Chapter 2 Literature Review

2.1 Introduction

In this chapter, review of the investigations related to the Onset of Gas Entrainment (OGE) through small branches with stratified flow is made. First, a review of investigations related to the commencement of OGE study for LOCA is done. Then, a review of the investigation related to branches mounted on a flat surface, and a curved surface is carried out.

2.2 Commencement of OGE Study for LOCA

Zuber (1980) systematically reviewed two-phase phenomena at a small branch. The critical height, h_{OGE} at which vortex-free OGE occurred was found to be related to the branch flow Froude number, Fr_L, as,

$$\frac{h_{OGE}}{d} = C_1\, Fr_L^{C_2} \tag{2.1}$$

Where,

$$Fr_L = \frac{4\,\dot{m}_L}{\pi\sqrt{g\, d^5\, \rho_L\, (\rho_L - \rho_G)}} \tag{2.2}$$

The result of Zuber (1980)'s report encouraged further investigations on the two-phase phenomena related to LOCA in the cooling systems of nuclear reactor. As a result, several studies were carried out to expand the knowledge regarding the critical phenomena.

Lubin and Hurwitz (1966) carried out experimental study for vortex free withdrawal of gas from a tank through the bottom branch (as cited in Zuber, 1980). A dip formed in the surface of liquid was believed as Vortex-fee OGE. Their experiment gave two correlations as;

$$\frac{h_{OGE,BB}}{d} = 0.574\ Fr_L^{0.667};\ \text{For}\ \left(\frac{h_{OGE}}{d}\right) < 1, \tag{2.3}$$

$$\frac{h_{OGE,BB}}{d} = 0.624\ Fr_L^{0.40};\ \text{For}\ \left(\frac{h_{OGE}}{d}\right) > 1. \tag{2.4}$$

2.3 OGE Studies with Branches Mounted On a Flat Surface

In this section, review of the investigations related to branches mounted on a flat surface on the side, inclined, and bottom of the test piece is carried out.

To understand the two-phase flow discharging from a stratified two-phase region through small branch, Yonomoto and Tasaka (1988) developed a simple analytical model. Their correlation assumed the flow directions were towards the branch inlet with uniform velocity. The pressure loss because of the two-phase interaction and flow contraction at the branch inlet neglected. An air-water experiment was also conducted to fit the results by modifying the constant derived from theoretical models. The experiment was conducted at maximum pressure of 7.0 bar using square duct of 190 mm x 190 mm connected with sharp-edged orifices of diameter 10 mm and 20 mm. The branches were mounted at the top, bottom, or side of the horizontal duct. The characterization of OGE was determined by visual observation through the glass windows provided on two sides normal to the branch plane. The investigators developed a theoretical model as;

For the side branch,

$$\frac{h_{OGE,SB}}{d} = 0.681\ Fr_L^{0.4} \tag{2.5}$$

For the bottom branch,

$$\frac{h_{OGE,BB}}{d} = 0.909\ Fr_L^{0.4} \tag{2.6}$$

The suggested simplified model neglected the effect of viscosity, compressibility, and phase change of fluid. The investigators compared theoretical and experimental results for OGE for the side and bottom branch, but it did not fit well with existing correlations. The authors clarified the reason of disagreement; they considered stable entrainment condition in the square test chamber instead of intermittent entrainment condition in the circular test chamber.

Parrot et al. (1991) investigated the phenomenon of gas pull through for the condition of simultaneous discharges from two small branches of 6.35 mm diameter located on the vertical wall of reservoir containing stratified air-water mixture. These two branches were separated by vertical distance ‘L’ in the ratio of $\frac{L}{d}$, 1.5, 2.0, 3.0, 4.0 and, 6.0. Each branch had a straight length of 20 diameters before any area change or bend in the brass block. A surveying transit was used to ensure that mounting flange and the faces of brass block were vertical and centreline of the branch was in a straight vertical line. The pressure in the test chamber was kept at 5.10 bar throughout the experiment. The experiment performed to obtain OGE with and without meniscus height of water by keeping the Froude number of the upper branch constant and by varying Froude number of the lower branch and separating distance, $\frac{L}{d}$. They worked with the Froude number range of 0 to 70 for the upper branch and 0 to 56.7 for the other lower branch. Their experiment showed that h_{OGE} influenced by $\frac{L}{d}$ ratio and Fr_L of the branch as well as the flow from the other branch mounted in the same plane. During the experiment, it was observed that height of the meniscus of height 3.3 mm formed along the outlet flange because of surface tension. This was significant compared to the branch diameter. An empirical relation for h_{OGE} developed for single discharge and dual discharge condition only for upper branch.

