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Investigation on the Onset of Gas Entrainment by Experimental Simulation of Two Side Branches of PHWR Header Using Air and Water

M. A. Ekbote[1], P. Prabhakaran[2]

[1] *Assistant Professor, Department of Mechanical Engineering, Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Vadodara.*

[2] *Professor, Department of Mechanical Engineering, School of Engineering & Technology, Navrachana University, Vadodara.*

Abstract-*An experimental investigation has been conducted to determine the vortex free critical height during single discharge and dual discharge from the smooth stratified air-water region through side branches mounted on a circular surface. The branches are of 9 mm internal diameter and oriented at 0^0 and 180^0. The experimental data are generated for branch Froude number in the range of 6.4 to 27.5. Both the branches are kept at equal Froude number. The results are compared with existing empirical and theoretical correlations. Experimental based correlations are developed relating critical height, branch diameter and Froude number.*

Key words: *vortex free, critical height, single discharge, dual discharge, and smooth stratified.*

I. INTRODUCTION

Various industries encounter several two-phase flow applications; one of them is PHWR of Nuclear Power Plant. In a typical PHWR, a horizontal header supplies heavy water as a coolant to the reactor core through a number of feeders attached to it. Usually, five feeders are mounted at an angle of 0^0, 45^0, 90^0, 135^0, and 180^0 on the header as shown in Figure 1. These feeders supply coolant to the fuel channels. During certain LOCA conditions, the stratified two-phase flow of steam-water occurs in the header, which leads to two-phase flow discharging from the various feeders. The two-phase flow quality from the feeders depends on the feeder location relative to the liquid height in the header.

Reference [1] carried out a theoretical study on a single discharge containing stratified layers of gas and liquid fluid phase. He identified a distinct phenomenon called vapor pull through occurring in the header. In case of vapor pull through, the interface is located above the branch, thus vapor could reach into the branch by two ways viz. either by vortex flow or by pulled through in vortex-free flow. Figure 2 shows the vapor pull through phenomena. At certain critical height (h_{OGE}), vortex-free Onset of Gas Entrainment (OGE) occurs. The h_{OGE} correlation given in equation (1), depends on the branch diameter (d), branch flow Froude number for liquid (Fr_L), coefficients C_1 and C_2.

$$\frac{h_{OGE}}{d} = C_1 \ Fr_L^{C_2} \tag{1}$$

Where,

$$Fr_L = \frac{4\dot{m}_L}{\pi\sqrt{gd^5\,\rho_L(\rho_L - \rho_G)}} \tag{2}$$

ρ_L is the density of liquid phase in kg/m^3 and ρ_G is the density of the gas phase in kg/m^3

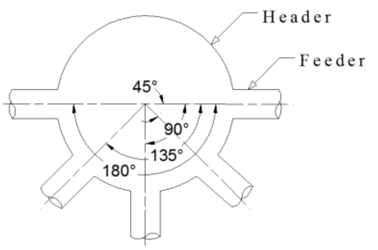

Figure 1. Schematic of typical PHWR header

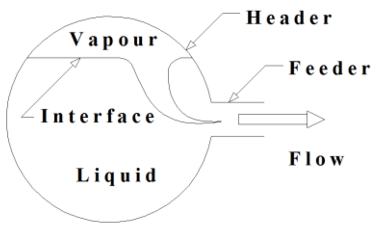

Figure 2. Vapor pull through phenomena

Later on, [2] , [3], [4], [5], [6], and [7] investigated OGE for a side branch mounted on vertical wall or circular wall and with or without the axial flow in the test chamber. Reference [8] and [9] developed theoretical model to predict the OGE during single discharge through a side branch installed on a vertical surface exposed to a smooth stratified region. Table 1compares the value of C_1 and C_2 obtained by earlier investigators through empirical and theoretical way with either vertical wall mounted or circular wall mounted branch.

