Fluctuating Phenomena and Flow Control of Bubbly Two-Phase Flow Through Sudden Expansion Pipe*

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Abstract
The fluctuating flow phenomena on a two-phase flow through a vertical sudden expansion pipe system are investigated experimentally and visually. The effect of the volumetric gas flow rate ratio within the range of bubbly flow is investigated. Simple flow control methods are proposed and tested in comparison with the normal expansion case. The first method applies control by mounting a ring shaped obstacle downstream the expansion, and the second by mounting a step-ring just downstream. These two methods are based on a different control concept. The first is based on splitting the vortex region, thus decreasing its intensity, and the second on decreasing the overall generated vortex region length. In single-phase flow, only one dominant frequency is observed. However, when gas is induced, two dominant peaks appear and a tendency of the second peak to shift to lower frequency values when increasing the volumetric gas fraction is observed. When the flow control methods are applied, the fluctuation frequency is not affected, but the fluctuation amplitude decreases. From pressure distribution measurements under several flow conditions, it was confirmed that when the flow control methods are applied, drag reduction is achieved as well.

Key words: Sudden Expansion Pipe, Bubbly Flow, Fluctuating Flow, Flow Control, Drag Reduction

1. Introduction
A gas-liquid two-phase flow system can be seen in a wide range of areas in advanced and conventional technologies. Energy conversion systems including nuclear power plants, petro-chemical plants, necessities of thermal management and power acquisition systems in space applications are only a few examples. Due to its physical and practical significance, as well as its feature complexity, many studies regarding phase change and flow regimes for various conditions (Choi and Fujii(1), Noghrehkar and Kawaji, et al.(2), Kelesidis and Dukler(3)), liquid velocity distribution and micro bubble size characteristics (Serizawa and Tomiyama, et al.(4),(6), Horie and Shirakawa, et al.(5), Zhang, Epstein and Grace(7)) have been carried out both experimentally and numerically in straight pipes, ducts and other. Similarly, many studies of gas-liquid two-phase flow past obstacles of various shapes and sizes, as well as aeration, have been extensively studied over several decades by many authors (Inoue, et al.(8), Shakouchi, et al.(9)-(11), Fdhila, et al.(12)) and information on their physical properties, bubble interaction forces and turbulence can be found in the bibliography(13)-(16). However, studies concerning a gas-liquid two-phase flow system, which consists abrupt changes such as sudden contraction and expansion have not to the author’s knowledge, been...
extensively carried out. Previously, two-phase flow in a sudden contraction pipe has been studied \((17)\)-(\(20\)) and gas-pocket phenomenon under high bubbly flow conditions just downstream the contraction was observed. In such cases, not only is the generation of vortex region affected significantly, but also has a direct effect on heat transfer mechanism that causes severe safety problems as well. In addition, fluctuation phenomena were observed that showed a dependency not only to superficial velocities, but void fraction as well. A simple flow control method was proposed and the results in fluctuation suppression and drag reduction were presented.

The importance in understanding the flow behavior and the effect of parameters such as liquid velocity in combination with gas fraction is obvious, as they can be seen in almost every mechanical system including oil transfer piping systems and heat exchangers.

In this study, two-phase flow through a vertical upward sudden expansion pipe and the fluctuating flow phenomena downstream are investigated. Simple and economic flow control methods are then proposed. The first method looks at mounting an annular shaped obstacle (ring) downstream the expansion at various distances [Fig. 2(a)], by which the flow is separated and the main vortex region is divided in two. The second proposition suggests mounting a step-ring [Fig. 2(b)] just downstream the expansion, where the vortex region is suppressed in size, reducing the losses due to the expansion effect.

Experimental and visual analyses were conducted for a wide range of parameters such as \(Re\) number, volumetric gas flow rate ratio, and ring position of which the comparative results are presented below. The effect on the fluctuation phenomena as well as the losses due to the expansion, are presented and discussed.

