Comparison of Gas–Liquid Flow Characteristics in Geometrically Different Swirl Generating Devices

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Abstract: The gas–liquid flow characteristics for blade, single, and the double-helical swirl elements were numerically investigated and compared in this work. The Euler–Euler model assuming bi-modal bubble size distributions was used. The experiment, conducted in a vertical pipe equipped with a static blade swirl element, was used as the basis for the computational fluid dynamics (CFD) simulations. In the experiment, high-resolution gamma-ray computed tomography (HireCT) was used to measure the gas volume fractions at several planes within the blade swirl element. The resulting calculated profiles of the pressure, liquid and gas velocities as well as the gas fraction showed a large influence of the swirl elements’ geometry. The evolution and characteristics of the calculated gas–liquid phase distributions in different measurement planes were found to be unique for each type of swirl element. A single gas core in the center of the pipe was observed from the simulation of the blade element, while multiple cores were observed from the simulations of the single and double helix elements. The cross-sectional gas distribution downstream of the single and double helical elements changed drastically within a relatively short distance downstream of the elements. In contrast, the single gas core downstream of the blade element was more stable.

Keywords: swirling flow; multiphase flow; inline separator; static mixer; CFD simulation; Euler–Euler

1. Introduction

Static swirl elements are usually used in inline gas–liquid separators and static mixers to produce swirling flow which is suitable for the separation and mixing process, respectively. For example, gas–liquid swirl vane separators are used in boiling water reactors (BWRs) to split a two-phase mixture from the reactor core into steam and water [1,2]. They are also seen in the thorium molten salt reactor (TMSR) to remove the fission gas [3,4]. In contrast to the separator, the static mixer is used for mixing gas with a liquid such as in the ozonation processes in wastewater treatment as well as scrubbing ammonia, hydrogen chloride, and hydrogen fluoride with water [5]. The use of swirl elements leads to a compact design of inline separators and static mixers which is beneficial in reducing the cost, solving limited space issues (e.g., in existing oil and gas production facilities), and also opens new opportunities, e.g., heavy oil and deep-water subsea applications [5–8].

The characteristics of gas–liquid flow may be highly influenced by the geometry of the swirl element. Yin et al. demonstrated that four different gas core structures may be formed upstream of the swirl element under the influence of the geometry and flow parameters [3,9]. However, despite the importance of understanding the influence of the geometric design, the knowledge obtained from both...
experimental and numerical studies is still limited [10]. Among those investigations, the experimental works done by Rabha et al. [5] and Putra et al. [11] provide valuable gas distribution profiles inside the helical static element and the blade element, respectively, which are useful for characterizing the multiphase flows inside the swirl generating devices. High-resolution measuring techniques, such as ultrafast electron beam X-ray tomography (UFXCT) and high-resolution gamma-ray computed tomography (HireCT), were used to provide radial gas-phase distributions [5,11]. Based on the work of Rabha et al. [5], Zidouni et al. [10] performed Euler–Euler computational fluid dynamics (CFD) simulations on gas–liquid flows in a single helical static mixer using a mono-dispersed bubble-sized distribution approach. Here, the diameter \( D \) of the mixer was 80 mm, and it was installed in a vertical pipe. They found that the inlet bubble size distributions, assumed in the simulation, did significantly affect the gas distribution profile inside the static mixer [10]. Putra et al. [11] presented Euler–Euler simulations for a blade swirl element in a vertical pipe \((D = 27 \text{ mm})\) using both mono-dispersed and bi-modal bubble size distribution approaches. They found that the bi-modal bubble size distribution approach can estimate the radial gas distribution at certain positions but not in the transitional flow region from bubbly to separated gas structures [11]. Considering the limitation in the available literature, more experimental and numerical studies are required to enhance the understanding of the flow characteristics around the various swirl generating devices.