Table 1 Summary of C_1 and C_2 constants

Investigators	Mounting surface of branch	Correlation	Constants		range	Branch size d (mm)
			C_1	C_2		
Yonomoto and Tasaka (1988)	Vertical wall	Empirical	0.681	0.400	-	⌀10 and ⌀20
Parrott et al. (1991)			0.887	0.334	0 to70	⌀6.35
Hassan et al. (1998)			0.570	0.400	10 to70	⌀6.35
Bartley et al. (2008)			0.475	0.444	1.5 to 70	⌀6.35
Ahmed et al. (2003)		Theoretical	0.625	0.400	-	Circular
Guyot et al. (2014)			0.636	0.390	-	6 X 6
Smoglie and Reimann (1986)	Circular wall	Empirical	0.681	0.400	1 to 110	⌀6, ⌀8, ⌀2, and ⌀20
Lee et al. (2007)		Semi-empirical	0.681	0.400	2 to 30	⌀16 and ⌀24.8

Reference [10] studied OGE for two side branches mounted horizontally on vertical wall using experimental setup of [4] . The following empirical correlation developed for predicting OGE by incorporating the separating distance, L between the branches on vertical wall;

$$\frac{h_{OGE}}{d} = 0.570\left(\left(1.0 + e^{\left[-0.613\left(\frac{L}{d}\right)^{1.5}(Fr_L)^{-0.4}\right]}\right) Fr_L\right)^{0.4} \tag{3}$$

The previous investigators studied the single discharge or dual discharge through the branches mounted on the vertical flat wall or circular wall. Thus, no information exists currently in open literature for two side branches mounted on a circular surface. The present work deals with the single discharge and dual discharge from a stratified reservoir with two side branches mounted on circular surface. This configuration of branches resembles the horizontal branches of PHWR header-feeder configuration. Experimental data for OGE are generated during single discharge from stratified air-water region over a Froude number range from 6.4 to 27.5.

II. EXPERIMENTAL INVESTIGATION

2.1. Experimental setup

A schematic diagram of the experimental test facility is shown in Figure 3. A 13 stage centrifugal pump was used to supply water from the underground tank to the test chamber. The air supply system connected to test chamber was used to keep steady pressure P_{TC} by operating air supply valve.

The test chamber 12 m long and 600 mm in diameter was manufactured from carbon steel material. The test section was bolted to the outlet end of the test chamber. This test section was provided with viewing windows at the front end. A pressure and temperature taps was provided at the top of the test section to measure the test chamber pressure(P_{TC}) temperature(T_G). The transparent test piece was inserted from the bottom flange of the test section. The transparent test piece having two horizontal branches was mounted on a circular surface placed in the test chamber as shown in Figure 4. The branch diameter (d) was 9.0 mm and header diameter (D) was 58.70 mm. A straight length of each branch was kept at least eighteen times the diameter of the branch. A camera with 30X optical zoom was focused inside the viewing window of the test section for continuous recording of entire phenomena. From this recording, OGE was identified and h_{OGE} was determined. Pressure and temperature taps were provided on airside of test section.

Each hydraulic line was calibrated by directing the discharge from the branch to the measuring phase separator. The measuring phase separator being smaller was sensitive to the discharge from the branch; therefore it helped to calibrate the hydraulic lines accurately. The liquid flow rate, leaving the measuring phase separator was measured by the coriolis mass flow meter. The mass flow meter could measure maximum water flow of 60 kg/min. Pressure tap was provided on airside of the measuring phase separator.

After the calibration of each hydraulic line, the discharges from both the branches were directed to auxiliary phase separator. The bigger auxiliary phase separator helped to keep the steady back pressure for both the branches during the entire experiment. To measure the air pressure, pressure tap was provided on airside of the auxiliary phase separator.