For upper branch during single discharge condition without considering the liquid meniscus height,

$$\frac{h_{OGE,UB}}{d} = 0.425\ Fr_L^{0.529};\ \text{For}\ \frac{h_{OGE,UB}}{d} \leq 1.15 \tag{2.7}$$

$$\frac{h_{OGE,UB}}{d} = 0.508\ Fr_L^{0.435};\ \text{For}\ \frac{h_{OGE,UB}}{d} \geq 1.15, \tag{2.8}$$

For upper branch during single discharge condition with liquid meniscus height,

$$\frac{h_{OGE,UB}}{d} = 0.887\ Fr_L^{0.334} \tag{2.9}$$

Though the branches of Smoglie and Reimann (1986) mounted on circular wall while Parrot et al. (1991) mounted the branches on a flat wall, the equation (2.9) was in good agreement with Smoglie and Reimann (1986) correlation.

In case of dual discharge condition the correlation proposed for upper branch with liquid meniscus height as,

$$\frac{h_{OGE,UB}}{d} = 0.887\left(Fr_{L,UB} + Fr_{L,LB}\ \exp^{\left(-2.52\left(\frac{L}{d}\right)^{1.1}(Fr_{L,UB})^{-0.22}(Fr_{L,LB})^{-0.16}\right)}\right)^{0.334} \quad (2.10)$$

Hassan et al. (1998) produced data using the experimental set up of Parrot et al. (1991) for OGE during single discharge through a small branch of 6.35 mm mounted on the side of the vertical wall under stratified condition of air-water mixture. The two-phase flow from the branch was directed to the phase separator, where air and water were split by centrifugal action. Pressure difference, ΔP, between test chamber and phase separator initiated the flow through the branch. The air and water flow rates were measured by the variable-area-type flow meters. They introduced new parameter, hydraulic resistance 'R' for each branch line. The R was given in terms of ΔP and mass flow rate of liquid as,

$$R = \sqrt{\frac{\Delta P}{\dot{m}_L}} \quad (2.11)$$

The h_{OGE} was obtained by keeping the values of test chamber pressure, ΔP and R constant. The h_{OGE} data were generated within the range of test chamber pressure of 316 kPa to 517 kPa, ΔP of 40 kPa to 235 kPa and R of 1000 to 3000 $(kg.m)^{-1/2}$. Empirical correlation was developed based on the experimental data as,

$$\frac{h_{OGE,SB}}{d} = 0.57\ Fr_L^{0.4} \quad (2.12)$$

The experimental data were compared with Schrock et al. (1986), Smoglie and Reimann (1986), Yonomoto and Tasaka (1988) and Parrott et al. (1991). The data were found to be in good agreement with Parrott et al. (1991). The reason for disagreement with the other investigator was attributed to different measuring and detection technique for the OGE and the difference in geometry and flow conditions.

Hassan et al. (1996a) stated to that in the nuclear reactor header, where multiple discharges takes place simultaneously from several branches the existing single branch correlations cannot apply. They carried out basic experiments with two branches of 6.35 mm internal diameter, d, while keeping the same hydraulic resistance for both the branches. The upper and lower branches were separated by vertical distance, L, on vertical plane of the mounting wall. The $\frac{L}{d}$ ratio of dual discharge was varied from 1.5 to 8.0 with different hydraulic resistance of the branches 'R' ranging from 1000 to 3000 $(kg.m)^{-1/2}$. The data were generated for test-section pressures of 316 and 517 kPa, and the branch pressure difference ranging from 40 to 235 kPa. A significant amount of deviation in dual discharge OGE was seen in lower $\frac{L}{d}$ ratio, when compared to the Parrott et al. (1991). Empirical correlations developed by least square fitting of experimental OGE for the upper and lower branches to predict OGE as,

$$\frac{h_{OGE,UB}}{d} = 0.570 \ (A_1 \, Fr_L)^{0.4} \tag{2.13}$$

$$\frac{h_{OGE,LB}}{d} = 0.570 \ (Fr_L)^{A_2} \tag{2.14}$$

Where,

$$A_1 = 1.0 + e^{\left[-1.96 \left(\frac{L}{d}\right)^{1.2} (Fr_L)^{-0.32}\right]} \tag{2.15}$$

$$A_2 = 0.4 - 0.223 \, e^{\left[-0.415 \left(\frac{L}{d}\right)^{1.5} (Fr_L)^{-0.2}\right]} \tag{2.16}$$

The above dual discharge empirical correlations were reduced to single discharge correlation by putting $\frac{L}{d} = 0$ in equation (2.15) and equation (2.16), which resulted in $A_1 = 2$, $A_2 = 0$. Thus, the single discharge correlation given in equation (2.13) was reduced to equation (2.12).