In this present work, CFD studies were performed to investigate the characteristics of the gas–liquid flow around various geometrically different swirl generating devices. These were the blade element, the single helix, and the double helix (Figure 1). The blade was an in-house designed swirl element which was used in Reference [11], while the single helix was the common insert which can be found, for example, in References [5,10,12,13]. The double helix used in this study was similar to the one used in the single-phase CFD study in Reference [13]. The three considered swirl elements were used as examples. For the different applications, a large variety of designs can be found. It is important to note that the objective of this study was to investigate the influence of the swirl element geometry on gas–liquid flow characteristics in a general manner (i.e., not specific to a certain application, either separator or mixer) using CFD. Although a helical swirl element is usually used as a static mixer, in the case of gas–liquid flows where the density difference among those two phases are quite large, the helical swirl element can also act as a separator. This fact can be concluded from the experimental studies in References [5,14]. They used a single helical swirl element and found that the gas can be separated downwards of the element. In this study, the numerically calculated radial gas fraction profiles for the single and double helical swirl elements were compared to the experimentally determined and calculated gas fraction profiles for the blade element from our previous work [11]. The unique characteristic of gas–liquid flow for each swirl element type is presented and discussed in this study.
Figure 1. Design of the static swirl elements (3D view): (a) blade [11]; (b) single helix [5,10,12,13]; and (c) double helix [13].

2. Summary of Experimental Data

The experiment [11] was carried out on a vertical pipe packed with an in-house designed static blade swirl element. A centrifugal pump was used to supply the liquid from the bottom of the pipe ($D = 25 \text{ mm}$). The gas was injected into the liquid flow for a distance of $12 \frac{L}{D}$ upstream of the lower edge of the swirl element, generating a dispersed gas–liquid flow. The static blade swirl element (see Figure 1a), with a height of 80 mm and diameter of 27 mm, was installed in the vertical test section which had an inner diameter of 27 mm. The bottom part of the element consisted of straight vertical plates, while the top part consisted of curvy blades inclined at a 20° angle. The experiment was carried out at the liquid superficial velocities of $J_L = 2$ and 4.7 m/s for two different inlet gas volume flow fractions ($\varepsilon_{in} = 5$ and 10%), where $\varepsilon_{in}$ was defined as:

$$\varepsilon_{in} = \frac{Q_G}{Q_G + Q_L}$$

The present numerical investigation was performed only for the experimental condition of $\varepsilon_{in} = 5\%$ at $J_L = 2 \text{ m/s}$.

Four measurement planes (see Figure 2 and Table 1), in which the radial gas fraction profiles can be estimated by the bi-modal bubble size approach as demonstrated in our previous work for the blade element [11], were used for the comparisons among various swirl elements. An experimental measurement uncertainty of less than 1% was assumed based on the work in Reference [15]. Figure 2 shows the domain of CFD simulations based on the relevant part of the experimental test section. A detailed explanation of the experimental setup is given in Reference [11], while the explanation of the system and the method for data processing can be found in References [16–18].
Figure 2. Graphical representation of the computational domain including positions for the measurement planes [11] (see Table 1).

Table 1. Distance relative to the inlet of the computational domain.

| Position | Distance (mm) |
|----------|---------------|
| Outlet   | 240           |
| H4       | 193           |
| H3       | 173           |
| H2       | 123           |
| H1       | 108           |
| Inlet    | 0             |

3. CFD Modeling

It can be concluded from the experimental work in References [5,11] that the gas–liquid flow around the swirl generating device was three dimensional (3D). Therefore, in this present work, our CFD modeling approach considered the 3D geometry of the test section. The simulations were performed with the commercial CFD code ANSYS-CFX. The Euler–Euler model was used in the numerical investigation with an assumption that the liquid and gas phases were adiabatic and incompressible. The continuity and momentum equations that had to be solved were given by [19]:

\[
\frac{\partial}{\partial t}(\alpha_j \rho_j) + \nabla \cdot (\alpha_j \rho_j \mathbf{u}_j) = S_j
\]  

(2)
\[ \frac{\partial}{\partial t}(\alpha_j \rho_j u_j) + \nabla \cdot (\alpha_j \rho_j u_j \times u_j) = -\alpha_j \nabla p + \nabla \left( \alpha_j \mu_j \left( \nabla u_j + \left( \nabla u_j \right)^T \right) \right) + M_j + S_{Mj} \]  

where \( \alpha_j, \rho_j, u_j, t, S_j \), and \( p \) are the volume fraction, the density, the velocity vector, the time, the mass source, and the pressure, respectively. The term in the bracket on the right-hand side of Equation (3) represents the viscous stress tensor. The subscript \( j \) represents the phase \( j \). \( M_j \) is the interfacial forces acting on phase \( j \) due to the presence of the other phase, while \( S_{Mj} \) is the momentum sources due to the external body forces [19].

