Building and Environment 84 (2015) 238–250

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Experimental investigation of the flow behavior of an isothermal impinging jet in a closed cabin

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ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form
23 October 2014
Accepted 25 October 2014
Available online 31 October 2014

Keywords:
Impinging jet
Flow behavior
Free-jet region
Wall-jet region
Multi-scale analysis

ABSTRACT

The impinging jet concept has been proposed as a new ventilation strategy for use in office and industrial buildings. To improve the performance of impinging jet ventilation system to create a better thermal comfort environment, quantifying the detailed information of the flow behavior of impinging jet should be an essential prerequisite. This study reports an experimental study of an isothermal turbulent jet impinging normally on a flat surface in a closed cabin. The air jet issued from a round pipe with an inner diameter *D*. 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 using cross hot-wire anemometry, mean velocity, turbulence intensity, and power spectrum results being presented. In addition, a multi-scale analysis technique based on empirical mode decomposition was used to analyze and gain deeper insight into the multi-scale characteristics of coherent structures of the jet impingement on flat surface.

1. Introduction

The quality of indoor environment directly affects occupants' health, comfort and productivity. Air distribution systems hence play crucial roles in maintaining a healthy and comfortable indoor environment. The way of distributing fresh air from supply diffuser into the confined space has a significant impact on the generated airflow pattern, which is essentially related to the indoor environment condition. For mixing ventilation (MV), conditioned air is supplied at high velocity from the ceiling level, and the contaminated air is evacuated through the exhaust outlets. However, MV has its limitations especially in a negative effect on thermal comfort, draught sensation and control the dissemination of airborne contaminants and biological active particles. It also suffers from unnecessary increase in the consumption of energy needed when delivering conditioned air to a partially occupied open space to keep it at uniform temperature and homogenous indoor air quality [1,2]. Displacement ventilation (DV), benefiting from the stratification principle [3], is a relatively efficient ventilation system which can provide a much better indoor air quality compared with MV. While, it also has some shortcomings such as the large vertical temperature difference, the big air supply inlet and the inefficiency in the control of floor level contaminants [4,5]. Furthermore, DV can only be operated in a cooling mode and is not suitable for winter heating. As a supplement to the MV and DV systems, personalized ventilation (PV) delivers clean and fresh air directly to the occupant's breathing zone so that it can prominently improve the inhaled air quality.

Recently, a new type of ventilation system, termed impinging jet ventilation (IJV), has received considerable attention [6–12]. Due to the potential for providing better air distribution and energy-efficient operation, as well as its flexibility for both cooling and heating, IJV has developed as an alternative to conventional ventilation systems used in office environments and industrial premises [6,9]. In impinging jet ventilation, a high momentum air jet is issued downwards, strikes the floor and spreads over it, thus distributing fresh air along the floor in the form of a thin layer. This method enables the air jet to overcome the buoyancy force generated from heat sources and reach further regions. However, the draught sensation must be taken into account when designing such systems, since the high velocity might occur in the occupied zone. Therefore, the flow behavior of impinging jet should be

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http://dx.doi.org/10.1016/j.buildenv.2014.10.024
0360-1323/

Nomenclature

D	inner diameter of jet pipe
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
$h_{1/2}$	half thickness of wall-jet (to 50% of V_m)
K_i	constants in the polynomial equation of calibration curve
$r_{1/2}$	half thickness of free-jet (to 50% of U_m)
$R_{jj}(\tau)$	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_{ec}	jet centerline velocity at pipe exit
U_m	maximum normal mean velocity
U_{prb}	velocity across the probe
υ	radial fluctuating velocity
υ_{rms}	root mean square of radial velocity fluctuation
V	radial mean velocity
V_m	maximum radial mean velocity
x	normal distance from pipe exit
x_1, y	radial distance from jet centerline
y_1	normal distance from impinging plate
η	Kolmogorov length scale
κ_1	wave number
ν	kinematic viscosity
ε	kinetic energy dissipation rate
τ	time interval
$< >$	mean time average

investigated elaborately, which not only presents an important test case for the future research on the development and validation of mathematical models of turbulent flow but also enables proper design for IJV system to create a most desirable indoor environment.