### Nomenclature

\[
\begin{align*}
A & : \text{ sudden expansion area ratio} \\
C_P & : \text{ pressure coefficient} \\
d_b & : \text{ bubble mean diameter [mm]} \\
d_1, d_2 & : \text{ pipe inner diameter [mm]} \\
g & : \text{ gravity acceleration [m/sec}^2\text{]} \\
H & : \text{ expansion step height, } (d_1-d_2)/2 \text{ [mm]} \\
h & : \text{ ring height (2H/5) [mm]} \\
h' & : \text{ step-ring height [mm]} \\
b & : \text{ step-ring width [mm]} \\
L & : \text{ length of experimental set-up [mm]} \\
L_r & : \text{ length installation of ring from expansion step [mm]} \\
D_R & : \text{ drag reduction rate [%]} \\
p & : \text{ pressure [kPa]} \\
P_l & : \text{ pressure loss coefficient} \\
Q & : \text{ flow rate [m}^3\text{/sec]} \\
U & : \text{ downstream velocity [m/sec]} \\
Re & : \text{ Reynolds number, } = Ud_2/\nu
\end{align*}
\]

#### Subscripts

\[
\begin{align*}
a & : \text{ air phase} \\
b & : \text{ bubble} \\
d & : \text{ downstream area} \\
e & : \text{ elevation} \\
m & : \text{ mean value} \\
v & : \text{ volumetric rate} \\
w & : \text{ water phase} \\
g & : \text{ gas phase} \\
t & : \text{ two phase} \\
\text{ref} & : \text{ pressure reference point}
\end{align*}
\]

#### Greeks

\[
\begin{align*}
\alpha_v & : \text{ volumetric gas flow rate ratio, } = Q_a/(Q_w+Q_a) \text{ [%]} \\
\Delta P & : \text{ expansion loss} \\
\varepsilon & : \text{ pressure gradient} \\
\nu & : \text{ kinematic viscosity of water [m}^2\text{/sec]} \\
\rho & : \text{ density [kg/m}^3\text{]}
\end{align*}
\]

### 2. Experimental Facility

The test section is made of a transparent acrylic acid resin channel with a total length of \(L=3950\text{mm}\). A water pump provides the necessary flow to pass through a float type water flow meter. An air compressor connected to an air dryer provides the necessary amount of
air, which passes through the air flow meter. As a bubble generator, a 150mm long and 20mm diameter porous fine ceramic, with porous diameter of approximately 0.01mm is installed at the center of the pipe upstream and the volumetric gas flow rate ratio is varied from $\alpha_v=0$~$30\%$. The water temperature is maintained constant, and the mean bubble diameter, measured at distance $2d_2$ upstream the expansion (Fig.1), is found to be approximately $d_b=2.5$mm, for $Re=1.0\times10^4$ and $\alpha_v=10\%$, from visualization results.

Figure 1 illustrates the schematic of the expansion area. The small pipe is of inner diameter $d_1=30$mm and the large pipe downstream is of $d_2=70$mm respectively ($A = 0.18$). Pressure taps of 0.8mm diameter are drilled prior to, and after the expansion, covering a distance of $8d_1$. As a reference point, a pressure hole at distance $2.14d_2$ prior to the expansion, where the flow is considered stable was chosen and a water column manometer measures the pressure difference from the reference point. Since pressure measurements in two-phase flow are instable, they were taken several times and the mean value was considered.

In order to achieve flow control, two methods are proposed and investigated in this study. The first method is by mounting an annular shaped obstacle (ring) of height $h=0.4H$ at various distances of $L_r=(2~5)H$, downstream the expansion area. The second method is that of mounting a step-ring of $b=10$mm width and height of $h'=0.875H$, as shown in the schematic (Fig.2).

When conducting visualization experiments of two-phase flow, the bubbles movements were observed, while styrene beads of 0.25mm diameter and 1.02kg/m$^3$ density were used as tracers for the case of single-phase flow. The flow was observed and recorded by a digital video camera and a digital high-speed video camera with shutter speed set at 1/4000 and frame rate at 240FPS, where a 5mm slit of light from halogen lamps were used to illuminate the flow passage. The test section, in which the visual observations were made, was immersed into a transparent container filled with water in order to hold off the distortion that occurs as a result of the pipe-wall curvature.

Time series data of the pressure fluctuation were measured with a semi-conductor type pressure transducer installed at distance $13.5d_2$ downstream the expansion. The pressure transducer and probe were connected to an oscilloscope (Kanomax, TDS 2002 series) and recorded by a personal computer.

Experiments were conducted under $Re=1.0\sim3.0 \times 10^4$, or in different terms, superficial liquid velocity $j_{wl}=0.14$~$0.51$ m/s. The flow regime under these conditions upstream the
expansion can be expressed as undisturbed bubbly and agitated bubbly.

3. Results and Discussion

3.1 Mean Flow Pattern

Figure 3 illustrates the schematic sketch of the flow stream into the expansion area. In the normal expansion case, Fig.3 (a), upstream the reattachment points the main vortex area is generated (vortex I) and an absolute gas-free area exists due to the buoyancy force acting on the bubbles. From flow visualization conducted in single-phase flow using tracers, it was confirmed that a secondary small vortex region exists (vortex II) at the corner of the expansion wall. This small vortex area was observed for all conditions but bubbles did not usually reach this area.