The baseline model concept [20] consisted of the set of closure models for the bubble forces used in the present work. The bubble force models selected according to the baseline model concept for poly-disperse flows are listed in Table 2. For the turbulence model, the two-equation shear stress transport (SST) model proposed in Reference [21] was used for the liquid phase. In addition, the curvature correction implemented in Reference [22] was applied to capture the effect of the swirling flow. Additional source terms, in which the parameter and coefficient values were defined based on References [23,24], were added into the turbulence model to consider the bubble-induced turbulence.

### Table 2. Baseline model concept for poly-disperse flows [20].

| Force          | Formulation                                                                 | Reference(s) | Number |
|---------------|----------------------------------------------------------------------------|--------------|--------|
| Drag          | \[ F_{\text{drag}} = -\frac{1}{2} \rho \beta L \alpha_j \nabla \left[ \left( \alpha_j \rho_j - \alpha_j \rho_l \right) \right] \] |              | (4)    |
|               | \[ C_{\text{D,wall}} = \min \left( C_{\text{D,sphere}}, \min \left( C_{\text{D,ellipse}}, C_{\text{D,cyl}} \right) \right) \] | [25]         | (5)    |
|               | \[ \frac{C_{\text{D,sphere}}}{\alpha} = \frac{24}{3 + 1.3R_e^{1/2}} C_{\text{D,ellipse}} = \frac{1}{2} \sqrt{\rho_0 C_{\text{D,cyl}}} = \frac{2}{3} \] |              |        |
| Lift          | \[ \frac{f(E_{\text{wL}})}{f(E_{\text{wL}})} \left\{ \begin{array}{ll} \min (0.288 \tanh (0.1212 \kappa_d), f(E_{\text{wL}})) & E_{\text{wL}} < 4 \\ f(E_{\text{wL}}) & 4 < E_{\text{wL}} < 10 \\ 0.27 & 10 < E_{\text{wL}} \end{array} \right. \] | [26]         | (6)    |
|               | \[ d_{\text{L}} = d_B \sqrt{1 + 0.163 E_{\text{wL}}^{0.578}} \] |              | (7)    |
| Wall lubrication | \[ C_{\text{W}}(y) = f(E_{\text{wL}}) \left( \frac{y}{y_0} \right)^{1/2} \] | [27]         | (8)    |
|               | \[ f(E_{\text{wL}}) = 0.0217 E_{\text{wL}} \] |              | (9)    |
| Turbulent dispersion | \[ F_{TM} = -\frac{1}{2} \rho \beta L \alpha_j \left( \frac{d_{\text{L} \text{cap}}}{d_{\text{L} \text{cap}}} \right) \left( \frac{1}{2} + \frac{1}{6} \right) \nabla \alpha_j \] | [28]         | (10)   |
| Virtual mass  | \[ F_{\text{VM}} = -C_{\text{VM}} \rho \alpha_j \left( \frac{\rho_{\text{L} \text{cap}} - \rho_{\text{L} \text{cap}}} {\rho_{\text{L} \text{cap}}} \right) \] | [30]         | (11)   |
|               | \[ C_{\text{VM}} = 0.5 \] |              | (12)   |

For inlet boundary conditions, the profile of the liquid velocity, turbulent kinetic energy, and rate of the turbulent kinetic energy dissipation were defined according to a previous simulation of fully developed single-phase flow. The corresponding turbulence intensities were approximately 3% [11]. For the gas phase at the inlet, the mass flow rate giving an equivalent of gas volume flow fraction \( \varepsilon_{\text{in}} = 5\% \) was defined. The experimentally determined gas fraction profile before the swirl element was also used at the inlet. For bubble size at the inlet, a bi-modal approach which gave the best estimation in the previous work [11] was used in the present study. The gas phase was divided into two velocity groups, where the first velocity group (G1) had a bubble size \( d_B = 0.5 \) mm, while the second velocity group (G2) had \( d_B = 8 \) mm. The composition of the bubble sizes consisted of 70% \( d_B = 0.5 \) mm and 30% \( d_B = 8 \) mm. For the outlet, a pressure boundary condition was defined, while for the wall, a no-slip wall and free-slip wall boundary were used for the liquid and gas phase, respectively. In addition, a wall function assuming a smooth wall was also used. The simulations were performed in the steady-state mode.