Later, Hassan et al. (1996b) further studied OGE for two side branches mounted horizontally on vertical wall using experimental setup of Hassan et al. (1996a). The separating distance between the branches, i.e. $\frac{L}{d}$ ratio for the two horizontal branches were varied between 1.5 to 8.0 keeping the same test chamber pressure, branch pressure difference and hydraulic resistance of Hassan et al. (1996a). New empirical correlation developed for predicting OGE as,

$$\frac{h_{OGE,SB}}{d} = 0.570\ (A\ Fr_L)^{0.4} \tag{2.17}$$

Where,

$$A = 1.0 + e^{\left[-0.613\left(\frac{L}{d}\right)^{1.5}(Fr_L)^{-0.4}\right]} \tag{2.18}$$

The above correlation predicted their data with root-mean-square error of 1.8 percentage.

Maier et al. (2001) identified four modes of gas entrainment. Initial Vortex Entrainment (IVE) was characterized by hair-thin, vortex, gas cone that originated from the flat interface over the branch or the bottom of the depression in the interface formed over the branch. IVE had been always intermittent. Continuous Vortex Entrainment (CVE) was identical in appearance to IVE and formed in the same manner; however, CVE was continuous and always formed at the bottom of the depression. Initial Depression Entrainment (IDE) was characterized by observing the first instance of the depression in the interface over the branch becoming fully entrained. As the interface was lowered, the depression in the interface over the branch deepened until it entrained. IDE had been always intermittent and prior to its occurrence, vortex cones, much like IVE, may have occurred. IDE was either vortex or no vortex in nature. Continuous Depression Entrainment (CDE) was identical in appearance to IDE and formed in the same manner, however, CDE was continuous. A typical order of entrainment appearance, as the interface was lowered was IVE, IDE, CVE, or CDE except few data points where IDE and CVE occurred in reverse order. In addition, at low Froude numbers sometimes CDE was the only entrainment mode occurred over the branch. They found that the amount gas entrained for IVE and IDE was significant with poor repeatability. Hence, they considered OGE height at the instance of CVE or CDE instead of IVE or IDE. They used the experimental setup of Parrott et al. (1991) to investigate the effect on OGE height during dual discharge from a stratified air-water region through branches mounted on a vertical wall. Two circular branches of 6.35 mm diameter with centreline falling in a common plane attached to the test chamber. The location of first branch was not changed while the angle of the second branch varied at 0^0, 10^0, 30^0, and 60^0 from the horizontal. Length to branch diameter ratio $\left(\frac{L}{d}\right)$ varied at 1.5, 2.0 and 8.0. The authors investigated the effect on critical height at OGE by varying the separating distance between the branches, the of Froude number of two branches and inclination of the branch. General trend of decrease in $\frac{h_{OGE}}{d}$ was noticed as $\frac{L}{d}$ ratio and the angle of second branch increased. At $\frac{L}{d}$ ratio is less than or equal to 2.0, $\frac{h_{OGE}}{d}$ increased with an increase in the Froude number of branches, whereas $\frac{h_{OGE}}{d}$ was unaffected by the increase of Froude number of branches at $\frac{L}{d}$ equal to 8.0. The critical height at OGE attained by experiment was compared and found in good agreement with dual discharge Hassan (1995).

Ahmed et al. (2003) suggested two different models to predict the OGE during single discharge through a side branch installed on a flat vertical surface exposed to a smooth stratified region. The first model called as point-sink analysis in which the effect of branch diameter ignored and in second model called as three-dimensional finite-branch analysis in which effect of branch diameter accounted with proper boundary conditions. Taylor (1950) was followed, to find out the onset of instability at flat interface because of downward acceleration of liquid equal to or greater than gravitational acceleration. For the disturbed interface, Bernoulli's equation applied between two convenient points, on each side of the interface to calculate the velocity of liquid. The first point chosen in the interface, far from the branch, where the kinetic energy of the liquid was negligible. The vertical distance between this point and the centre of branch was considered as critical height. The second point chosen at the bottom of the steady dip in the interface, just before the OGE. Both the models ignored the effect of gas, while water considered as incompressible, homogeneous, and irrotational in stratified reservoir. Collectively, all these assumptions led to the potential flow problem and solved by two different methods. The critical height at the OGE was given by,

$$\frac{h_{OGE,SB}}{d} = Fr_L^{0.4}\left[\frac{1}{2}\left(\frac{\Delta\rho}{\rho_L}\right)^{0.2} + \frac{1}{8}\left(\frac{\rho_L}{\Delta\rho}\right)^{0.8}\right] \tag{2.19}$$

