International Communications in Heat and Mass Transfer 70 (2016) 9–14

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Onset of exchange flow in combined buoyancy and forced pipe flow in unstable density gradient☆

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ARTICLE INFO

Available online 19 November 2015

Keywords:
Buoyancy
Exchange flow
Forced pipe flow
Unstable density gradient
Critical condition
Flow structure
Laser induced fluorescence

ABSTRACT

The onset of exchange flow and the flow structure in a combined buoyancy and forced pipe flow are experimentally studied at Reynolds number up to 7000. The experiment is carried out in a vertical pipe flow of water issuing into a still brine water environment of various concentrations and flow rates. The critical Froude number for the onset of exchange flow is evaluated by the laser-induced fluorescence technique and the velocity fields near the pipe exit are measured by the particle-image velocimetry. The critical Froude number in the laminar regime increases with increasing the Reynolds number and the onset of inflow and the purging of the exchange flow are deviated due to the hysteresis effect, while it is not observed in the turbulent regime. It is found that the laminar exchange flow is characterized by the large-scale structure and the turbulent exchange flow is featured by the small-scale structure near the wall. The enhancement of velocity fluctuation near the pipe exit is clearly observed in the laminar regime due to the occurrence of exchange flow, while it is limited to the near-wall region in the turbulent regime.

1. Introduction

Vertical buoyant flow is one of the fundamental thermal-flow phenomena and has been studied for many years, because it is important for application to the industrial problems in thermal and fluid engineering [1–3]. The far-field characteristics of the buoyant flow issuing from a pipe into still environment have been studied and the mean flow characteristics are well summarized in a review paper [4] and the turbulence characteristics are reported in some research papers [5–13]. On the other hand, the near-field characteristics of the buoyant flow are less understood due to the complex nature of the flow influenced by the unstable density gradient, which is related to the complex flow phenomenon, such as the onset of instability and the transition to turbulent flow [9].

When a low-density fluid flows through a vertical pipe and issues into a high-density fluid environment against the gravity, the unstable density gradient is generated near the pipe exit due to the buoyancy force. This results in the appearance of inflow issuing from the surrounding high-density-fluid into the low density fluid in the pipe, which is called “exchange flow”. The onset condition of the exchange flow and the purging flow rate are important topics of interest in thermal and fluid engineering, such as the design of nuclear reactor to prevent from the depressurization accident, where the buoyancy force arising from the gas inside the reactor vessel and the cool air outside is the major driving force of the exchange flow [14]. According to the experiments [15], the penetration distance of the exchange flow increases with a decrease in the Froude number, while the critical Froude number seems to be almost independent of the Reynolds number in large Reynolds number beyond 10^4.

Later, several experimental studies on the buoyancy driven flow arising from the unstable density gradient have been carried out to understand the influence of buoyancy on the flow rate through the pipe, while most of the previous researches are focused on the buoyancy-driven exchange flow without forced flow through a pipe [16–20]. The flow rate of the exchange flow through a pipe for various ratios of length to pipe diameter are studied and the classification of the flow pattern inside the pipe is carried out [19]. Then, the combined buoyancy and the forced flow through a pipe is investigated to understand the purging condition [21]. The structure of the exchange flow in a vertical pipe flow is studied by flow visualization and the result shows the presence of highly turbulent flow inside the pipe arising from the unstable density gradient [22]. On the other hand, the onset of the exchange flow in a laminar flow through a square pipe is studied experimentally and the generation of highly turbulent flow is observed for the combined buoyancy and forced flow [23]. Later, the onset of the exchange flow in a forced pipe flow of square cross-section is examined in the laminar regime of the flow up to the Reynolds number 2000 [24,25], while the onset of inflow and purging of exchange flow in laminar and turbulent forced flow through a circular pipe has not been studied yet.

The purpose of this paper is to study experimentally the onset of the exchange flow in laminar and turbulent forced flow in the Reynolds

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☆ Communicated by W.J. Minkowycz.
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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.11.003
0735-1933/

Nomenclature

C	concentration
d	pipe diameter
Fr	Froude number $(= W_0/\sqrt{dg(\rho_b - \rho_w)/\rho_w}\,)$
g	gravitational acceleration
Re	Reynolds number $(= W_0 d/\nu)$
r	radial distance
t	time
W_0	bulk velocity
w_m	mean velocity
w_{rms}	fluctuating velocity
ν	viscosity of fluid
ρ	density of fluid

Subscripts

w	water
b	brine water

number up to 7000 under the influence of unstable density gradient. An attention is placed on the presence of hysteresis loop for the inflow and purging flow condition of the exchange flow in the laminar regime.