Bubble coalescence and break-up were neglected in the present work, since the experimental data on the bubble size were not available. Existing coalescence and breakup models are not yet...
reliable without validation with experimental data. Therefore, following our previous work [11],
the coalescence and break-up model were not used in this study to avoid more uncertainties and
speculative results. In the bubble force models used for \( d_B = 8 \text{ mm} \), the wall lubrication force was
switched-off due to the fact of a convergence issue. This problem is not usually encountered in a
simple geometry, such as in a pipe domain without a swirl element, since the migration of a relatively
large bubble toward the center of the pipe (i.e., avoiding the wall) is expected. However, in the case of
a complex geometry, such as a pipe with a swirl element as in this work, there are additional walls
provided by the surface of the swirl elements. In this situation, the numerical stability of the wall
lubrication force for a relatively large bubble cannot be guaranteed.

The mesh structure and the number of elements used were similar for each simulation of the
different swirl element (see Figure 3). The previous mesh independence study for the blade element,
as reported in References [11], shows that some differences can still be observed after the refinement
of the mesh. However, the trend in the radial gas distribution profile for the measurement planes
evaluated in this study, especially for the bi-modal bubble size approach, can be sufficiently captured
by the simulation using 600,000 elements (for details, see Reference [11]). Based on this reason and also
the computational cost consideration, the mesh with around 600,000 elements was used in this work.
To be more specific, the mesh for the blade, single helix, and double helix devices consisted of 662,359,
684,775, and 646,724 elements, respectively, with a minimum element size of approximately 0.3 mm.

Figure 3. Graphical representation of the computational mesh: (a) blade; (b) single helix; and
(c) double helix.
4. Results and Discussions

An important parameter for investigating characteristics of the flow in static swirl generating devices is pressure. Moreover, a comparison among various swirl elements was carried out in this work. Figure 4a shows the axial profiles of absolute pressure obtained by averaging over the cross-section of the pipe. Note that, although the same pressure boundary condition was applied at the outlet for each simulation, the pressure drop was not the same. Therefore, the pressure around the inlet was different among the simulations. The largest pressure drop for all simulations occurred in the region close to the entrance of the swirl element. Although the largest pressure drop close to the entrance was observed for the double helix, the largest total pressure drop was observed in the case of the blade swirl element (see Table 3). The reason is that, in the case of the blade, the geometry of the element consisted of two parts: the straight vertical plates at the bottom part and the curvy blades at the top part. It can be seen from Figure 4a that the significant pressure drop in the case of the blade was observed not only in the entrance of the straight plates but also in the entrance of the curvy blades. As to expect the pressure drop in the double helix is larger than in the single helix.

Table 3. Calculated differential pressure (see Figure 4a).

| Swirl Element   | ΔPsim (m·bar) |
|-----------------|---------------|
| Blade           | 42            |
| Single helix    | 30            |
| Double helix    | 38            |

Figure 4b–d represents the axial profiles of the cross-sectional averaged gas G1 velocity, gas G2 velocity, and liquid velocity, respectively. For all swirl elements, no differences in the velocity profiles can be observed in the region upstream of the elements (i.e., region A). The most significant velocity component in this region was the vertical velocity (see Figure 5a–c). Figure 6 shows the axial profile of the ratio of G2 vertical velocity to G1 vertical velocity. It can be observed from the figure that, in region A, the vertical velocity of G2 is larger than that of G1 which is indicated with the ratio bigger than one. This can be explained by considering the equilibrium between the buoyancy and drag force. The buoyancy force is proportional to the bubble volume. This has to be compensated by the drag force which requires a larger relative velocity. Therefore, the vertical velocity of G2 was larger than that of G1. In other regions, where significant swirling flow was generated, other forces beside buoyancy and drag force (e.g., virtual mass) play a significant role. Therefore, at this condition, the vertical velocity of G2 can also be smaller than that of G1. The axial profile of the tangential velocity component shows that the magnitude of this velocity component was negligible (see Figure 5d–f) in region A. This indicates that the swirling flow had not yet been generated in this region as visualized by the smooth and straight streamlines of the liquid velocity for all swirl elements (see Figure 7). It is interesting to note that the axial profile of the radial velocity component of the larger bubble size (i.e., G2) showed negative values in region A. This was caused by a negative sign of lift coefficient of G2 which led this gas structure to migrate in the radially inward direction (i.e., toward the center of the pipe) as reflected by the converging streamlines of G2 velocity (Figure 8).
Figure 4. Axial profiles of: (a) pressure, (b) G1 velocity, (c) G2 velocity, (d) liquid velocity, (e) G1 fraction, and (f) G2 fraction and (g) liquid turbulence intensity obtained from simulations using various swirl elements.
Figure 5. Axial profiles of velocity components obtained from simulations using various swirl elements: (a–c) vertical velocity of liquid, G1 and G2, respectively; (d–f) tangential velocity of liquid, G1 and G2, respectively; and (g–i) radial velocity of liquid, G1 and G2, respectively.
Figure 6. Axial profile of the ratio of G2 vertical velocity to G1 vertical velocity for various swirl elements.

