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ENTRAINMENT BEHAVIOR ON DENSITY INTERFACE OF TWO STRATIFIED FLUIDS

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ABSTRACT

The entrainment behavior on a density interface of stratified fluids is very important for the design of innovative nuclear reactors, fast breeder reactors and fish breeding tanks. In the present study, a pair of injection and extraction nozzle supplied the turbulent energy in the upper stratified fluid. Two kinds of eddy, the vertical and horizontal (swirl), were generated in the upper fluid with the different nozzle pair. The entrainment was done by lift up of filaments from the interface. The large single filament existed at the center of horizontal eddy but the multiple small filaments existed at the peaks of interfacial wave driven with the vertical eddy. The entrainment was significantly promoted with the horizontal eddy compared to the vertical eddy. The entrainment rate was compared with the energy balance model where the turbulent energy released from the energy-containing eddy is equal to the energy consumption by entrainment and dissipation. The comparison indicated the larger turbulent intensity in the horizontal eddy than that of the vertical eddy at the same nozzle velocity.

INTRODUCTION

In the innovative reactors, steady reactor operations can be obtained when the cold boron water tank is directly connected to the hot primary loops as shown in Fig.1. If there is an accident in the primary system, the cold boron water is immediately fed to the depressed primary loops and shuts down the nuclear reactions. At the steady state, the density interface exists between the high-temperature primary water and the cold boron water. To make a stable density interface, a honeycomb is proposed to install at the interface for the depression of the turbulent intensity in the some challenging design. The entrainment behavior on the density interface of stratified fluid is strongly affected with the turbulence of the fluids.

The entrainment behavior on a density interface of stratified fluids is very important for the design of innovative nuclear reactors. In the previous study (Osakabe et al., 1992, 1993), a pair of injection and extraction nozzle supplied the turbulent energy in the upper stratified fluid and the entrainment behavior was studied experimentally. The entrainment rate was compared with the energy balance model where the turbulent energy released from the energy-containing eddy is equal to the energy consumption by entrainment and dissipation. Osakabe et al.(1993) proposed the following semi-empirical correlation based on the energy balance.

$$\frac{u_e}{u^*} = 0.5\left(\frac{1}{Ri^*} - \frac{1}{150}\right) \tag{1}$$

Where u_e is the entrainment velocity indicating the descending velocity of interface and u^* is the turbulent intensity at the upper fluid. Ri* is the Richardson number using the turbulent intensity and defined as,