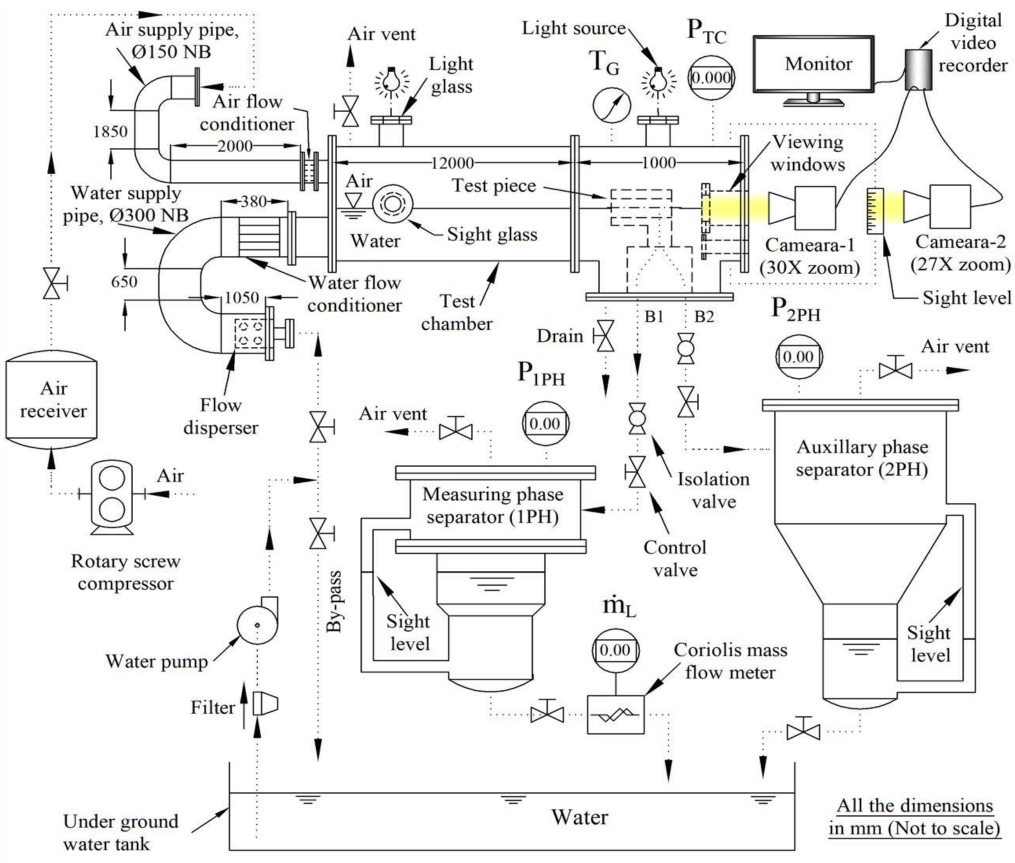

Figure 3. Schematic of experimental setup

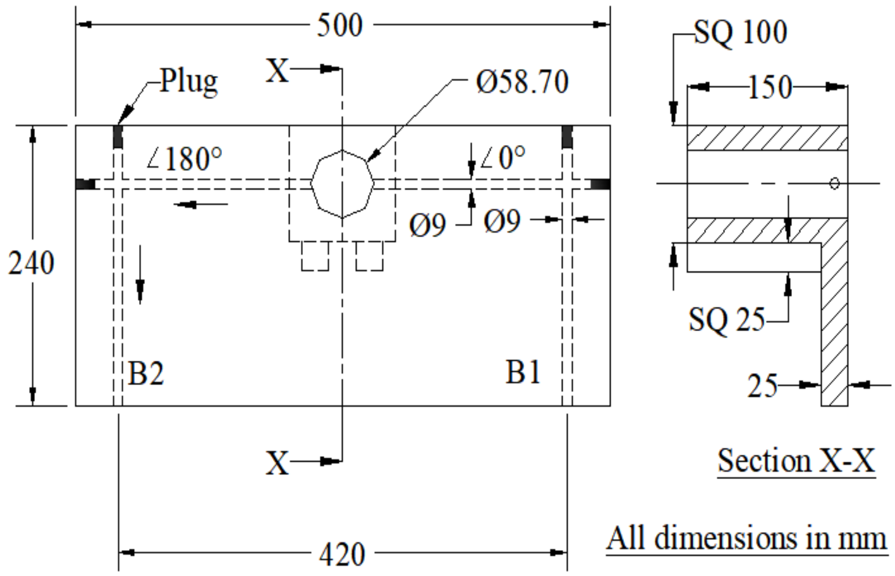

Figure 4. Schematic of test piece

2.2. Experimental procedure

Two phase separators were used in the present investigation, smaller measuring phase separator, and bigger auxiliary phase separator. The smaller measuring phase separator was sensitive to the liquid flow from the branch line; therefore it was used for the calibration of branch lines. The bigger auxiliary phase separator was used to keep steady back pressure during the entire experiment. The following procedure was followed for the dual discharge experiment, and the modification applicable for the single discharge experiment was discussed later in this section.

First the water in the test chamber was pumped up to the top of the header and was kept steady to avoid the gas flow to enter the branch. Then, the test chamber was charged with air at pressure P_{TC}. The measuring phase separator was connected with the B1 line and was charged with air at pressure P_{1PH}. Thus, the pressure difference, ΔP, between test chamber and measuring phase separator initiated the liquid flow in the B1 line. The control valve placed in the B1 line was adjusted to obtain the required $\dot{m}_{L,B1}$ corresponding to $Fr_{L,B1}$. Under the steady ΔP condition, the total mass flowed was measured in kg for not less than 180 seconds, and average $\dot{m}_{L,B1}$ was calculated. Equation (2) was used to calculate the average $Fr_{L,B1}$ from the average $\dot{m}_{L,B1}$. Similar procedure was followed to set the same Fr_L for B2 line. Every time before starting with new Fr_L, both the branch lines were calibrated. The maximum variation in setting the Fr_L between the branch lines B1 and B2 was within ±4.8 percentage for single and dual discharge condition.

Both the branch lines were connected to the auxiliary phase separator after the calibration. The test chamber and auxiliary phase separator were kept at P_{TC} and P_{2PH} respectively for entire experiment. Thus, a pressure drop across each branch, ΔP was kept same for each experiment and for each line. Under these conditions the quantity of the liquid flow ($\dot{m}_L$) discharging through two branches depends upon ΔP and location of the air-water interface relative to the branches.