Figure 7. Visualization of streamlines of liquid velocity obtained from simulations for various swirl elements.
Figure 8. Streamlines of G1 velocity $U_{G1}$ and G2 velocity $U_{G2}$ obtained from simulations of various swirl elements.

The velocity profile among the various types of swirl elements started to differ around the entrance to the elements (see Figure 4b–d). The velocity fluctuated around this region which led to the fluctuation of the gas fraction (see Figure 4e,f). This fluctuation can also be described by the increase of liquid turbulence intensity (see Figure 4g). For all swirl elements, the increase of liquid velocity, G1 velocity, and G2 velocity in region B was observed. In the case of the blade element, the increase in these velocities was mostly associated with the reduction of the cross-sectional area of the pipe (i.e., the area decreased around 6%) due to the presence of the blade element. The swirling flow had not yet been generated as indicated by a negligible value of the tangential velocity component for the blade element (see Figure 5d–f) except in the near end of this region. In the case of the single helix, the increase of the liquid, G1, and G2 velocity was caused mostly by the generated swirling flow, as no reduction of the cross-sectional area occurred in the domain. The tangential velocity increases significantly as the flow enters this region. In the case of the double helix, both the reduction of the cross-sectional area and the generated swirling flow contributed to the increase of the velocities. The streamlines of liquid velocity (Figure 7) and gas velocity (Figure 8) show the different flow characteristics in region B among the...
various swirl elements. In contrast to the streamlines of the blade which still show a relatively smooth and straight flow for both liquid and gas, the streamlines of the single and double helix in this region indicate that the flow had been twisted following the curvature of the elements in that region. It can be inferred from Figure 5d–f that the tangential velocity in the case of the double helix was larger than that of the single helix reflecting that a stronger swirling flow was generated in the case of the double helix.

A significant increase of liquid velocity, G1 velocity, and G2 velocity for the blade element occurred in region C (see Figure 4b–d). The major contribution of this velocity increase came from the tangential velocity component that increased drastically (see Figure 5d–f), indicating that a significant swirling flow was generated in this region. This generated a swirling flow even more intensive compared to the one achieved in the single and double helix as reflected by the largest tangential velocity obtained by the blade element. The streamlines of the liquid velocity (Figure 7) show that a swirling flow bounded by the pipe wall formed for the liquid. In contrast to the streamlines of the liquid velocity, the streamlines of gas velocity, both for G1 and G2 (Figure 8), concentrated in the center of the pipe indicating that the gas immediately migrated toward the center of the pipe in this region. In contrast to the increase of tangential velocity for the blade element, the tangential velocity for the single and double helix remained relatively constant in this region. It is interesting to observe that the increase in the tangential velocity for the blade element was followed by a smooth decrease in its vertical velocity (see Figure 5a–c). A gradual increase in the cross-sectional area, as the area occupied by the blade swirl element decreased due to the geometry of the curvy blades, contributed to the decrease in the vertical velocity. In contrast to the blade element, a sudden increase in the cross-sectional area just downstream of the single and double helix led to a steeper decrease of the vertical velocity. The largest drop in the vertical velocity for all swirl elements occurred for G2 which led to the large increase of the cross-sectional averaged G2 fraction (see Figure 4f). The highest peak of the G2 fraction was observed from the plot for the double helix due to the largest decrease of its vertical velocity. It seems that a local region with the lowest G2 velocity formed in the center region of the pipe just downstream the double helix as shown in the G2 velocity streamlines (see Figure 8). The drastic increase of gas volume fraction close to this region can also be related to the increase of liquid turbulence intensity (see Figure 4g).