The length of the area is related to the liquid velocity, which affects the vorticity, and the bubble size induced into the flow. This up and down bubble movement trapped in the force balance between vortex and buoyancy force in combination with the already existing turbulence caused by the two-phase flow, affects the flow significantly and cause flow instability resulting in pressure fluctuating phenomena.

In Fig.3 (b), the flow when a ring is mounted is shown. The concept of this method is to extend the vortex region in total length by creating a bounding step and to cut in two the main vortex region, meaning that the absolute vorticity will be reduced. Since the low-pressure region within the vortex core will be suppressed, the forces responsible for the fluctuating flow and the losses generated from it will be suppressed as well. In Fig.3 (c) the flow pattern when a step-ring is mounted is shown. In this case, instead of extending the vortex region as was previously done, adjusting this leading edge shortens the length of the vortex region. Therefore, the flow reattaches at an earlier stage affecting the downstream flow in respect of losses and fluctuation.

3.2 Visualized Flow Pattern

Extended visualization experiments were conducted in order to observe the flow pattern downstream the expansion area. A digital video camera and a digital high-speed camera were used, and flow conditions in respect to Reynolds number and volumetric gas fraction were recorded.

In Fig.4 (a), the visual
result for the case of normal expansion is illustrated under the given flow conditions. The arrow line shows the average length of vortex region. It is clearly seen that a gas-free region exists just downstream the expanded area, where the recirculation zone is generated. It was observed that the area of this region is strongly affected by the superficial liquid velocity, which affects the overall reattachment point as well. Tracking the bubbles, an almost periodical up and down movement was recorded, which is easily understood if the downwards-acting force due to vortex generation and buoyancy force of the bubbles is considered. Moreover, even though dealing with an axisymmetric sudden expansion, small changes in the force balance within the vortex (I) region, cause instabilities in the flow and pressure fluctuation takes place, which is discussed in the following section.

In Fig.4 (b), results under the same flow conditions but with ring mounted is shown. It is clearly observed that the vortex region generated is divided in two sections as was explained previously. The reattachment point was extended, but further flow differences were difficult to be proved.

Finally in Fig.4 (c), the result when the step-ring is attached is shown. As expected, the flow reattaches at an earlier position compared to the normal expansion and the gas-free region was suppressed as well. These kinds of changes affect the overall flow pattern, but sufficient information was difficult to retrieve, and further investigation considering the fluctuating phenomena downstream was conducted.

3.3 Pressure Fluctuation

Time series data of pressure fluctuation were measured for the three cases mentioned. The effect on the flow was investigated and FFT analysis was conducted.

At the first stage, the fluctuating phenomena for a normal expansion pipe were investigated. For the case of single-phase flow the frequency value of the fluctuation was maintained almost constant at approximately 1~1.2Hz for all the investigated Reynolds number, which is the same with the case of a sudden contraction [20], as shown at Fig.5.

Interesting data are retrieved
when gas is inserted in the flow and a two-phase flow system is evaluated. It was found that by increasing the volumetric gas fraction, two dominant peaks appear. The first peak, in the same frequency with the case of single-phase flow, and a second peak in a higher frequency range of 8.8Hz for the case of \( Re = 1.0 \times 10^4 \) and \( \alpha_v = 1.5\% \) as shown in Fig.6.

Thereafter, by increasing the volumetric gas flow rate it was observed that the frequency of the second primary peak shows a tendency to shift to lower frequencies. The more the gas volume is increased, the more the frequency drops to lower values until it reaches a constant value of approximately 2.2Hz as shown in Fig.7, under steady Reynolds number. This phenomena and the effect of gas fraction on the fluctuation phenomena, investigated under different Reynolds number showed similar results. However, the original starting value of the second peak when \( \alpha_v = 1.5\% \), was lower when the \( Re \) number was higher, as shown in the same figure. In addition, the effect of liquid velocity was stronger for low gas fraction than high. Moreover, under all \( Re \) number, when the gas fraction was set at \( \alpha_v = 30\% \) the second peak took almost the same frequency of 2.2Hz. This denotes that the effect of the liquid velocity is stronger at low gas fractions.