Neglecting the effect of the density of lighter fluid, the simplified point-sink analysis reduced the model in the following form,

$$\frac{h_{OGE,SB}}{d} = 0.625\ Fr_L^{0.4} \tag{2.20}$$

For the finite-branch analysis, continuity equation solved by Fourier cosine and Fourier sine transformations. Comparison between finite-branch analysis and point-sink analysis showed large deviation when Fr less than 1.0 because of the strong influence of viscous force and surface tension. The magnitude of deviation was about 80% at Fr_L equal to 0.01, 15% at Fr_L equal to 1.0, and 3% at Fr_L equal to 10. The authors validated both the models with experimental results found by Parrot et al. (1991), Hassan et al. (1998), Smoglie and Riemann (1986). The finite- branch model predicted the data trend of Parrot et al. (1991) at less than 2.5%, and the data trend of Hassan et al. (1998) at less than 10%. The point-sink model predicted the data trend of Smoglie and Riemann (1986) in good agreement with different branch sizes.

Ahmed et al. (2004) extended the work of Ahmed et al. (2003) of single discharge. They carried out a theoretical analysis for the OGE of upper and lower side branches during dual discharge from a stratified two-phase region. The analysis used the case of vertical wall mounting of the branches with the centreline of the branches falling on a vertical plane. Point-sink model and finite-branch model was developed to predict OGE. Their predicted OGE was a function of the corresponding Froude number of each branch and the vertical distance between the centrelines of the two branches. The value of OGE found consistent with the experimental data of Parrott et al. (1991) and Hassan et al. (1996a) for dual discharge. The developed models showed that if the Froude number of the lower branch increased, the height of OGE of the upper branch was also increased.

The OGE phenomena were investigated experimentally by Bartley et al. (2008) with a circular branch of diameter 6.35 mm mounted on a flat plane. This flat plane placed in a large tank containing a stratified mixture of air and water under pressure of 317 kPa and 520 kPa for the experiments. The flat plane varied at an angle of 0^0, 30^0, 60^0, and 90^0 with respect to the top of the vertical plane in clockwise direction as well as in counter clockwise direction. In case of the clockwise movement of the flat plane, the angle was assumed positive while counter clockwise movement assumed as negative angle. On the other hand, if the flat plane moved counter clockwise then angle was assumed negative. Neglecting surface tension effect, empirical correlation proposed for horizontal branch as;

$$\frac{h_{OGE,SB}}{d} = 0.475\ Fr_L^{0.444} \tag{2.21}$$

They found a new trend of negative $\frac{h_{OGE}}{d}$ at low Froude numbers when a branch mounted at -30^0 and -60^0. According to the investigators, this is obvious, as the surface tension force became significant at lower Froude numbers. Therefore, the flow of liquid was not strong enough to break the meniscus formed at the top edge of the branch. This new trend might be because the size of the branch was comparable with that of the meniscus size.

Bowden and Hassan (2009) modelled the critical height at the OGE, in a single branch oriented vertically downward from a stratified gas-liquid region. Two different cases investigated in the analysis, first, without the liquid velocity in the test chamber, and second with the uniform velocity of the liquid moving along the axial direction of the chamber. The latter case termed as cross flow of liquid in the test chamber. The flow field assumed quasisteady, incompressible, inviscid, and irrotational, with negligible surface tension to reduce the problem to a potential flow. Thus, the potential flow problem was governed by forces of inertia and gravity and modelled as point-sink with uniform cross flow in the test chamber. The analysis carried out on the effect of cross flow on h_{OGE} showed that, as cross flow increased the h_{OGE} decreased for the bottom branch for vortex free entrainment. For low Fr_L the effect of cross flow on h_{OGE} was more pronounced. Neglecting the effect of lighter density fluid and cross flow of liquid, the equation proposed as;

$$\frac{h_{OGE,BB}}{d} = 0.625\ Fr_L^{0.4} \tag{2.22}$$

The above model showed the maximum error of ± 30%, when compared with experimental results of Andaleeb et al. (2006), Bowden and Hassan (2007), Ahmad and Hassan (2006), Hassan et al. (1997), Abdalla and Berenyi (1969), and Lubin and Springer (1967).

The critical height at OGE with cross flow comparison with correlations developed by Smoglie and Reimann, (1986), Schrock et al. (1986), Kowalski and Krishnan (1987), and Yonomoto and Tasaka (1991). The poor agreement between these correlations and the OGE model with cross flow was observed. The authors did not give the reason for the disagreement explicitly.