In case, the interface level is kept above B1, the discharge from both the branches is essentially single-phase liquid with equal mass flow rates, i.e. $\dot{m}_{L,B1} = \dot{m}_{L,B2}$. As an interface level, h is lowered; a critical height is reached where OGE occurs at B1and B2. During OGE at B1 and B2, the gas entrainment through the branch is insignificant. At this instance $h_{B1} = h_{OGEB\ 1}$, $\dot{m}_{L,B1} = \dot{m}_{L,OGEB\ 1}$, $h_{B2} = h_{OGEB\ 2}$, and $\dot{m}_{L,B2} = \dot{m}_{L,OGEB\ 2}$. The h_{OGE} was measured from the center of the respective branch.

For the single discharge experiment, the above procedure was followed by connecting one branch line at a time to the auxiliary phase separator. The objective of this investigation is to focus on effect on h_{OGE} of the branches during single discharge and dual discharge condition, when branches are mounted on circular surface.

2.3. Procedure of determination of h_{OGE}

Figure 5 shows the schematic of the liquid level measurement in the test section. First, water was filled above the bottom of the header, and then the drain valve was opened to drain out the water from the header, until the water level touched the bottom of the header. This height of the water in the test chamber was the bottom of the header, and 59 mm measurement of the transparent flat rule was precisely aligned with the bottom meniscus of the water seen through the glass tube. To align the water height of the test chamber and 59 mm of flat rule, a 27x zoom camera was used. The output of the camera was seen on the 32 inch screen monitor. The header diameter was 58.7 mm while the bottom meniscus of water was set on flat rule at 59 mm. This resulted in 0.3 mm higher height of water measured by flat rule; therefore 0.3 mm was subtracted from the every liquid height measured. A calibration curve was prepared between the height of water measured by the flat rule and the water height seen on the monitor by camera. At the instance of the OGE, h_{OGE} was calculated using calibration curve from the liquid height seen through the camera.

