International Journal of Heat and Mass Transfer 103 (2016) 305–318

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Velocity field characteristics of the turbulent jet induced by direct contact condensation of steam jet in crossflow of water in a vertical pipe

Qiang Xu, Liejin Guo *, Liang Chang, Yechun Wang

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 6 July 2016
Accepted 14 July 2016

Keywords:
Velocity field
Turbulent jet
Direct contact condensation
Crossflow
Particle Image Velocimetry

ABSTRACT

Direct contact condensation of jets in fluid has been widely applied in many industrial applications owing to the low requirement of driving potential and high efficiency of heat and mass transfer. Here, experiments are carried out to investigate the velocity field characteristics of the turbulent jet induced by direct contact condensation of steam jet in crossflow of water in a vertical pipe. Visual equipment is specially invented to investigate the velocity field characteristics by using Particle Image Velocimetry (PIV) measurement technique. The high intensity laser light reflected by the pure steam region just outside the nozzle-exit brings out severe damage to the CCD camera. To solve this technical problem, a black plate is adopted to shield the pure steam region. According to the contours of the velocity fields and streamlines, the influences of jet momentum ratio, jet Reynolds number and water temperature on the jet flow field are explored. The jet centerline trajectory equations in exponential form are established based on the local maximum mean velocity. By introducing the jet Reynolds number and jet momentum ratio, the correlation for prediction of jet centerline trajectory equations is proposed, and the predicted results are within 30% of the experimental data. The reciprocal of the local maximum mean velocity and the half-width of the jet are proportional to the downstream coordinate along the jet velocity centerline trajectory. The scaled velocity field complies with the self-similarity principle.

1. Introduction

Direct Contact Condensation (DCC) of a vapor jet in liquid has attracted much interest in recent years due to its high efficiency of heat and mass transfer and low requirement of driving potential. It is frequently encountered in lots of industrial applications, such as vapor jet condensing in nuclear industry, vapor jet pumping in process industry, vapor jet heating in power industry, and vapor jet driving in aerospace industry [1–4].

Previous work on DCC of a vapor jet in liquid reported in literature primarily focused on jet penetration length, condensation regime diagram, heat transfer coefficient, pressure oscillation and turbulent jet flow field. Kerney et al. [5] established the first correlation of jet penetration length as a function of condensation driving potential and steam mass flux. After that, a lot of improved correlations were reported by other researchers based on their respective background and experiments [6–14]. The interface behavior of the vapor jet was commonly illustrated in a condensation regime diagram, which were generally divided into three main regimes, such as chugging, bubbling and jetting [13,14,8,15]. Heat transfer mechanisms were generally explored by theory analysis and numerical simulation, and many correlations of heat transfer coefficient were proposed [16–20]. Studies on pressure oscillation induced by vapor jet in liquid usually focused on amplitude and frequency [21,22]. To obtain the detailed velocity and temperature fields of turbulent jet induced by vapor jet in liquid, techniques such as Particle Image Velocimetry (PIV), Planar Laser Induced Fluorescence (PLIF) and mobile thermocouples were used [23–26].

For experimental study on jet interaction with crossflow, fruitful achievements about velocity field, centerline trajectory and jet shape were reported [27–34]. The flow and geometry characteristics of DCC of a vapor jet in crossflow have been studied thoroughly in our previous work [35–37]. However, due to the lack of the basic information on the velocity field of the turbulent jet, the interfacial transport mechanism of the condensing jet in crossflow in pipes is not well understand. The research work on single-phase jet in crossflow has already confirmed that the velocity fields of the turbulent jet contribute a lot to reveal the mass and momentum transport mechanism underlying of this complexity flow phenomenon [27–30]. But the condensation of the jet leads to significant change of the flow field structure and also difficult measurement of the velocity field. Clerx et al. [38–40] conducted a pioneer work on exploring the velocity field characteristics of

---

* Corresponding author. Fax: +86 29 82669033.
E-mail address: lj-guo@mail.xjtu.edu.cn (L. Guo).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.07.047
0017-9310/

Nomenclature

A	constant in exponential equation, 1
B	constant in exponential equation, 1
d	inner diameter of the nozzle, m
D	inner diameter of the vertical round pipe, m
$\boldsymbol{e_y}$	unit vector in ordinate direction, m/s
G_s	steam mass flux at the nozzle exit, kg/m^2 s
J	jet momentum ratio equals to $\rho_s V_s^2/\rho_w V_w^2$, 1
l	ordinate in the Cartesian coordinate system (n, l), m
m	mass flow rate, kg/s
n	abscissa in the Cartesian coordinate system (n, l), m
N	sequence sample size, 1
p_s	steam inlet pressure, MPa
p_w	water pressure at the steam injection point, MPa
Re_s	jet Reynolds number equals to $4m_s/\pi d\mu_s$, 1
Re_w	Reynolds number of water flow equals to $4m_w/\pi D\mu_w$, 1
T	inlet temperature, °C
u	velocity in the abscissa direction, m/s
$\boldsymbol{u}$	velocity vector, m/s
U_{mean}	mean horizontal velocity, m/s
v	velocity in the ordinate direction, m/s
v_ε	velocity in the ordinate direction in the Cartesian coordinate system (n, l), m/s
$v_{\varepsilon,\,c}$	jet centerline velocity in the ordinate direction in the Cartesian coordinate system (n, l), m/s
$\boldsymbol{v}_\infty$	crossflow velocity vector, m/s
V_a	magnitude of velocity, m/s
V_{mean}	mean vertical velocity, m/s
x	abscissa in the Cartesian coordinate system (x, y), m
y	ordinate in the Cartesian coordinate system (x, y), m