First time commercial ANSYS CFX 14.5 CFD codes used by Guyot et al. (2014) to develop a numerical model to predict the height of OGE. They selected simple geometry with a rectangular tank of 246 × 125 × 720 mm size with a small side branch of square cross-section of 6 × 6 mm with a length of 120 mm. Air and water used to stimulate the study. A steady P_{TC} was imposed on the top surface of water and zero pressure was imposed at the outlet of the branch. The water flow rate entering the tank were adjusted to the water flow rate exiting the branch, and iterations continued until the liquid height, P_{TC} and mass flow rates of water and air entering and exiting the tank became steady with time. The authors used 1.3 to 1.8 million nodes to find a simple correlation in the form of,

$$\frac{h_{OGE,SB}}{d} = 0.636\ Fr_L^{0.39} \tag{2.23}$$

The authors compared h_{OGE} and found in good agreement with the experimental results of Yonomoto and Tasaka (1991) and Hassan et al. (1998).

However, the authors reported the time needed to converge the results was excessive of the order of weeks for one data point using 8-core computational facility.

2.4 OGE Studies with Branches Mounted On a Curved Surface

This section reviews the literature related to side, inclined and bottom branches mounted either on semi-circular or circular surface.

Reimann and Khan (1984) experimentally investigated OGE of bottom branches consisted of 6 mm and 12 mm diameter with length of 75 mm. The horizontal two-phase test chamber was 0.206 m in diameter pipe charged with air at 0.5MPa pressure. The ΔP varied between 10 kPa to 400 kPa with the help of throttle valve provided at the downstream of the branch. The interface height was peculiarly determined by the input flow rate to the test chamber. The lowest 14.00 mm interface height determined with the 0.2 kg/s of liquid mass flow rate, while 94.76 mm interface height determined with the 11.0 kg/s of liquid mass flow rate. Besides, they observed no change in OGE of the bottom branch with respect to the change in the input mass flow of gas. The investigators observed the dependency of onset because of either vortex, vortex induced or vortex-free gas pull through depending on the gas and liquid flow direction towards the bottom branch from the test chamber. In the first condition of vortex gas pull through, the horizontal test chamber opened from both the sides such that, the gas and liquid could flow towards the bottom branch axisymmetrically from all the direction. A weak vortex gas pull through occurred, but disappeared again at a certain lower interface height. After that, a sudden vortex-free gas pull through observed. In case of the vortex induced gas pull through, the gas and liquid entered the test chamber from one end and did not leave the chamber from the other end. A thin gas tube was seen followed by stronger vortex induced gas pull through. In case of vortex-free or continuous gas pull through, first gas bubble pull through viewed, followed by a strong continuous gas pull through. The vortex OGE correlation resulted similar correlation as presented by Lubin and Hurwitz (1966), equation (2.4). They developed correlation for vortex induced and vortex-free or OGE as;

For vortex induced OGE of bottom branch,

$$\frac{h_{OGE,BB}}{d} = 1.904\ Fr_L^{0.4} \tag{2.24}$$

For first gas bubble OGE of bottom branch,

$$\frac{h_{OGE,BB}}{d} = 1.025\ Fr_L^{0.4} \tag{2.25}$$

And for vortex free or continuous OGE of bottom branch,

$$\frac{h_{OGE,BB}}{d} = 0.963\ Fr_L^{0.4} \tag{2.26}$$

Experiment carried out by Smoglie and Reimann (1986) was on air-water flows through branches simulated by the pipe stubs of various diameters placed at the bottom, and horizontal side. They used the experimental setup of Reimann and Khan (1984). The experiment was conducted at steady state and unsteady state to visualize onset of gas entrainment for vortex and vortex free flow at room temperature. The circular test chamber pressurized to 5.0 bar. Various branches of 6, 8, 12, or 20 mm inner diameter were used to find the critical height at the OGE. The pressure difference between test chamber and branch was varied between 0.1 and 4.0 bar by the throttle valve connected to the downstream of the branch. To find out the gas entrainment in horizontal and bottom branch, two methods were used. In the first method, the liquid height in the chamber kept constant and gradually pressure difference was increased. In the second method, the system pressure kept constant, and slowly liquid height in the chamber was decreased at the rate of 3 mm/min. The investigators developed empirical correlation for the onset of gas entrainment as a function of Froude number and branch diameter as,