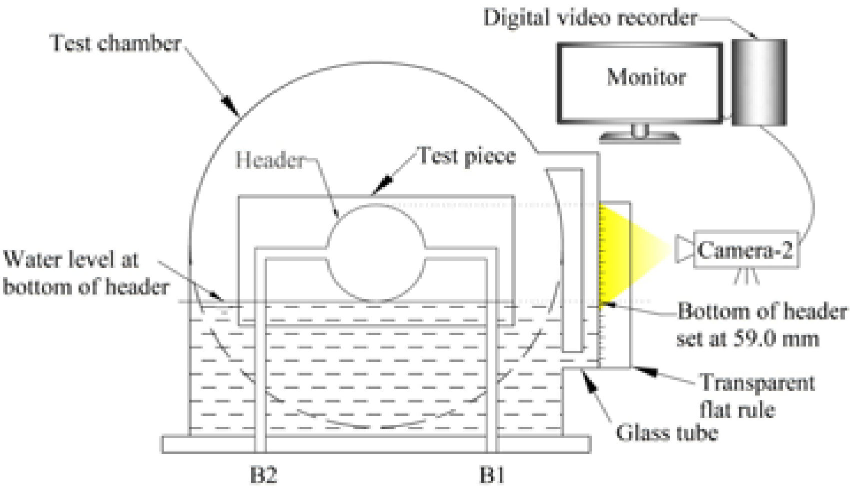

Figure 5 Schematic of liquid level measurement

III. EXPERIMENTAL UNCERTAINTY

Uncertainty in the independent and dependent variables was estimated as per the method suggested by [11] and [12] at odds of 20:1 and includes bias, precision, and fluctuation in process conditions. The pressure transmitters, temperature gauge, and coriolis mass flow meters were factory calibrated. The maximum uncertainty in P_{TC} was ±1.5%, the uncertainty in ΔP ±28.9% for the smallest Fr_L of 6.4 and less than ±14.8% for rest of Fr_L, and the uncertainty in Fr_L ±2.1%. A flow meter was used to measure the liquid flow rate through the branch. The uncertainty in liquid flow rate was estimated as ±2.0%. The uncertainty in the measurement of h_{OGE} was ±0.25 mm and in T_G ± 0.5^0C.

IV. EXPERIMENTAL TEST CONDITIONS

Total thirty two observations corresponding to data series no. 1, 2 and 3 are taken for the single discharge and dual discharge condition as shown in Table 2. Single phase liquid flowed at constant mass flow rate through each branch line. The Froude number is the dimensionless parameter to describe the flow phenomena related to branch. The OGE depends on the interface height and Froude number of the branch. Before starting the experiment with new Froude number, each branch line was adjusted until Froude number of the two side branches was within ± 4.8%. Series no. 1 and 2 investigates the OGE for a side branch, whereas series no. 3 shows the effects of discharges through two side branches on the OGE.

Table 2. Nominal operating conditions

Series. no.	Activated line(s)	Fr_L range	Total number of OGE
1	B1 only	6.4 to 27.5	8
2	B2 only		8
3	B1 and B2		16

V. RESULTS AND DISCUSSIONS

Section 5.1 gives discussion and results of a typical visual observation of OGE for single discharge and dual discharge. Results of single side branches and dual branches are presented and discussed in section 5.2 and section 5.3 respectively.