The swirling flow in the region downstream of the swirl elements (i.e., region D) for the blade element remained stronger in comparison to that of the helical elements as can be observed from the plot of tangential velocity (see Figure 5d–f). From the images of the iso-surface of the gas volume fraction (Figure 9), it is inferred that a single gas core in the center of the pipe formed downstream of the blade element, while a multiple gas core was observed for the single and double helix. This phenomenon reflects the influence of the swirl geometry on the characteristic of gas and liquid separation due to the swirling elements. From the perspective of the effectiveness of the inline separator design, a single gas core in the center of the pipe is preferable, since the gas will be easier to be removed by the gas removal mechanism which is located in the center of the pipe. Therefore, the blade swirl element is suitable to be used for inline separator. For the helical swirl elements, the formation of a single gas core in the center was not necessary, since the intended application of those elements is in a static mixer.
Detailed local information of the gas fraction profile of the calculated gas distribution over several measurement planes are presented in Figures 10–14. Figure 10 shows the gas fraction for various swirl elements at the measurement plane H1. For all swirl elements, a similar trend was observed in terms of smaller bubbles (i.e., G1) occupying almost all of the cross-sectional area of plane H1, while the larger bubbles (i.e., G2) occupied the center of each divided area. The difference was observed in the location of the maximum value of the G1 fraction. In the case of the blade swirl element, the swirl flow was not yet formed in this region; thus, the peak of G1 seemed to stay at a similar position, close to the wall of the pipe in each quarter of the element. In the case of the single helix and the double helix, the distribution of the gas had already been affected by the generated swirling flow. Therefore, the location of the maximum gas fraction followed the orientation of the rotation. It is interesting to note that the location of the maximum gas fraction of G2 remained at the center of each divided area which can be attributed to the negative sign of the lift coefficient. From the plot of the radial gas distribution in Figure 14, it was inferred that the profile retained a similar trend for all swirl elements with a central peak of the gas fraction.

Figure 9. Images of the iso-surface for a selected gas fraction of $\alpha_G = 0.2$ obtained from simulations: (a) blade; (b) single helix; and (c) double helix.
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![Figure 10](image_url)  
*Figure 10.* Images of gas fraction distribution in the measurement plane H1 obtained from simulations for various swirl elements.
The calculated gas distribution at the measurement plane H2 are presented in Figure 11. For the blade element, a similar trend was observed as in the measurement plane H1, since H2 was located in the same region as H1 (i.e., the straight plates) in which the swirling flow was not yet generated. In contrast to the blade element, gas distribution in the case of the single and double helix was further developing under the influence of the centrifugal force generated by the swirl elements. The gas phase migrated toward the center of the pipe; thus, the location of the maximum gas fraction shifted from the center of each divided area to the center of the pipe. The radial gas profiles in Figure 16 confirmed this fact. The peak at the center of the pipe for the single and double helix was approximately twice the peak value as in the case of the blade element.

From Figures 10 and 11, it can be inferred that the gas fraction was quite high near the single and double helical elements. The interfacial forces acting on the bubbles influenced the distribution of the gas fraction. One of them was the lift force which is formulated in Equation (6). Therefore, to give a description of the influence of the lift force, the distribution of lift force magnitude in plane H1 and plane H2 is presented in Figures 15 and 16, respectively. It can be observed from Figures 10, 11, 15 and 16 that the gas distribution was significantly influenced by the lift force magnitude. For example, the location of the maximum G2 fraction near the single and double helical element, shown

|      | Blade | Single helix | Double helix |
|------|-------|--------------|--------------|
| G1   | ![Blade_G1](image) | ![Single_helix_G1](image) | ![Double_helix_G1](image) |
| G2   | ![Blade_G2](image) | ![Single_helix_G2](image) | ![Double_helix_G2](image) |
| Total| ![Blade_Total](image) | ![Single_helix_Total](image) | ![Double_helix_Total](image) |

0.0 $\alpha_c(\%)$ 0.2

**Figure 11.** Images of gas fraction distribution in the measurement plane H2 obtained from simulations for various swirl elements.
in Figures 10 and 11, was strongly related with the position of the G2 maximum lift force magnitude shown in Figures 15 and 16.