$$Ri^* = \frac{g(\rho_s - \rho_L)Le}{\rho_m (u^*)^2} \tag{2}$$

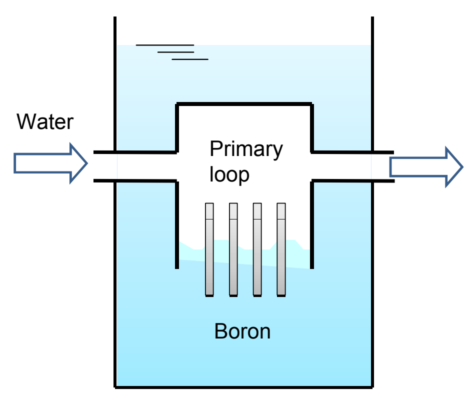

Fig. 1 Density lock

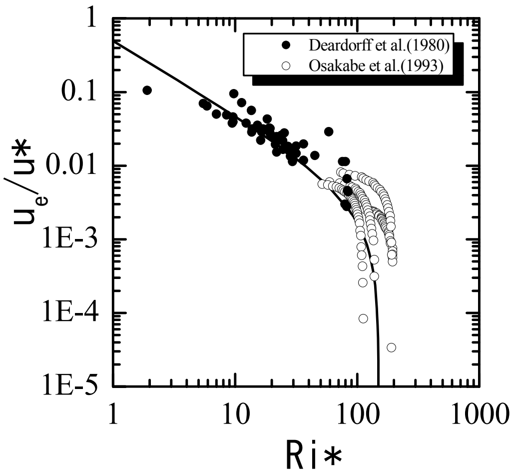

Fig. 2 Relation of entrainment velocity and Ri number

Shown in Fig.2 is the relation between non-dimensional entrainment velocity and Richardson number for the experiments conducted by Osakabe et al.(1993)) and Deardorff et al.(1980). The solid line in the figure indicates Eq.(1). The figure shows the rapid decrease of entrainment velocity at Ri of approximately 150. The rapid decrease means the appearance of stable interface at the Richardson number. In the experiment by Osakabe et al., the rectangular vessel was used and the two-dimensional eddy was successfully formed at the upper fluid with a pair of injection and extraction nozzle. On the other hand, in the experiment by Deardorff et al., the eddy in the lower fluid was generated with the natural convection. In spite of the difference of eddy generation method, Eq.(1) agrees well with the experimental results.

However, Eq.(1) is derived with an assumption of homogeneous turbulent theory that is different from the actual non-homogeneous turbulent motion such as the vertical or horizontal eddies. So it is very important and interesting to find out the condition where the entrainment is strongly depressed and the stable interface appears under the actual eddy configuration.

NOMENCLATURE

D: diameter of vessel [m]
g: acceleration due to gravity [m/s^2]
L_e: size of energy containing eddy [m]
Ri: Richardson number
t : time [s]
$u*$: turbulent intensity [m/s]
u_N: nozzle velocity [m/s]
u_e: entrainment velocity [m/s]
z: distance between interface and nozzle center [m]
ρ: density [kg/m^3]

EXPERIMENTAL APPARATUS AND METHOD

In the present study, a density interface of stratified fluids was formed in a cylindrical vessel. A pair of injection and extraction nozzle supplied the turbulent energy in the upper stratified fluid and the entrainment behavior was studied experimentally. Two kinds of eddy, the vertical and horizontal (swirl), were generated in the upper fluid with the different nozzle pair.

Shown in Fig.3 is the schematic of experimental apparatus. The apparatus made of the transparent acrylic cylindrical vessel to contain the stratified fluids. Salt water colored with red ink was gently injected to the vessel filled with water and the density interface was formed at the center line of injection nozzle. The concentration of salt was between 10 to 20%. After confirming the stable interface, water was injected from the injection nozzle and discharged from the extraction nozzle. The entrainment behavior from the interface was observed.

To generate the different eddy in the upper fluid, the different combination of injection and extraction nozzles were used. For the horizontal swirl and vertical eddies, swirl (SW) and straight (ST) nozzles shown in the figure were used respectively. By using the SW nozzles, water was injected tangentially and rotated around the center of vessel. After forming the horizontal eddy, water was extracted from the upper nozzle at the center of vessel. By using the ST nozzles, water was injected from one side of vessel and extracted from another. The diameter of all nozzles was 14mm and the nozzle velocity was between 0.1 to 0.5m/s. The descending density interface with the entrainment was recorded with a video camera. The location z of interface from the centerline of injection nozzle was measured with the video images.