5.1. Flow visualization

The flow visualization experiments revealed that OGE depends on Fr_L of the branch and the interface height in the header. The gas entrainment phenomenon described by Froude number of liquid phase at side branch and form of interface. During the study of gas entrainment at side branch B1of series no. 1, the interface height 'h' was flat when liquid height was well above the branch as shown in Figure 6(a). The Froude number of the branch was $Fr_{L,B1}$. As the interface lowered, a dent in the flat interface surface was viewed, and gradually deepened with the fall in interface height as shown in Figure 6(b). Further, little decrease in the interface height, suddenly a thin gas tube had emerged at the bottom of the dent and jumped into the B1 as shown in Figure 6(c). The gas started flowing steadily into the B1 from the thin gas tube. The visual observation showed that at that position the flow was a vortex. Soon after, the vortex disappeared and stopped the gas flow into the B1. This gas entrainment mode is termed as unsteady entrainment, as initially the gas started flowing into the branch and then failed to flow continuously as shown in Figure 6(d). Further lowering the interface level, a critical height of the interface was reached and yet again, a hair-thin gas tubes emerged from the dent reaching to the B1. At this instance, the flow of gas into the B1 was continuous and did not disappear with further lowering of the interface height. This mode of gas entrainment is termed as steady entrainment as shown in Figure 6(e). Visual observation showed at that position, the gas entrainment was vortex-free. The unsteady gas entrainment occurred several times before steady gas entrainment occurs; therefore, a steady gas entrainment condition was identified as the OGE. The thin gas tube carried a little quantity of the gas from the header, thus pressure in the phase separator did not rise and Froude number of the branch was $Fr_{L,B1} = Fr_{LOGE,B1}$.
A similar gas entrainment phenomenon was observed for other side branch of series no. 2 as shown in Figure 6(f) to Figure 6(j). The Froude number of the branch was $Fr_{L,B2} = Fr_{LOGE,B2}$. Figure 6(k) to Figure 6(o) shows the two identical gas entrainment phenomena for B1 and B2 of series no. 3. The Froude number of the branches was $Fr_{L,B1} = Fr_{LOGE,B1} = Fr_{L,B2} = Fr_{LOGE,B2}$.