Figure 12. Images of gas fraction distribution in the measurement plane H3 obtained from simulations for various swirl elements.
|       | Blade | Single helix | Double helix |
|-------|-------|--------------|--------------|
| G1    | ![Blade G1](image) | ![Single helix G1](image) | ![Double helix G1](image) |
| G2    | ![Blade G2](image) | ![Single helix G2](image) | ![Double helix G2](image) |
| Total | ![Blade Total](image) | ![Single helix Total](image) | ![Double helix Total](image) |

![Color bars](image)

**Figure 13.** Images of gas fraction distribution in the measurement plane H4 obtained from simulations for various swirl elements.
The calculated gas distribution at the measurement plane H2 are presented in Figure 11. For the blade element, a similar trend was observed as in the measurement plane H1, since H2 was located in the same region as H1 (i.e., the straight plates) in which the swirling flow was not yet generated. In contrast to the blade element, gas distribution in the case of the single and double helix was further developing under the influence of the centrifugal force generated by the swirl elements. The gas phase migrated toward the center of the pipe; thus, the location of the maximum gas fraction shifted from the center of each divided area to the center of the pipe. The radial gas profiles in Figure 16 confirmed this fact. The peak at the center of the pipe for the single and double helix was approximately twice the peak value as in the case of the blade element.

From Figures 10 and 11, it can be inferred that the gas fraction was quite high near the single and double helical elements. The interfacial forces acting on the bubbles influenced the distribution of the gas fraction. One of them was the lift force which is formulated in Equation (6). Therefore, to give a description of the influence of the lift force, the distribution of lift force magnitude in plane H1 and plane H2 is presented in Figures 15 and 16, respectively. It can be observed from Figures 10, 11, 15 and 16 that the gas distribution was significantly influenced by the lift force magnitude. For example, the location of the maximum G2 fraction near the single and double helical element, shown in Figures 10 and 11, was strongly related with the position of the G2 maximum lift force magnitude shown in Figures 15 and 16.
was observed for those two swirl elements. In contrast to the single and double helix, the gas profile in the experiment with the blade element showed a relatively stable gas distribution with a peak value close to the center of the pipe around 0.4. The results indicate that the blade element is preferable to be used in an inline separator. The helical swirl elements, although they may cause separation of gas and liquid to some degree, are preferable to be used in the mixing process. The results also suggest that the gas removal mechanism in an inline separator should be designed with care. This means that the location for placing the gas outlet should consider the evolution of gas structures specific for the type of swirl element used in the device. For example, if the blade element should be used in an inline separator, it is the best option if the gas outlet is located in the measuring plane H4, since the gas core is already relatively stable at this location. However, the design of this blade swirl element should also be optimized, since the peak value was still rather low. The gas should be more concentrated in the center of the pipe to increase the performance of the inline separator.

**Figure 15.** Images of lift force magnitude distribution in the measurement plane H1 obtained from simulations for various swirl elements.

**Figure 16.** Images of lift force magnitude distribution in the measurement plane H2 obtained from simulations for various swirl elements.
Figure 12 shows the calculated gas fraction at the measurement plane H3. Since this measurement plane was located in region D (i.e., downstream of the elements), the characteristics of the gas–liquid flow in all of the swirl generating devices was highly influenced by the swirling flow. A round concentric gas located at the center of the pipe was observed in the simulation of the blade element. The shape of the gas distribution obtained from the simulations of the single and double helix was rather different to the one observed in the blade element. The gas core in the center of the pipe surrounded by two and four round shape gas structures was observed in the simulations of the single and double helix, respectively. Figure 16 shows that the largest peak of the gas fraction close to the center of the pipe was obtained in the case of the double helix. The value of the gas fraction at this peak was larger than twice that of the peak value obtained in the simulation as well as in the experiment of the blade swirl element. It is also inferred from Figure 14 that the calculated peak value obtained in the simulation of the single helix was also significantly higher than the one obtained in the blade element. It is also interesting to note that the gas fraction of G2 contributed most of the gas fraction in the center of the pipe in the case of the single and double helix. However, the gas distribution drastically changed within only a 20 mm distance in the case of the single and double helix. Figure 13 shows that the gas concentration in the center of the pipe became smaller, while the concentration of the surrounded gas structure became stronger in the measurement plane H4 for the aforementioned swirl elements. The plot of the gas fraction profile (Figure 14) shows that the peak value in the center of the pipe, for the case of the single and double helix, decreased to less than 50% of the one obtained in the plane H3. However, an increase in the area of the peak closer to the wall was observed for those two swirl elements. In contrast to the single and double helix, the gas profile in the experiment with the blade element showed a relatively stable gas distribution with a peak value close to the center of the pipe around 0.4. The results indicate that the blade element is preferable to be used in an inline separator. The helical swirl elements, although they may cause separation of gas and liquid to some degree, are preferable to be used in the mixing process. The results also suggest that the gas removal mechanism in an inline separator should be designed with care. This means that the location for placing the gas outlet should consider the evolution of gas structures specific for the type of swirl element used in the device. For example, if the blade element should be used in an inline separator, it is the best option if the gas outlet is located in the measuring plane H4, since the gas core is already relatively stable at this location. However, the design of this blade swirl element should also be optimized, since the peak value was still rather low. The gas should be more concentrated in the center of the pipe to increase the performance of the inline separator.