For the vortex-free OGE side branch,

$$\frac{h_{OGE,SB}}{d} = 0.681\ Fr_L^{0.4} \tag{2.27}$$

For the vortex OGE of bottom branch,

$$\frac{h_{OGE,BB}}{d} = 1.816\ Fr_L^{0.4} \tag{2.28}$$

For the vortex free OGE of bottom branch,

$$\frac{h_{OGE,BB}}{d} = 0.626\ Fr_L^{0.4} \tag{2.29}$$

Schrock et al. (1986) carried out experiments with air-water and steam-water fluids for the OGE, at the side and bottom branch of 4, 6, and 10 mm diameter. The experimental test facility consisted of 102 mm diameter horizontal pipe pressurized up to a pressure of 1.07 MPa. Considering the effect of viscosity (μ_L), and surface tension (σ_L) a new form of correlation proposed by relating viscosity number (N_μ), Bond number (B_O), and Froude number as,

For side branch,

$$\frac{Fr_L\ {B_O}^2}{\sqrt{N_\mu}} = 40.6 \left(\frac{h_{OGE,SB}}{\sqrt{\frac{\sigma_L}{g\ (\rho_L - \rho_G)}}} \right)^{2.2} \tag{2.30}$$

For bottom branch,

$$\frac{Fr_L \, B_O^{\,2}}{\sqrt{N_\mu}} = 19.4 \left(\frac{h_{OGE,BB}}{\sqrt{\frac{\sigma_L}{g\,(\rho_L - \rho_G)}}} \right)^{2.2} \tag{2.31}$$

The effect of σ_L is accounted in the B_O defined as,

$$B_O = \frac{d}{\sqrt{\frac{\sigma_L}{g\,(\rho_L - \rho_G)}}} \tag{2.32}$$

The effect of μ_L is accounted in the N_μ defined as,

$$N_\mu = \mu_L \left(\frac{g\,(\rho_L - \rho_G)}{\rho_L^{\,2}\,\sigma_L^{\,3}} \right)^{0.25} \tag{2.33}$$

Hassan et al. (1997) further studied the single, dual, and triple discharge from a stratified air-water region. Three branches of 6.35 mm diameter were drilled at 0^0, 45^0, and 90^0 in a semicircular shape brass block of diameter 50.8 mm. The investigators defended the use semicircular test section giving the reasons that it helped for better flow visualization, ease of measuring interface height about the branches, and a good approximation of the circular cross-section geometry with five branches, as in case of real header-feeder system of PHWR. The study showed the flow from the 90^0 branch was independent, whether the flow was present in the 0^0 or 45^0 branches. Based on this fact, the investigators assumed that it was unlikely for the missing two branches of the other half of the header to have any impact on the flow from the bottom branch. Further, the missing two branches were far enough to make any influence on 0^0 or 45^0 branch. The comparison of their previous investigations on a flat wall with single and dual branches revealed the strong influence of wall curvature on the branch flow. However, the investigation gave limited information for OGE as their focus was on the mass flow rate and two-phase quality.

The experimental work of Hassan et al. (1997) was extended by Ahmad and Hassan (2006) on single, dual and triple discharges by covering the large range of Froude numbers, using the same experimental setup. The branches of 6.35 mm diameter were mounted at an angle of 0^0, 45^0, and 90^0 from the horizontal on the semicircular wall of 50.8 mm diameter. The dimensions of branch diameter and the header were approximately $1/8^{\mathrm{th}}$ of CANDU header-feeder system. For easy viewing the flow phenomena occurring at the branches, a semi-circular shape of the header used, and camera was mounted at the transparent test section. The meniscus height of water in single discharge was considered to calculate h_{OGE} of single discharge and found in good agreement with Hassan et al. (1997). While comparing the single discharge, dual discharge h_{OGE} of horizontal branch increased with the increase of the Froude number of inclined branch while the activation of the vertical branch had a minor effect on it. On the other hand, h_{OGE} of an inclined branch during dual discharge decreased compared to single discharge with respect to increase of Froude number in horizontal branch. For low Froude number, h_{OGE} of horizontal branch during triple discharge showed significant deviations compared to single discharge and dual discharge. The authors argued that divergence is due to higher inertia force developed due to activation of inclined and vertical branches. As a general trend highest h_{OGE} was observed during triple discharge, then dual discharge and single discharge.

The point sink analysis and two-dimensional finite branch analysis were carried out by Andaleeb et al. (2006) for the OGE of single branch located on a semi-circular wall under stratified region. For theoretical model development, three different combinations of a single branch mounted at 0^0, 45^0, and 90^0 with respect to horizontal were considered to predict the OGE. The critical height at the OGE for point sink analysis was predicted by using special numerical technique, and for finite branch analysis, the OGE was predicted by potential function. The authors pointed out significant deviation between their results and the results of Ahmad and Hassan (2006) for the horizontal branch. This deviation was because of the branches mounted on the semi-circular wall instead of on the flat wall. At low Fr_L, point-sink analysis predicted 50% higher h_{OGE} and at moderate Fr_L 32% lower h_{OGE} compared to finite-branch analysis. At higher Froude number, the difference between the h_{OGE} predicted by the point-sink analysis and finite-branch analysis was negligible. The h_{OGE} comparison with Hassan et al. (1997), Smoglie and Reimann (1986), Parrot et al. (1991), and Ahmad and Hassan (2006) showed that finite-branch analysis was in good agreement compared to the point-sink analysis for all the branch combinations.