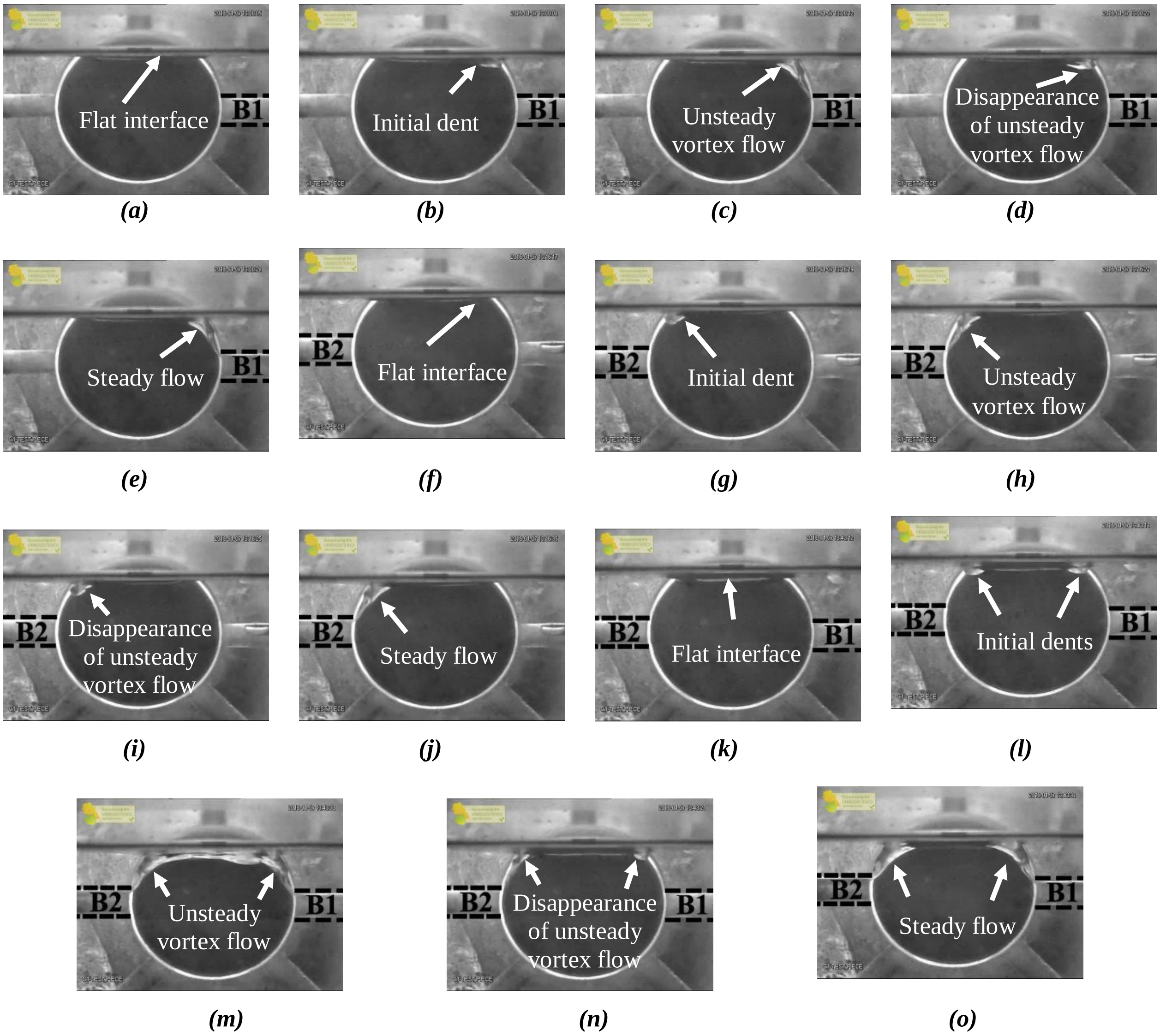

Figure 6 . Typical Gas entrainment phenomena for series nos. 1, 2, and 3

5.2. Single discharge

Figure ***7*** shows comparison between the present data of single discharge with the existing correlations. Significant deviations can be seen among the different correlations of $\frac{h_{OGE}}{d}$. Experimental data of side branches were in good agreement with that of [5] and [7] with deviation of ±3.4 percentage and ±4.1 percentage respectively as shown in Figure *7*. The deviation between the present data and other correlations was between -11.1 percentage to -31.5 percentage. The following empirical correlation is proposed by least square fitting of the present data

$$\frac{h_{OGE}}{d} = 0.557\ Fr_{L,}^{0.4} \tag{4}$$

with a Root Mean Square Error (RMSE) of ± 7.2 percentage. The RMSE was calculated using following equation.

$$\text{RMSE}\ (\%) = \pm\sqrt{\left(\frac{1}{N}\sum_{i=1}^{i=N}\left|\frac{h_{OGE\ (Experiement\ )_i} - h_{OGE\ (Correlation\ )_i}}{h_{OGE\ (Experiement\ )_i}}\right|^2\right)}\ \text{X}\ 100 \tag{5}$$

5.3. Dual discharge

Figure ***8*** compares the present results with the previous investigation of [10]for two side branches. They mounted the branches on the same vertical plane; however the present data are compared because this is the only correlation available for the two branches in open literature. The comparison showed that experimental values were in good agreement with [10] with the deviation of ±3.7 percentage. The least square fitting of the present data gave the following correlation,

$$\frac{h_{OGE}}{d} = 0.582\ Fr_L^{0.4} \quad (6)$$

Fitting of the experimental values of $\frac{h_{OGE}}{d}$ in correlation resulted in RMSE of ±6.0 percentage.