Greek letters

α	angle between the abscissa x and the velocity centerline trajectory-normal direction, °
β	angle between the nozzle center line and the pipe wall, °
θ	angle between the fixed x or y lines and the velocity centerline trajectory-normal direction, °
μ	dynamic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

s	the steam phase
w	the water phase

DCC of steam jet in crossflow in a square channel at relatively low steam mass flux ($G_s < 120$ kg/m^2 s). However, in actual industrial systems, the approaching fluid flows in round pipes rather than square channels. Besides, when the steam mass flux increases up to a certain value, the condensation regimes change from chugging to bubbling and then to jetting regime [15,35–37]. Therefore, it is desirable to perform investigation on velocity field characteristics of the turbulent jet induced by jet condensation in crossflow in pipes with a large range of steam mass flux.

This paper focuses on the velocity field characteristics of the turbulent jet induced by DCC of steam jet in crossflow of water in a vertical pipe, with a range of high steam mass flux up to 740 kg/m^2 s. The velocity field, jet centerline trajectory and lateral distribution of velocity are investigated. Visual equipment is specially invented to study the velocity field characteristics of the turbulent jet by means of PIV measurement technique. The high intensity laser light reflected by the pure steam region brings about severe damage to the CCD camera. A black plate is adopted to shield the pure steam region to solve this problem. The influences of jet momentum ratio, jet Reynolds number and water temperature on the velocity field are discussed. Furthermore, empirical correlation for prediction of jet centerline trajectory equations is proposed as a function of jet Reynolds number and jet momentum ratio. Finally, the lateral distribution of the velocity field is discussed and analyzed. This study provides new insights into velocity field characteristics of turbulent jet induced by DCC of steam jet in crossflow of water in pipes. The results would be useful for further theoretical and experimental research on the interfacial transport mechanism underlying DCC of steam jet in crossflow of water in pipes.

2. Experiments

2.1. Experimental setup

In order to investigate the velocity field characteristics of the turbulent jet induced by DCC of steam jet in crossflow of water in pipes, a steam water two-phase flow system has been specially designed and built up. A sketch of the experimental system is shown in Fig. 1. It can be divided into four main components, such as a water supply line, a steam supply line, a test section and a data acquisition unit.

The main part of the steam supply line is an electric heating boiler (72 kW), which generates saturated steam with a maximum mass flow rate of 0.03 kg/s. To keep the supplied steam saturating, the steam supply line is first covered with tap heaters, and then the tap heaters is wrapped with fiberglass coverings. The steam mass flow rate is measured by a vortex flowmeter with relative maximum deviation of 0.5%. The water volume flow rate is measured by a magnetic flowmeter with relative maximum deviation of 0.5%. In order to eliminate the effects of vibrations on the test section, two flexible metal hoses are connected between the water loop and the vertical pipe, and also a flexible hose is connected between the steam loop and the test section.

The vertical pipe has a total length of 4100 mm with an inner diameter of 80 mm. Before entering the visual test section, the water flows in a smooth steel pipe of length 2400 mm (30 times of the hydraulic diameter of the vertical pipe), which is long enough to insure a fully developed turbulent flow entering the visual test section. The visual test section is well designed to investigate the velocity field characteristics of the turbulent jet, as displayed in Fig. 2. The vertical pipe in the visual test section is made of transparent silica glass with 5 mm wall thickness. The steam is discharged into the vertical pipe through a flush-mounted nozzle with 3.2 mm inner diameter. The nozzle centerline is perpendicular to the pipe centerline. The temperature and pressure of discharged steam are measured at an upstream position of the nozzle exit. The visual test section is enclosed in a transparent silica glass box, which is filled with deionized water in order to eliminate distortions caused by the curvature of the round pipe. In this study we focus on the center plane A–A, defined by the vertical pipe centerline and the nozzle centerline.

The experimental system is configured with high precision instrumentation. The fluid pressure is measured with pressure transducer, which is in the range of 0–1.0 MPa with relative maximum deviation of 0.1%. The fluid temperature is measured with K-type thermocouple, which is in the range of 0–200 °C with