Lee et al. (2007) carried out semi-theoretical and experimental investigation to understand the effect of branch diameter and direction of branch pipe on OGE. A single branch of 16.0 mm or 24.8 mm mounted at 0^0, 30^0, 45^0, 60^0, and 90^0 attached to the circular test chamber of 184 mm diameter. The inertial and gravitational force balance at the stratified interface surface of the gas and liquid assumed to develop the semi-theoretical model. A hypothetical spherical surface of uniform liquid velocity proposed in the vicinity of the branch to determineh_{OGE}. The authors could not produce the data for 0^0 branch angle because of an unsteady liquid level near the branch.

The following semi-theoretical correlation proposed by considering the effect of diameter ratio of header to the branch diameter and the inclination angle.

Semi-theoretical correlation for side branch,

$$\frac{h_{OGE,SB}}{d} = 0.681\ Fr_L^{0.4} \quad (2.34)$$

Semi-theoretical correlation for inclined branch,

$$\frac{h_{OGE,IB}}{d} = 2.041\ Fr_L^{0.4} - \left(0.8535\ \left(\frac{D}{d}\right)\right) \quad (2.35)$$

Semi-theoretical correlation for bottom branch,

$$\frac{h_{OGE,BB}}{d} = 1.816\ Fr_L^{0.4} - \left(\frac{D}{d}\right) \quad (2.36)$$

During the comparison by the authors, the data showed disagreement in the trend with RELAP5/MOD3 and Reimann and Khan (1984). The authors argued that disagreement in the trend was because of instability in the flow at the branches.

First time for inclined branch, Lee et al. (2007) gave the correlation. Therefore, Barteley et al (2008) compared their results of inclined branch with Lee et al. (2007), even though their branch mounted on inclined plane. The deviation in their results was attributed to different branch geometry used by Lee et al. (2007).

Saleh et al. (2009) developed a hybrid model to predict OGE of single downward branch in stratified region. This model combined a point-sink model and Kelvin-Laplace equation to accommodate the effects of surface tension. The results of the analysis compared with the experimental work of Ahmad and Hassan (2006). At the low Froude numbers the analytical model, diverged from the experimental results. It was hypothesized this was because of the surface tension effects. To address this point, investigators used the dip radius of curvature obtained by empirical method to compensate the effect of surface tension. As a result, the predicted critical height at low Froude numbers, showed excellent agreement with experimental data of Ahmad and Hassan (2006) compared to simple point-sink models.

Bowden and Hassan (2011) performed experiments to investigated single discharge OGE with co-current flow of air and water in smooth stratified test chamber. The test section was having three branches of 6.35 mm diameter attached to 50.8 mm diameter inlet pipe made from transparent acrylic rod. These branches oriented at 0^0, 45^0, and 90^0 down from the horizontal. The hydraulic resistance 'R' of all the branches adjusted at 1032 $(kg.m)^{-1/2}$ with the spread of 50 $(kg.m)^{-1/2}$ and the test chamber pressure kept at 206 kPa. Three different ΔP, 34.5 kPa, 51.7 kPa and 68.9 kPa were selected for the study. Initially, in the test section the water was filled up to 25.4 mm height, and equilibrium between the liquid and gas inlet mass flow and outlet liquid and gas mass flow in the test chamber was established without activating any branches. After that, any one branch under the study activated. This disturbed the flow equilibrium in the test chamber as inlet liquid and gas mass flow was less than the outlet liquid and gas mass flow through the activated branch and exit of the test chamber. The equilibrium between the inlet liquid and gas mass flow and outlet liquid and gas mass flow was again established by increasing the liquid and gas mass flow entering the test chamber. The critical height was obtained by gradually lowering the liquid height in the test chamber. The above procedure was followed for all the single discharge studies. Therefore, the authors could not record critical height for side branch as the initial interface height in the test section was below the critical height of the side branch.

For inclined branch, the empirical correlation of smooth stratified flow given as,

The empirical correlation for inclined branch was given as,

$$\frac{h_{OGE,IB}}{d} = 1.840\ Fr_L^{0.4}\ ;\ \text{For}\ 2 \leq\ Fr_L \leq 9 \tag{2.37}$$

The experimental critical height at OGE was in good agreement with the results of Ahmad and Hassan (2006), and Hassan et al. (1997).