One thing to be noted, is that for the case of \( Re = 3.0 \times 10^4 \), the first peak at approximately 1Hz, could not be observed besides the single-phase flow case and only the second peak appears. Even though the second peak shows a pattern agreement under all \( Re \) number, concerning the first peak it differentiates than the other two lower liquid velocity cases.

Since the second dominate peak appears only for the case of two-phase flow, it is most definite that the cause lays to the effect of bubbles into the system. The relation of \( Re \) and \( \alpha_v \) is clear. As a first explanation model, the volume effect is considered. Under small gas volume the generated vortex zone affects strongly the movement and gives high frequency values. Increasing the gas volume, the
manipulation of the system becomes harder and slows the fluctuation frequency. However, since differences appear for high Reynolds number, the exact physical mechanism explaining completely this phenomenon requires an even more thorough investigation.

After the results of the fluctuation phenomena were extracted for the normal expansion, similar measurements when applying the flow control methods were conducted.

Figure 8, illustrates the FFT analysis result for $Re=1.0 \times 10^4$ and $\alpha_v=5\%$ for the case of normal expansion and ring position at $L_r/H=3$ were a maximum PSD value reduction of $\cong 71\%$ was attained. As shown, two primary peaks are observed at 1 Hz and 5 Hz for both cases, which means that the frequency is not affected by the obstacle. Moreover, under the same Reynolds number for lower gas fraction it showed the second peak at 9 Hz, while increasing $\alpha_v$, a peak-to-peak distance shortening was observed, which is exactly the same with the normal expansion. In addition, for different flow conditions the optimum ring position varied, with a general tendency of which increasing $\alpha_v$, the ring position shifted at higher positions downstream. For the case of $Re=2.0 \times 10^4$ similar results were obtained. Finally for $Re=3.0 \times 10^4$, only one primary peak was observed in all $\alpha_v$ spectra (Fig.9), with the tendency of the frequency moving to lower values like the normal expansion case.

In Fig.10, the pressure fluctuation result when a step-ring is mounted is presented for the same flow conditions as Fig.8. The reduction of PSD value is clearly shown with 57% and 62% decrease respectively, which represents the fluctuation intensity, and means that the flow is more smoothly. Once again, the frequency values remain the same even after changing the expansion construction, while the same tendency towards lower frequency values when increasing $\alpha_v$ was observed. Since even applying the two flow control methods, having a different control concept, did not change the frequency values but just its intensity (PSD value), enable us to claim that the additives downstream the expansion do not affect the fluctuation frequency.

3.4 Pressure Distribution

The pressure distribution was measured between the pressure $p_1$ at the reference point, which is located at distance 2.14 $d_2$ upstream the expansion and the pressure $p_i$ taken at a distance $x$ from the reference point. The pressure coefficient is given as shown:

$$C_p=2(p_i-p_1-p_e)/(\rho U_m^2)$$

where, $p_e$ is the vertical elevation

![Fig.11 Pressure distribution, (Re=2.0×10^4)](image-url)
pressure (=\rho H_h H_h : \text{elevation between } p_1 \text{ and } p_i )

Figure 11 (a) illustrates the pressure distribution for the normal expansion case in single and two-phase flow, varying volumetric gas fraction, at \( Re=2.0 \times 10^4 \). The expansion is located at distance \( y/d_2=2.14 \) denoted by “SE” in the figure, while \( y/d_2=0 \) denotes the reference point. After the expansion, the pressure decreases for some distance due to the vortex region existence and then pressure recovery starts due to energy conversion from kinetic to dynamic, due to the expanded area. The flow stabilizes from \( y/d_2>7 \) downstream the expansion and for the case of single-phase flow, it follows the pressure decrease gradient (Eq. of Blasius) caused by friction losses. The equation giving this gradient is given below:

\[
\frac{\partial C_p}{\partial (y/d_2)} = -\lambda = -0.3164 \text{Re}^{-0.25}
\]  

(2)

The pressure gradient \( \varepsilon \) for area ratio \( A=0.18 \) calculated by the above equation is found to be \( \varepsilon =-0.0266 \) and is plotted with a solid line in Fig.11. The gradient extracted from the experimental results was \( \varepsilon =-0.0259 \) and shows good agreement with the value given by the equation. The experimental value \( \varepsilon \) is estimated by connecting two points at \( y/d_2=8.71 \) and 11.57.