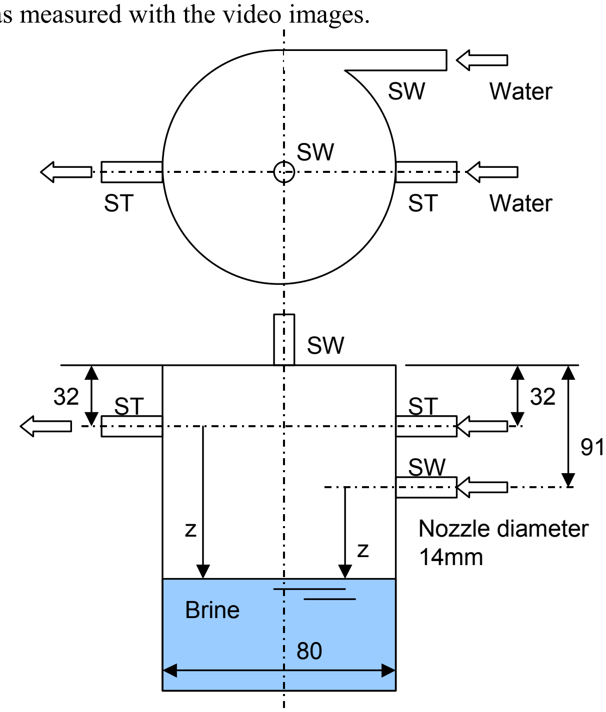

Fig. 3 Schematic of experimental apparatus

Fig. 4 Density interface at horizontal eddy

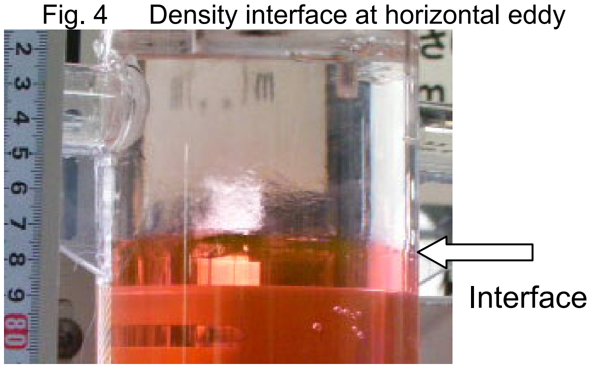

Fig. 5 Density interface at vertical eddy

EXPERIMENTAL RESULT

Shown in Fig.4 is photograph of descending interface due to the horizontal eddy. The horizontal eddy provided the rising and rotating flow at the center of cylindrical vessel. The lower salt water was mainly entrained at the center. The region above the deep colored interface is pale suggesting the mixing of salt water and water. The interface was approximately horizontal and the location of density interface was defined at the vessel wall as shown in Fig.4.

Shown in Fig.5 is photograph of descending interface derived with the vertical eddy. Multiple vertical eddies made the interfacial waves and the entrainment took place from the wave crests. The interface was approximately horizontal and the location of density interface was defined at the vessel wall.

Figure 6 shows the schematic image of the entrainment behavior. In the horizontal eddy, fluid elements such as filaments are picked up from the lower salt water and are mixed into the upper water at the center of vessel. On the other hand, in the vertical eddy, the filaments are picked up from the multiple wave crests. The location where the filaments are released is fixed at the center in the horizontal eddy but not fixed in the vertical eddy.

Figure7 shows the transient location of descending interface due to the horizontal eddy. The location is defined as the distance from the center line of injection nozzle. The experimental result was obtained at the density ratio of 1.2 and the nozzle velocity between 0.18 and 0.32m/s. The larger descending velocity was obtained at the larger nozzle velocity.

