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# Characterization of exchange flow in vertical pipes of circular and square cross-sections under unstable density gradient

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ABSTRACT

The exchange flows in a buoyancy driven forced flow in vertical pipes of circular and square cross-sections were studied experimentally and the flow structure was examined by proper orthogonal decomposition (POD) analysis. The experiments were carried out in the vertical pipes issuing into a still brine water environment and the flow fields were visualized by the laser-induced fluorescence (LIF) technique. The flow visualization study showed that the critical inflow condition was deviated from the purging boundary due to the influence of hysteresis, and they are shifted to the high Froude numbers in the square pipe compared to the circular one. The POD analysis of the exchange flow indicates that the fluctuating energy is increased in the lower POD modes due to the formation of large-scale structure of the exchange flow. It is found from the analysis that the exchange flow in the low Reynolds number is promoted at the corners of the cross section in the square pipe, while it is randomly distributed in the circular pipe. This corresponds to an increased critical Froude number in the square pipe than that of the circular pipe, which is due to the presence of exchange flow through the corners. With increasing the Reynolds numbers, the flow becomes turbulent and the scale of the exchange flow is decreased and restricted to the near-wall region, while the location of the exchange flow becomes random along the pipe wall irrespective of the cross-sectional shape of the pipes.



## 1. Introduction

When a low-density fluid issues into a high-density fluid environment through a vertical pipe against the gravity forces, the pipe flow becomes unstable to the buoyancy force arising from the unstable density gradient. This buoyancy-driven instability of the pipe flow results in the appearance of inflow, which is a countercurrent flow directing to the lower density fluid through the pipe against the forced pipe flow. This flow phenomenon is called "exchange flow", and the countercurrent flow supplied to prevent the exchange flow is called "purging flow".

In the past, several experimental studies on the buoyancy driven exchange flow arising from the unstable density gradient have been carried out to avoid the depressurization accident in the nuclear reactor arising from the density gradient of the gas inside the reactor vessel and the cool air outside [1,2]. These experiments were carried out in vertical and horizontal pipes in unstable density gradient with the aid of the brine water of high density fluid and the water of low density fluid, and the purging flow rate of the exchange flow to avoid the inflow was evaluated. The governing parameters of this problem are the Reynolds number and the Froude number, which is the ratio of the inertia force to the buoyancy. Later, the purging flow rate of the exchange flow through a broken pipe during a standpipe rupture accident was examined experimentally and numerically in a high temperature gas cooled nuclear vessel [3–5]. Furthermore, an attention has been focused on the unexpected hydrogen explosion accident in the reactor vessel and the high pressure vessel [6], where the exchange flow plays an important role arising from the density gradient of hydrogen and air. The other example of the exchange flow can be found in the ventilation of air through windows of building, where the high density gradient of air appears in the case of fire [7].

In order to understand the complex flow physics of the exchange flow, some fundamental studies were carried out in the buoyancy-driven exchange flow through a horizontal and vertical pipes to characterize the exchange flow in a rectangular pipe [8,9]. Furthermore, the experiments on the exchange flow rate through a vertical circular pipe [10,11] were carried out, and the results indicated that the exchange flow rate varied with the length to diameter ratio of the pipe. It should be mentioned that the exchange flow rate became a maximum in the small length to diameter ratio. They also noticed that the flow regimes of exchange flow could be categorized into four regimes, such as oscillatory flow, Bernoulli flow, combined turbulent diffusion and Bernoulli flow and turbulent flow, depending on the Froude number.

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**Nomenclature**

| | |
|---|---|
| $C$ | concentration |
| $\mathbf{C}(x,t_k)$ | instantaneous concentration field |
| $\mathbf{C_k}(x)$ | POD mode of concentration field |
| $\overline{C_k}$ | concentration fluctuation normalized by the maximum |
| $C_m$ | mean concentration |
| $C_{rms}$ | RMS concentration |
| $d$ | diameter of circular pipe or side length of square pipe |
| $E_t$ | total fluctuating energy |
| $Fr$ | Froude number ($=W_0/\sqrt{dg\rho_b-\rho_w/\rho_w}$) |
| $g$ | gravitational acceleration |
| $Re$ | Reynolds number ($=W_0d/\nu$) |
| $r$ | radial coordinate for circular pipe |
| $t$ | time |
| $W_0$ | bulk velocity |
| $x,y,z$ | coordinates (see Fig. 2) |
| $\nu$ | kinematic viscosity of fluid |
| $\rho$ | density of fluid |

*Subscripts*

| | |
|---|---|
| w | water |
| b | brine water |
| $k$ | $k$-th value |

The experimental investigations on the structure of buoyancy-driven exchange flow in a vertical pipe were conducted to understand the origin of irregular fluctuation in the exchange flow [12–14], where the flow visualization played an important role. The numerical visualization of the flow through the horizontal vent was also carried out and the exchange flow structure of a buoyancy driven vertical rectangular pipe flow was examined [15]. These results showed that the exchange flow was highly irregular and chaotic in space and time even in a laminar flow arising from the unstable density gradient of fluid in the vertical pipe flow.

