Donovan [18]. Distributions of the mean and the fluctuating component of the surface heat transfer were reported for a jet Reynolds number of 10,000, nozzle to impingement surface distance from 2 to 8 and impingement angle from 30° to 90°. The study showed that the vortical characteristic of the flow was vary considerably with the angle of impingement; depending on the distance between the near nozzle edge and the impingement surface, vortices at different stages of development impact with the target surface.

Wavelet transforms, based on group theory and square integrable representations, allow one to unfold a signal or a field into both space and scale, and possibly directions. They use analyzing functions, called wavelets, which are localized in space. The scale decomposition is obtained by dilating or contracting the chosen analyzing wavelet before convolving it with the signal. Wavelet transforms are a popular signal processing technique which have received wide attention over the past few years. Comprehensive reviews of the wavelet transforms technique applied in turbulence are available in Farge [19,20]. Li et al. [21,22] employed one-dimensional continuous and discrete wavelet transforms to analyze the experimental velocity signals of turbulence in the dimensions of time and frequency. Li [23–26] proposed the wavelet correlation method and wavelet spatial statistics based on wavelet transform, and revealed the multiscale structure of eddy motion in the turbulent shear flow in both Fourier and physical spaces. Li et al. [27] developed an application of two-dimensional orthogonal wavelets to the turbulent images for the identification of the multiscale turbulent structures. The two-dimensional orthogonal wavelet transform was applied to the LIF image of lobed mixing jet for identifying the multiscale turbulent structures, and a wavelet-based vector multiresolution technique was developed and applied to a high-resolution stereoscopic particle image velocimetry system for studying the three-dimensional multiscale structure features of the lobed jet mixing flow by Li et al. [28]. Camussi [29] applied wavelet decomposition to the longitudinal and transverse velocity data series obtained by X-probe hot-wire anemometry measurements for the coherent structures identification in the near region of a turbulent jet flow. Camussi [30] applied wavelet transform to bidimensional velocity fields obtained by PIV measurements to extract and characterize the swirling motion associated with the coherent structures.