Figure8 shows the transient location of descending interface

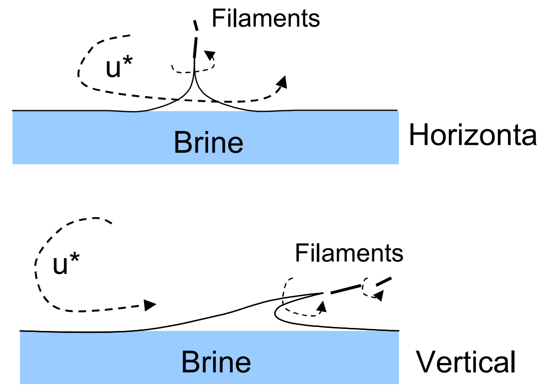

Fig. 6 Entrainment behavior

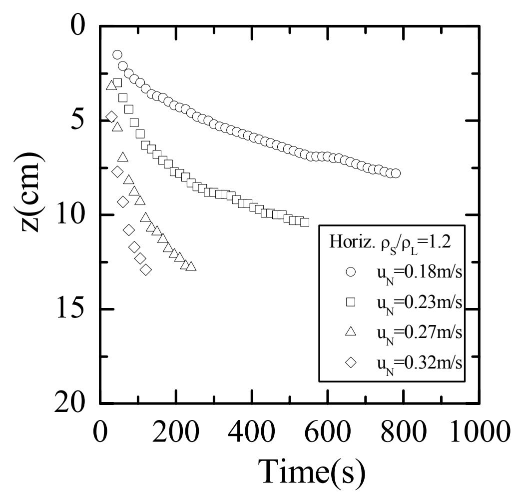

Fig. 7 Transient location of density interface by horizontal eddy

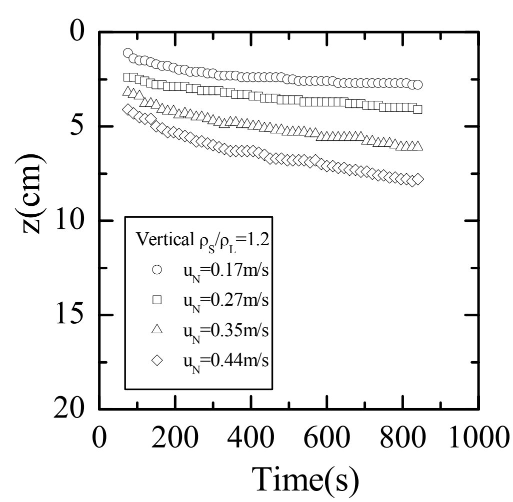

Fig. 8 Transient location of density interface by vertical eddy

driven with the vertical eddy. The experimental result was obtained at the density ratio of 1.2 and the nozzle velocity between 0.17 and 0.44m/s. As same as the horizontal eddy, the larger descending velocity was also obtained at the larger nozzle velocity. The descending velocity is significantly lower than that at the horizontal eddy.

By using the least squares method, the location of density interface can be expressed with the second-order curves as

$$z(t) = a_0 + a_1 t + a_2 t^2 \qquad (3)$$

The entrainment velocity can be obtained by differentiating the curves with time as,

$$u_e = dz(t)/dt = a_1 + 2a_2 t \qquad (4)$$

Shown in Fig.9 is the relation between the interface location and non-dimensional entrainment velocity divided by the nozzle velocity corresponding to Fig.7 for the horizontal eddy. The entrainment velocity was between 0.1 and 0.01 % of the nozzle velocity, and quickly decreased to zero at a certain location. The larger nozzle velocity resulted as the deeper terminal location where the entrainment velocity became zero.

Shown in Fig.10 is the relation between the interface location and non-dimensional entrainment velocity corresponding to Fig.8 for the vertical eddy. The entrainment velocity was between 0.001 and 0.0001 % of the nozzle velocity, and quickly decreased to zero at a certain location as same as that of the horizontal eddy.

Shown in Fig.11 is the relation between the interface location and non-dimensional entrainment velocity at the density ratio of 1.2 and 1.1 for the horizontal eddy. The smaller density ratio resulted as the deeper terminal location where the entrainment velocity became zero.

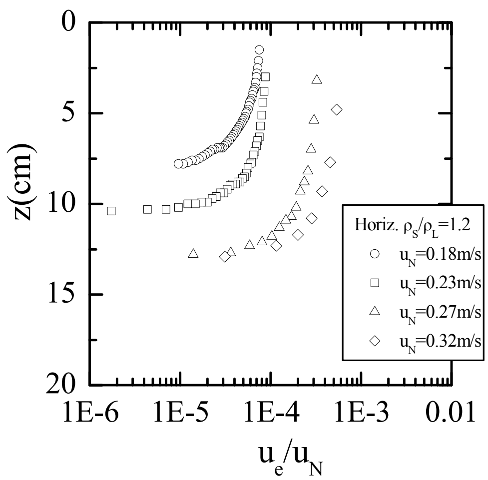

Fig. 9 Relation of density interface location and entrainment velocity by horizontal eddy