2. Experimental methods

Fig. 1 shows the illustration of the test section for studying the combined buoyancy and forced flow through a vertical circular pipe, where a low-density fluid (water) issues from a circular pipe into a still surrounding of high-density fluid (brine water) against the gravity. A large volume of water prepared in a lower tank is driven by a pump to the settling chamber and the water flows into the test circular pipe against the gravity in the test section. The working fluid water exits from the pipe and flows into an upper tank filled with brine water. The details of the test pipe are illustrated in Fig. 2. The inner diameter of the test pipe is 40 mm and the thickness of the pipe is 2 mm. The length of the test pipe is set to 800 mm, while the experiment is conducted in a short pipe length 40 mm to study the sensitivity of the pipe length on the occurrence of exchange flow. These test pipes are made transparent for flow visualization purposes. The cross-sectional area of the large tank is 400 × 400 mm^2 and the height is 760 mm. To keep a constant pressure head during the experiment, the working fluids are discharged from the top hole of the tank to the outside. The concentration of the brine water was measured by a hydrometer, while the mean velocity through the pipe was measured by a digital flowmeter. In the present study, the brine water concentration was ranged from 0 to 4%, while keeping the temperature of the fluids to a constant 293 K.

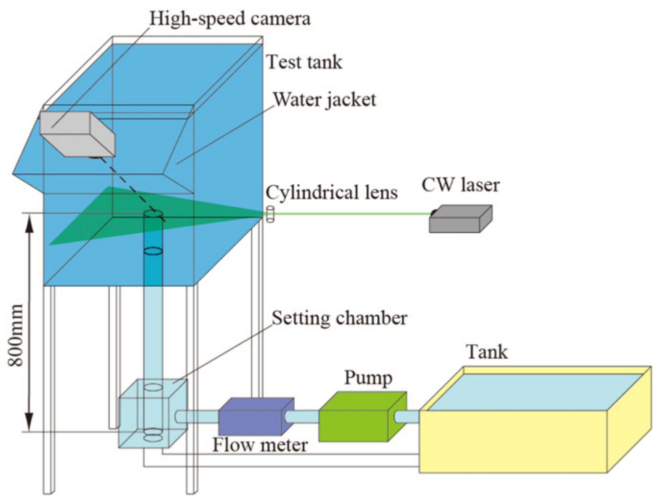

Fig. 1. Experimental apparatus and flow visualization system.

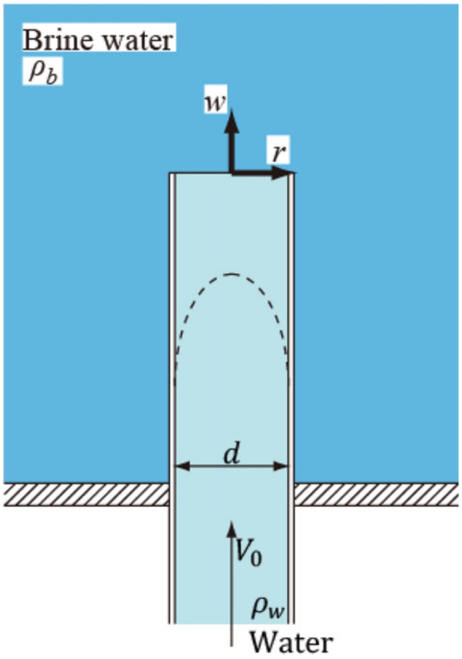

Fig. 2. Details of test pipe.

The flow visualization was carried out by using a laser-induced fluorescence (LIF) system, which consisted of a high-speed CMOS camera having a spatial resolution of 1018 × 1018 pixels with 8 bits, as shown in Fig. 1. This system allows the cross-sectional visualization of the concentration field using the light-sheet optics [8,9,23–25]. The LIF visualization was carried out to determine the inflow and purging conditions of the exchange flow at the exit of the pipe. The dilute solution of Rhodamine 6G was added to the working fluid water through the pipe and was illuminated by a laser sheet of 1 mm in thickness emitted from CW Nd:YAG laser of 8 W. The concentration of the fluorescent dye solution was set to 1 ppm to confirm the linear response of the intensity to the change of the dye concentration [24].

The measurement of velocity field near the exit of the pipe was carried out using a particle image velocimetry (PIV), where the nylon tracer particles of diameter 40 μm are added for the flow visualization. The

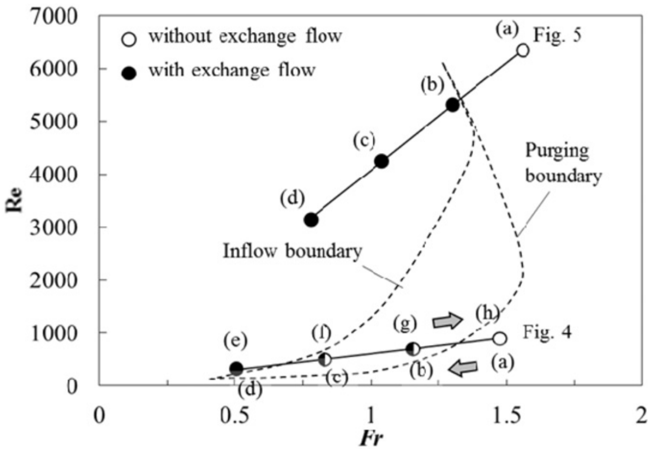

Fig. 3. Occurrence of exchange flow in buoyancy driven forced pipe flow.