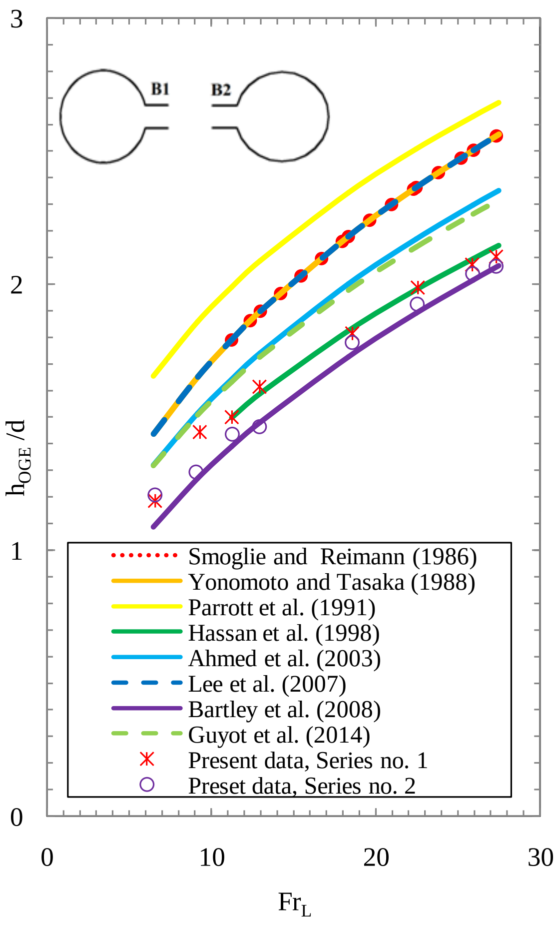

Figure 7 : Interface level at the OGE for single discharge

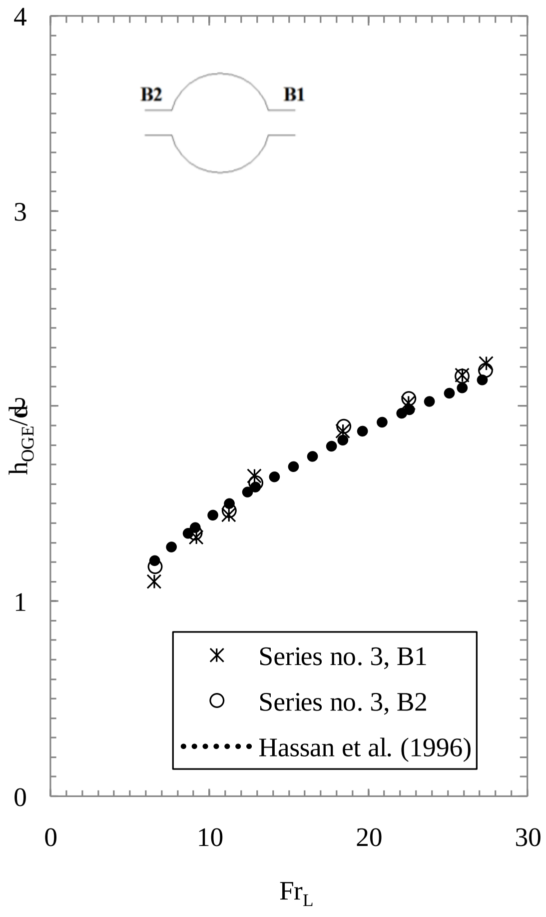

Figure 8 : Interface level at the OGE for dual discharge

VI. CONCLUDING REMARKS

The experimental data are reported for the critical height of liquid at the onset of gas entrainment and Fr_L intended for two side branches at single discharge and dual discharge conditions from the smooth stratified reservoir. The present investigation produced experimental data for 9.0 mm branch diameter (d) mounted on circular surface of diameter (D) 58.7 mm. Dimensions of the circular surface and branches were selected to be in direct proportion to those of the PHWR header-feeder system with branches mounted at 0^0 and 180^0 from the horizontal. The experiments were conducted under the condition of equal Fr_L for two branches. Thirty-two data sets were investigated covering the range of $6.4 < Fr_L < 27.5$. Both the branches were geometrically similar; therefore, the present result showed identical onsets of gas entrainment during single discharge and dual discharge condition. A comparison of data on dual discharge condition with single discharge condition showed a small effect on the critical height of the onset of gas entrainment at low Fr_L, while at higher Fr_L the effect was significant. Two empirical correlations were developed for the prediction of the onsets of gas entrainment for side branch during single discharge and dual discharge conditions. These relations represent the data with high degree of closeness; however, they should be used only within the range of experimental conditions.

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