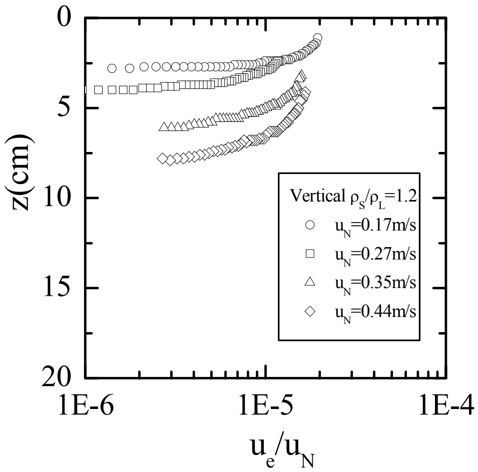

Fig. 10 Relation of density interface location and entrainment velocity by vertical eddy

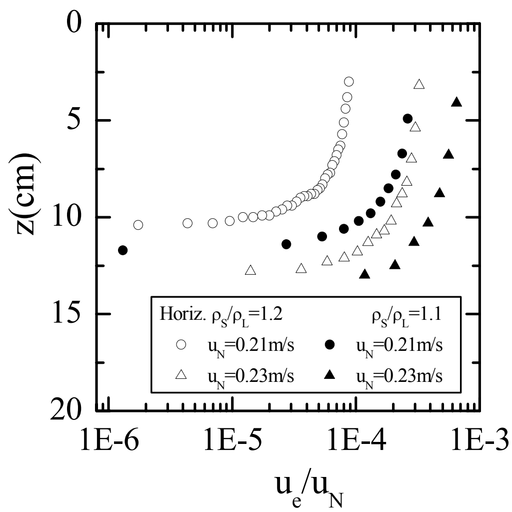

Fig. 11 Transient location of density interface by vertical eddy

Generally in the present experiment, the larger nozzle velocity and smaller density ratio resulted as the higher entrainment velocity and the deeper terminal location where the entrainment velocity became zero. As the entrainment is conducted with the large eddy driven by the injected nozzle flow, the nozzle velocity is the key parameter for the entrainment. Even at the same nozzle velocity, the more efficient work for the entrainment is possible for the horizontal eddy compared to the vertical eddy.

DISCUSSION

As the turbulent intensity of upper fluid is proportional to the nozzle injection velocity u_N,

$$u^* = \beta u_N \tag{5}$$

In the previous experiments (Osakabe et al., 1992,1993) using the rectangular vessel, the constant β was approximately constant depending on the diameter of nozzle but not on the vessel size and interface location. Substitution of Eq.(5) into Eq.(1) gives the non-dimensional entrainment velocity as,

$$\frac{u_e}{u_n} = 0.5\beta\left(\frac{\beta^2}{Ri} - \frac{1}{150}\right) \tag{6}$$

where Ri is the Richardson number using the nozzle velocity defined as,

$$Ri = \frac{g(\rho_s - \rho)Le}{\rho_m (u_N)^2} \tag{7}$$

As mentioned above, the size of energy containing eddy *Le* was considered to be the distance between the injection nozzle center and the interface in the vertical eddy observed in the previous study. For the horizontal eddy, it is considered that the effect of vessel diameter should be incorporated into the eddy size. As a first attempt, the size of eddy was assumed as the average of vessel diameter and the distance between the interface and the nozzle center as,

$$Le = \frac{z + D}{2} \tag{8}$$

This new and conventional definition of eddy size gives the relation between Ri number and non-dimensional entrainment velocity for the horizontal eddy as shown in Fig.12. The conventional eddy size z is used for the open symbol and the new definition is used for the closed symbol. The solid and dashed lines show Eq.(6) using β of 0.15 and 0.1, respectively. Equation (6) gives the sudden decrease of entrainment velocity at a certain Ri number. This indicates the termination of interface at a certain Ri number. But when Ri becomes smaller, Eq.(6) gives a gradual and monotonous increase of entrainment velocity.