Numerous studies, mostly experimental, on impinging jets have been widely reported with various flow configurations. The flow field of impinging jet can be divided into three distinct regions: free-jet region, in which the flow characteristics are identical to those of the free jet; impingement region, in which the jet intensively interacts with the impingement surface and undergoes considerable deflection, and wall-jet region, where the jet becomes almost parallel to the wall assuming a flow pattern resembling that of the wall jet. Comprehensive reviews of impinging jets have been presented by Donaldson et al. [13,14] and Beltaos et al. [15–17]. Among the more recent works available on flow characteristics for jet impingement, Cooper et al. [18] 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. [19] to assess and examine the performance of four different turbulence models: the $\kappa-\varepsilon$ model and three-second order moment closures. Kim [20] investigated the flow and heat transfer characteristics of a heated axisymmetric round jet impinging on a normal plate, describing the flow field of three-dimensional mean flow and turbulent flow quantities in free-jet, stagnation and wall-jet regions, and presenting the convective heat transfer coefficient distributions on the impingement plate. Knowles and Myszko [21] performed measurements in the free- and wall-jets for various nozzle-to-ground board separation distances of a single circular jet impinging on a flat ground board. The nozzle height was found to affect the initial thickness of the wall jet leaving the impingement region, and the wall jet thickness increased with increasing H/D. The nozzle height was also found to have a large effect on the peak turbulence level for radial distances up to $r/D \approx 4.5$ and lower nozzle-to-wall ratios caused an increase in the peak level measured in all turbulent stresses within the impingement region. The flow field between two horizontal surfaces arising from jet issuing from the lower surface and impinging normally on the upper surface have been experimentally investigated for a single jet and double jet by Baydar [22]. The velocity and pressure distributions in the impingement region were obtained over a Reynolds number range of 300–10,000 and a nozzle-to-plate spacing range of 0.5–4, moreover, the effects of Reynolds number and nozzle-to-plate spacing on the flow structure were reported. Yoon et al. [23] experimentally investigated the turbulent flow and heat transfer characteristics of a two-dimensional oblique plate impinging jet. The jet mean velocity and turbulent intensity profiles were measured as well as the local heat transfer coefficients. The jet Reynolds number ranged from 10,000 to 35,000, the nozzle-to-plate distance from 2 to 16, and the oblique angle from 60 to 90°. It has been found that the stagnation point shifted toward the minor flow region as the oblique angle decreased and the position of the stagnation point nearly coincided with that of the maximum turbulent intensity. Nevertheless, some studies investigate the characteristics of turbulent jet impingement with non-intrusive optical measurement techniques. Tummers et al. [24] performed measurements of the turbulent flow in the stagnation region of a single impinging jet. The mean velocity components and Reynolds stresses were determined by using a two-component LDV and the instantaneous reversals in the near wall region were studied by applying PIV. Hassan et al. [25] investigated the wall shear stress and the vortex dynamics in a circular impinging jet for Reynolds numbers of 1260 and 2450 by using the time resolved particle image velocimetry (TR-PIV). The velocity field is given in both the free jet region and near the wall in the impinging region. The wall shear stress is obtained at different radial locations from the stagnation point using the polarographic method and the distribution of the momentum thickness is also inspected from the jet exit toward the impinged wall. Nishino et al. [26] reported the turbulence statistics in the stagnation region of an axisymmetric jet impinging vertically on a flat plate by using PTV. The measurements were made in a submerged water jet facility at a Reynolds number of approximately 13,000 based on the nozzle exit velocity and the nozzle diameter.

Coherent structures existing in turbulent jets are responsible for most of the mass, momentum and heat transfer, which also influence the human comfort from the perspective of the environmental science and engineering due to their affection of the entrainments in the jets and their spread. Furthermore, turbulent jets exhibit a complex structure with a wide range of coexisting scales and a variety of shapes in the dynamics. Different scale structures have different average burst periods, and the large scale structures with low frequency may cause draught discomfort [27,28]. Most of the literatures presented in impinging jets are concerned with the flow characteristics and heat transfer. However, few works exist on the multi-structures of the jet impingement. This study presents an experimental study of an axisymmetric turbulent jet impinging orthogonally on a flat surface. Measurements were performed in the free- and wall-jets regions using cross hot-wire anemometry. A