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The effect of coflows on a turbulent jet impacting on a plate

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ABSTRACT

The study examines the dynamic and the turbulent behavior of a plane jet impinging normally on a flat target plate in a flow at rest or in a coflow stream. First, numerical and experimental investigations of the characteristics of a turbulent plane jet impinging on a flat surface in still air are depicted. The measurements are conducted using Particle Image Velocimetry (PIV). A comparison has been carried out between numerical results of three turbulence closure models (k–ε standard model, RNG k–ε model and a second-order model RSM) and experimental data. It has been found that the second order turbulence model (RSM) reasonably predicts the mean flow properties of the flow field. Next, a numerical study of the flow field of an impinging jet in a coflow stream is conducted. The study of the jet in a no-directed coflow stream shows the presence of a phenomenon of recirculation near the flat plate. In addition, the study focuses on the influence of the coflow velocity ratio on the behavior of an impinging jet and the influence of the directed co-flow on various physical parameters such as the mean and the turbulent quantities. The results clearly show that the coflow stream imposed noticeable restrictions on the spreading of the impinging jet and decreases considerably the entrainment of air jet.

1. Introduction

For more than half a century [1], the impinging flows over a plane surface were subject to great interest in several industrial and engineering applications. For instance, impinging jets are encountered in aeronautics [2], in cooling systems [3,4] and the drying of textiles, paper and foodstuffs [5].

Many authors [6,7,8] reported interesting phenomena about the development of the impinging jet. Generally, the flow structure of an impinging jet is characterized by three regions: the free jet, the impact zone, and the wall jet region. In the first region, the behavior of the impinging jet is the same as the free jet where the plate does not affect the flow. This region extended from the nozzle up to a certain distance from the surface and can be divided, in turn, into the potential core region, the developing flow region and the developed flow region. The second zone, the stagnation flow (impingement) region, includes the interaction between the jet and the plate producing a strong deceleration of the flow and the jet velocity decay intensifies on approaching the plate. In addition, previous research noted loss of the kinetic energy that is converted into pressure energy. The increased pressure is then transformed into the radial momentum of the fluid and the boundary

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Nomenclature

Symbols

e	width of the jet nozzle	mm
l	length of jet nozzle	mm
h	distance between pipe exit and impingement plate	mm
Re	Reynolds number ($\mathrm{Re} = v_j \times d_h/\nu$)	
d_h	hydraulic diameter	m
R	ratio velocity ($R = v_{co}/v_j$)	
$\overline{u_i' u_j'}$	Reynolds stress	m^2/s^2
u, v, w	velocity components along x, y, and z directions	m/s
x, y, z	cartesian coordinates	m

Greek symbols

ν	kinetic velocity of air	m^2 s
α	deviation angle	°

Subscripts

j	exit of the jet
co	coflow

Superscripts

$\bar{}$	Reynolds average
$\tilde{}$	Favre average

layer thickness tends to keep constant. After this zone, and where the velocity of the jet is parallel to the plate, the wall jet region starts. The fluid in this region spreads radially over the plate, with a maximum radial velocity and with growth of the boundary layer.

Numerous studies of plane impinging jets have been conducted both experimentally and numerically over the last decades. Most previous studies were more focused on the mean fluid flow characteristics [9–12]. Sakakibara et al. [13] have presented experimental comprehensive reviews of the dynamic and turbulent impinging jets. They studied the heat transfer behavior of a turbulent jet impinging on the plate with special attention to the stagnation region. They visualized the dynamic behavior of an impinging rectangular jet. The nozzle exit of the jet had a uniform velocity profile. They simultaneously used a digital particle image velocimetry (PIV) and laser-induced fluorescence (LIF). A counter-rotating vortex pairs is formed adjacent to the stagnation region. The authors conclude that the streamwise vortex pair is transported from the free-jet region to the stagnation region and the vorticity is amplified by the main stream in the vicinity of the wall.

Angioletti et al. [14] continued research in this area. To characterize the flow field in jet impingement configurations, a combined approach has been employed: a mass transfer experiment and a digital visualization technique. A jet velocity range is spanned to ensure flow regime transition. In their experiments, coherent structures are observed both at the interface of the free jet and upon impingement at the plate. Therefore, a PIV system is exploited to extract the two-component velocity instantaneous information. The instantaneous velocity field reveals that, vortices are created on the stagnation zone side even for the smallest Re and nozzle height $h = e$ values. The visualizations emphasized a sequence of discrete toroidal vortices. These vortices are created along the interface, between the jet and the surrounding air, and subsequently impinge on the plate.

The near-wall behavior of turbulent impinging jets has been studied experimentally by Koched et al. [15] using visualization, a PIV technique. This study is performed for a submerged turbulent water slot jet impinging normally on a flat plate. The PIV measurements are carried out for four different Reynolds numbers; 3000, 6000, 11000 and 16000. They put an emphasis on the flow field characteristics and on the flow structure in the impingement region where the transfers of heat/mass occur. They tried to understand the flow structure by employing the vortex detection criteria on the instantaneous velocity vector field. In addition, they found that the fraction of vortices having clockwise rotation direction is close to the proportion of vortices having a counter clockwise rotation direction.

Special attention was brought over the flow field visualization using other techniques of measurements. Gutmark and Wygnanski [16] utilized hot wire technique to measure mean velocity and the turbulent stresses of a plane turbulent impinging jet. All the velocity measurements were done using DISA hot-wire anemometers and conventional analog equipment for signal processing. The flow velocity at the exit is 35 m/s and the Reynolds number is 30,000. The plate on which the jet impinges is installed 100 slot widths downstream of the nozzle. Kuang et al. [17] contributed for similar configuration by employing the laser Doppler velocimetry (LDV). Both papers provided a qualitative and quantitative description of the resulting flow field and they identified the different regions and the turbulence structure.

An experimental and analytical study of a plane turbulent jet impinging on a flat wall was carried out by Beltaos and Rajaratnam [18]. Eight experiments were conducted with the jet Reynolds number varying from 5270 to 9400. They focused on