The open symbol using the conventional eddy size tends to stay at a constant when Ri becomes smaller. As the interface depth is small at the region of small Ri number, it is expected that the injection energy of nozzle efficiently converts to the large eddy energy. So it is difficult to consider the decrease of β to stay at a constant entrainment velocity in the small Ri region. However the close symbol using the new definition of eddy size shows a gradual increase of entrainment velocity as same as Eq.(6). So the new definition of eddy size was used in the below discussion.

Shown in Fig.13 is the relation between Ri number and non-dimensional entrainment velocity for the horizontal eddy. The new definition of eddy size was used. The experiments were conducted at the different density ratio and nozzle velocity. The lines with Eq.(6) gives the sudden decrease of entrainment velocity at a certain Ri number. This sudden decrease was also observed in the experimental results. These indicate the termination of interface at a certain Ri number. The experimental data agree well with Eq.(6) using β of 0.15 to 0.1. The previous semi-empirical model gives proper estimation of the entrainment velocity if the turbulent intensity is assumed as approximately 15% of the nozzle injection velocity for the horizontal eddy.

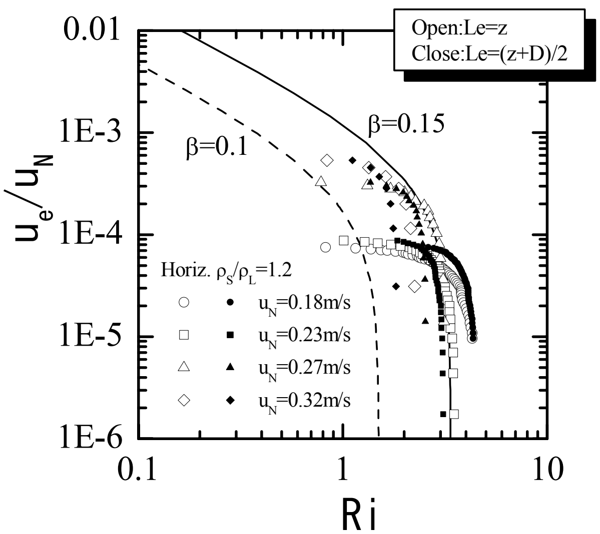

Fig. 12 Relation of Ri number and entrainment velocity by horizontal eddy

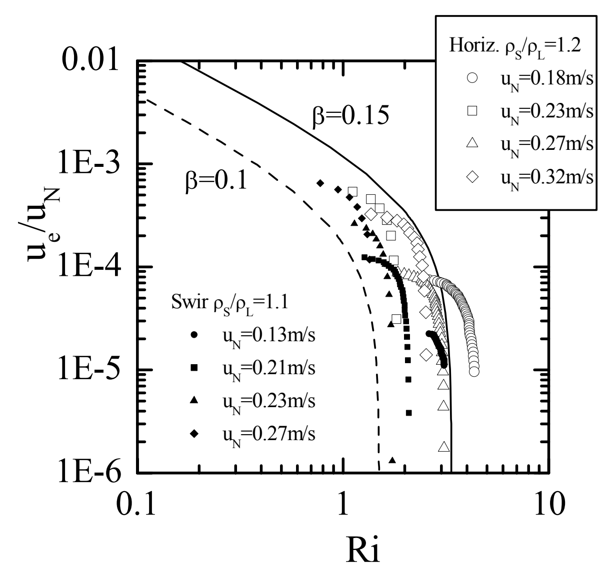

Fig. 13 Relation of Ri number and entrainment velocity by horizontal eddy at different density ratio

Shown in Fig.14 is the relation between Ri number and non-dimensional entrainment velocity for the vertical eddy. The conventional definition of eddy size defined as the distance between the interface and nozzle center was used. The experimental data agree well with Eq.(6) using β of 0.065. The turbulent intensity for the vertical eddy is significantly lower than that for the horizontal eddy and the more efficient work for the entrainment is possible for the horizontal eddy compared to the vertical eddy at a given nozzle velocity.