From the pressure distribution measurements it is made apparent that by increasing the air volume ratio \( \alpha_v \%), the pressure gradient is increased (in absolute value), which means we have a larger slope. An increased gradient denotes an increase in the frictional factor. This is explained by the fact that when gas is inserted and the flow becomes two-phase we have an increase of the friction level in the pipe surface, the interaction between bubbles and interaction of bubble buoyancy force and downward vortex force. Just after the expansion area, the increase of gas fraction causes a lower pressure core at the vortex region. This is why increasing gas fraction, Fig.11, increases the absolute drop on the \( C_p \) value.

When pressure recovery, due to energy conversion, starts to take place (\( y/d_2>4 \)), two main parameters influence the process. The first is the size and intensity of the vortex area and the second is the interaction of bubbles in combination with the effect on the wall surface. Increasing \( \alpha_v \) both parameters increase, which gives the results presented. After the flow stabilizes (\( y/d_2>7 \)), the wall friction is increased with increasing \( \alpha_v \), since they generate additional small eddies near the wall and as a result we have different pressure gradients depending on \( \alpha_v \).

Pressure distribution results when ring is mounted at \( L_r/H=4 \) and with step-ring are shown in Fig.11 (b), (c), and the effect on the flow pattern and drag of the sudden expansion area are investigated. It is shown that by mounting an obstacle the pressure recovery is increased (higher values of \( C_p \)), meaning that losses at the expansion have been reduced and a higher amount of kinetic energy is reduced into dynamic. Mounting a ring divides the vortex area into two areas and reduces the vorticity, leading to the present results. After the recovery, the flow follows the same pattern as in the case of the normal expansion.

In Fig.11 (c), results for the step-ring mounted are illustrated. In this case, where the expansion area is smoothened, the pressure decrease observed in Fig.11 (a) was drastically reduced. The step-ring shortens the reattachment point and the vortex area reduces, which causes the pressure drop decrease. Pressure recovery occurs and like in Fig.11 (b) it has higher values than that of normal expansion, meaning that more energy is converted into dynamic. The concept is, as mentioned above, that the reattachment occurs at an earlier stage and smaller scale vortex region generates, which is directly related to the loss reduction.
3.5 Drag Reduction

In the previously section, the pressure distributions for the three cases were presented and a reference on their differences was made. From these results the drag of the expansion area is extracted and the pressure loss difference between the normal expansion and the two proposed methods is introduced as drag reduction rate $D_R\%$, in order to have a clear view of how much the losses have been reduced as shown in Fig.12. The expansion loss $\Delta P$ was evaluated by $\Delta P=|P_{E1}-P_{E2}|$, where $P_{E1}$ is the pressure at the expansion $y/d_2=2.14$, and $P_{E2}$ is the pressure at the expansion when the constant pressure gradient line is extended in $-y$ direction.

The drag reduction rate is presented in respect to the volumetric gas flow rate from single-phase up to 30% gas. For the whole range, a positive reduction rate is seen, meaning that flow control has been achieved. Similar positive results were attained for the rest of Reynolds number as well. In single-phase flow the reduction rate is similar with a diverging nozzle angle of approximately $\theta=30^\circ$.

Several choices to connect two pipes having different diameters exist with one of most common, that of a diverging nozzle. However, these kind of connecting methods have the disadvantage of being costly and requiring an extra mechanical process. Furthermore, there are cases and situations that a method that requires additional space (length), as for the case of a diverging nozzle, is not allowed. Considering these facts, the proposed flow control method in the present study requires minimum process and cost, while it does not require any additional spacing and can be adjusted and attached easily at any pipe diameters.

4. Conclusions

Upward two-phase flow with a sudden expansion was investigated under various flow conditions and two methods were proposed in order to achieve flow control in terms of fluctuation phenomena and sudden expansion losses.

(1) From flow visualization, it was made apparent that the gas free region observed just downstream the expansion is strongly affected by the Reynolds number and volumetric gas fraction.

(2) Fluctuation phenomena were investigated downstream the expansion, and the primary fluctuation frequency was affected significantly by gas fraction. Two primary peaks were observed up to $\alpha_v=20\%$, while just one was seen for higher values, showing a tendency to shift its frequency to lower values in all cases.

(3) When a ring was mounted, the frequency value did not change, which leads to the conclusion that the geometric structure does not affect it. In addition, increasing gas fraction the most effective ring position shifts downstream for all Re number.

(4) With the second flow-control method, that of installing a step-ring, the fluctuation frequency was not affected. However, the fluctuation intensity of the dominant peak was reduced significantly, reaching values up to 70% depending on the flow conditions.

(5) The losses occurring due to the expansion were investigated and by the proposed methods, drag reduction was achieved. Positive results could be retrieved at all conditions with values reaching up to 35%.
References