The empirical correlation for bottom branch was given as,

$$\frac{h_{OGE,BB}}{d} = 1.072\ Fr_L^{0.45}\ ;\ \text{For}\ 2 \leq Fr_L \leq 30 \tag{2.38}$$

The authors compared the above correlation with various studies conducted by Ahmad and Hassan (2006), Hassan et al. (1997), Lubin and Springer (1967), Smoglie and Reimann (1986), Schrock et al. (1986), and Yonomoto and Tasaka (1991). The best agreement was found with Smoglie and Reimann (1986), Schrock et al. (1986) among above studies.

2.5 Closure

The literature review was organized into three main sections relating to OGE, commencement of OGE study for LOCA, studies for the branches mounted on a flat surface, and studies for the branches mounted on a curved surface.

The previous literature review shows that substantial information available for a single discharge. In particular, three theoretical models were reviewed for predicting the OGE in which two models were for side branch and one model for bottom branch. Ahmad and Hassan (2006) provided extensive data for OGE on single, dual, and triple discharges. The data for the dual and triple discharge OGE considered the case of variable Fr_L of the branches.

Table 2.1 describes relevant experimental details and provides summaries of semi-empirical, empirical, and theoretical models available for vortex-free OGE. This shows remarkable different prediction of critical height at OGE in comparison to each other. This difference may be the result of different ratio of header size to branch size, different experimental condition, or different mounting surfaces of the branches. There are also few studies dealing with dual and triple discharges branches showed that multiple discharge can affect the OGE in the header. Thus, in a situation where discharge takes place simultaneously at the same cross-section of pipe, and with the different combinations of branches, such as the case with the cooling headers of the PHWR nuclear reactor, the existing correlations for the OGE may not apply.

Several situations of multiple discharges for different combinations of the branches at the same cross-section are still not investigated. This investigation is intended to provide better understanding of the OGE during different combinations of the branches for multiple discharges, where discharge from a stratified reservoir is induced through the branches of the same diameter mounted on a curved surface.

Table 2.1: Description of the relevant coefficients for vortex-free OGE of single discharge investigations

Investigators	Mounting surface of branch	Branch orientation	Correlation	OGE coefficients		Fr_L range	Branch size d (mm)	Header size D (mm)
				C_1	C_2			
Yonomoto and Tasaka (1988)	Vertical wall	Side (0^0)	Empirical	0.681	0.400	X	Ø10 and Ø20	190 × 190 (Square)
Parrott et al. (1991)				0.887	0.334	0 to70	Ø6.35	Ø255
Hassan et al. (1998)				0.570	0.400	10 to 70	Ø6.35	Ø255
Bartley et al. (2008)				0.475	0.444	1.5 to 70	Ø6.35	Ø305
Ahmed et al. (2003)			Theoretical	0.625	0.400	X	Circular	X
Guyot et al. (2014)				0.636	0.390	X	6 × 6 (Square)	246 × 125 (Rectangular)
Lubin and Hurwitz (1966)	Horizontal wall	Bottom (90^0)	Empirical	0.624	0.400	0.1 to 14	Circular	Circular
Yonomoto and Tasaka (1988)				0.909	0.400	X	Ø10 and Ø20	190 × 190 (Square)
Bowden and Hassan (2009)			Theoretical	0.625	0.400	X	Circular	X

Table 2.1 : Description of the relevant coefficients for vortex-free OGE of single discharge investigations (cont.)

Investigators	Mounting surface of branch	Branch orientation	Correlation	OGE coefficients		Fr_L range	Branch size d (mm)	Header size D (mm)
				C_1	C_2			
Smoglie and Reimann (1986)	Circular wall	Side (0^0)	Empirical	0.681	0.400	10 to70	Ø6, Ø8, Ø12, and Ø20	Ø206
Lee et al. (2007)			Semi-empirical	0.681	0.400	2 to30	Ø16 and Ø24.8	Ø184
Bowden and Hassan (2011)		Inclined (45^0)	Empirical	1.840	0.400	2 to 9	Ø6.35	Ø50.8
Reimann and Khan (1984)		Bottom (90^0)	Empirical	0.963	0.400	10 to70	Ø6 and Ø12	Ø206
Smoglie and Reimann (1986)				0.626	0.400	1 to110	Ø6, Ø8, Ø12, and Ø20	Ø206
Bowden and Hassan (2011)				1.072	0.450	2 to 30	Ø6.35	Ø50.8