In the previous study using the rectangular vessel, two-dimensional vertical eddy was observed. In the present experiment using the cylindrical vessel, the various size of vertical eddy was observed in the upper fluid. Specially at smaller nozzle velocity, it is difficult to define a constant *Le* or β. Actually in Fig.14, the termination Ri at the smallest nozzle velocity of 0.17m/s was slightly large. Eliminating the data at the smallest nozzle velocity, the previous semi-empirical model gives proper estimation of the entrainment velocity if the turbulent intensity is assumed as approximately 6.5% of the nozzle injection velocity for the vertical eddy.

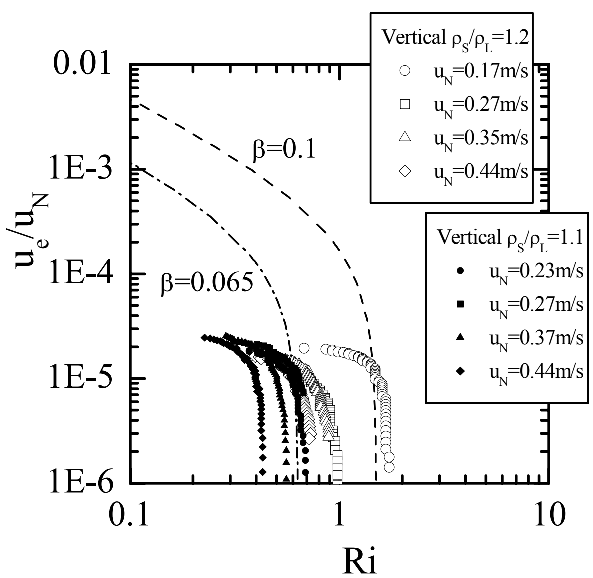

Fig. 14 Relation of Ri number and entrainment velocity by vertical eddy at different density ratio

CONCLUSION

To study the stable condition of density interface, the entrainment experiments were conducted with two stratified fluids in the cylindrical vessel. A pair of injection and extraction nozzle supplied the turbulent energy in the upper stratified fluid. Two kinds of eddy, the vertical and horizontal (swirl), were generated in the upper fluid with the different nozzle pair. The followings are major results.

(1) In the horizontal eddy, fluid elements such as filaments were picked up from the lower salt water and were mixed into the upper water at the center of vessel. On the other hand, in the vertical eddy, the filaments were picked up from the multiple wave crests. The location where the filaments were released was fixed at the center in the horizontal eddy but not fixed in the vertical eddy.

(2) The larger nozzle velocity and smaller density ratio resulted as the higher entrainment velocity and the deeper terminal location where the entrainment velocity became zero. As the entrainment is conducted with the large eddy driven by the injected nozzle flow, the nozzle velocity is the key parameter for the entrainment. Even at the same nozzle velocity, the more efficient work for the entrainment was possible for the horizontal eddy compared to the vertical eddy.

(3) The experimental results and semi-empirical correlation gives the sudden decrease of entrainment velocity at a certain Ri number. This indicates the termination of interface at a certain Ri number.

(4) The previous semi-empirical model gives proper estimation of the entrainment velocity if the turbulent intensity is assumed as approximately 15% of the nozzle injection velocity for the horizontal eddy. However, the model gives proper estimation of the entrainment velocity if the turbulent intensity is assumed as approximately 6.5% of the nozzle injection velocity for the vertical eddy.

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