5. Conclusions

Gas–liquid flows in the blade, single helix, and double helix swirl generating devices were investigated by means of multiphase CFD simulations using the Euler–Euler approach. The flow structure was highly influenced by the geometry of the swirl element. The blade swirl element caused the largest pressure drop, followed by the double helix. The fluctuations of the important parameters for each swirl element, such as pressure, liquid and gas velocity, and gas fraction, can be observed from the plot of the axial profiles of those parameters. The evolution of the gas structures in the swirl generating devices was also unique for each of the swirl elements. Besides the geometry, the bubble size played a key role in shaping this gas evolution. Special care should be taken when designing the gas removal mechanism, including the determination of the optimal position to place the gas outlet, since the gas distribution may drastically change over a relatively short distance within the device. Furthermore, additional experiments to investigate the gas–liquid flow in various swirl generating devices are necessary. The data obtained from these experiments will be useful not only for the validation of CFD simulations but also to explore the physics of the gas–liquid flow which are unique for each type of the swirl elements.
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Nomenclature

Latin symbols

- $C_D$: drag coefficient (dimensionless)
- $C_L$: lift coefficient (dimensionless)
- $C_{\text{scale}}$: scaling coefficient (curvature correction) (dimensionless)
- $C_{\text{VM}}$: virtual mass coefficient (dimensionless)
- $C_W$: wall force coefficient (dimensionless)
- $C_\mu$: shear-induced turbulence coefficient (dimensionless)
- $D$: pipe diameter (m)
- $d_B$: bubble diameter (m)
- $d_L$: maximum horizontal dimension of a bubble (m)
- $E_0$: Eötvös number (dimensionless)
- $E_{0,\perp}$: modified Eötvös number (dimensionless)
- $F$: force (N·m$^{-3}$)
- $g$: gravitational acceleration (m$^2$·s$^{-2}$)
- $f$: superficial velocity (m·s$^{-1}$)
- $L$: length of domain (m)
- $M$: momentum transfer term (kg·m$^{-2}$·s$^{-2}$)
- $p$: pressure (Pa)
- $Q$: volume flow rate (m$^3$·s$^{-1}$)
- $Re$: Reynolds number (dimensionless)
- $S_M$: momentum source due to external body forces (kg·m$^{-2}$·s$^{-2}$)
- $U$: mean velocity magnitude (m·s$^{-1}$)
- $u$: velocity vector (m·s$^{-1}$)
- $t$: time (s)
- $y$: distance to the wall (m)
- $z$: axial distance (m)

Greek symbols

- $\alpha$: volume fraction (dimensionless)
- $\varepsilon_{\text{in}}$: inlet gas volume flow fraction (%)
- $\mu$: dynamic viscosity (Pa·s)
- $\rho$: density (kg·m$^{-3}$)
- $\sigma$: surface tension (N·m$^{-1}$)
- $\sigma_{\text{TD}}$: turbulent Schmidt number (dimensionless)

Subscripts and superscripts

- $j$: phase index
- $G$: gas
- $L$: liquid
- $VM$: virtual mass
- $W$: wall
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