Further study on the inflow condition of the vertical exchange flow was examined experimentally by laser-induced fluorescence at low Reynolds numbers in the exit of a buoyancy driven forced flow through a vertical square pipe [16]. This experiment studied the inflow condition of the exchange flow through a square pipe. It was also observed that the penetration of the inflow through the corners of the square pipe triggered the highly chaotic mixing of the fluid and resulted in the large spreading of the buoyant jet downstream of the pipe. Furthermore, the three-dimensional velocity field measurements by particle-image velocimetry (PIV) and the proper orthogonal decomposition (POD) analysis were carried out in the highly buoyant jet at low Reynolds number issuing from the square pipe [17,18], while the focus of these studies were placed on the buoyant jet downstream of the vertical pipe. More recent study on the buoyancy driven exchange flow [19] showed that the inflow and the purging conditions of the exchange flow were deviated in a vertical circular pipe at low Reynolds number. Such complexity of the exchange flow characteristics in laminar region suggested further study on the exchange flow structure through the vertical pipe of various cross-sectional shapes in unstable density gradient.

The purpose of this paper is to characterize the inflow and purging flow conditions of the exchange flow and the flow structure in vertical pipes of circular and square cross-sections under the influence of unstable density gradient of fluid in a wide range of Froude/Reynolds numbers. Furthermore, the mechanism of exchange flow is evaluated by the introduction of POD analysis to understand the structural change of the exchange flow.

## 2. Experimental methods

Fig. 1 shows the illustration of the test section for studying the forced buoyant flow through a vertical pipe, where a low-density fluid (water) issues from a pipe into a still surrounding of high-density fluid (brine water) against the gravity. A large volume of water prepared in a lower tank was driven by a centrifugal pump and forced into the test pipe with straight section through the settling chamber. The working fluid water spreads into a brine water in the upper tank after exiting from the pipe. The details of the test pipe are illustrated in Fig. 2. Circular and square cross-sections of pipes were examined in the present experiment. They were made of acrylic material for flow visualization purposes. The diameter of the circular pipe was 40 mm and the side length

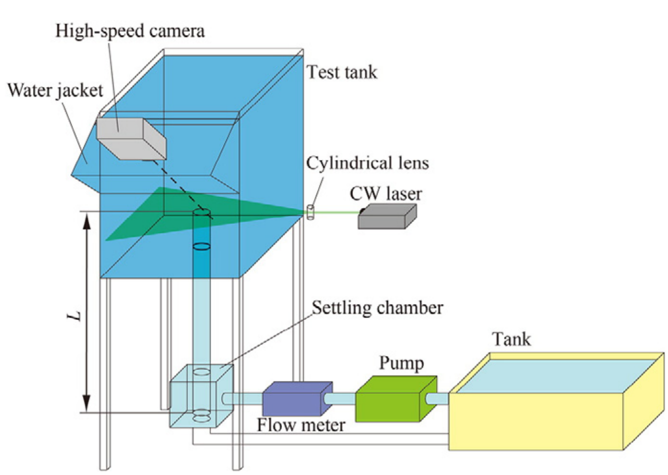


**Fig. 1.** Experimental apparatus and flow visualization system.

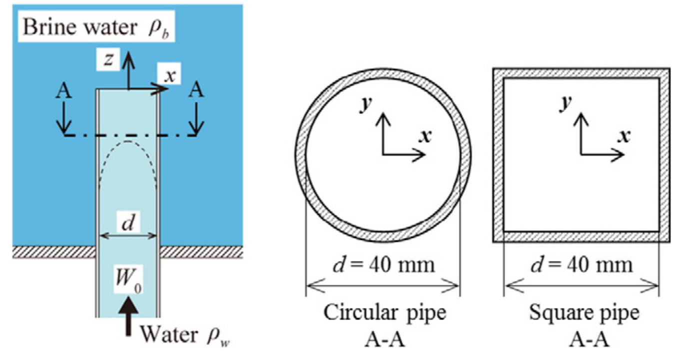


**Fig. 2.** Details of test pipes.

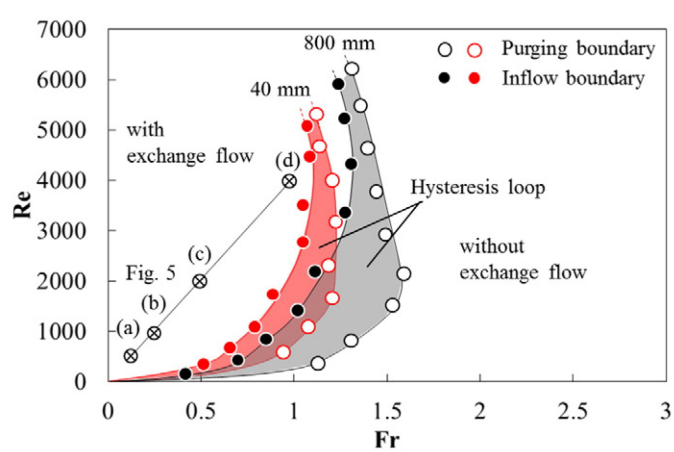


**Fig. 3.** Onset of exchange flow in circular pipes.