Secondary Flow of Liquid-liquid Two-Phase Fluids in a Pipe Bend

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Abstract: A simulated study of oil and water in 90 degree bend was carried on COMSOL 5.1 to characterize flow pattern and analyze the secondary flow. The Euler-Euler k-e Reynolds Averaged Navier-Stokes model was used to represent the fluid motion. Changes in the Reynolds number, curvature ratio and direction of gravity were made to evaluate the effects in the intensity of the secondary flow. In the end, it was possible to see that the bend direction does not affect the formation of secondary flow for Reynolds above 100,000. It appears that the fluid behavior on the pipe bend is strongly related to gravitational and centrifugal force ratio.

Keywords: Secondary Flows, Liquid-Liquid, Two-phase flow, Vorticity

1. Introduction

The world is progressively requiring more energy with the main one coming from petroleum. The difficulties in the whole process of its production are enormous, from the exploration to its transport through pipelines. In the oil industry, its production often involves the presence of water (brine), sand and other types of solid particles. These particles can be harmful to pipeline and equipment's life cycle as they can erode their walls, which increments companies cost of maintenance due to necessary pipe (or equipment) replacement. The highest erosion rate is most commonly found in bends, as particles are dragged towards the wall due to the streamwise and secondary flows. When brine is present in the oil the fluid is considered a Liquid-liquid two-phase fluid and it could affect the secondary flow development. A better understanding of the secondary flows in a liquid-liquid two-phase flow is required to gage their impact in the particle trajectories. Two-phase flow in bends is a complicated phenomenon that has been extensively studied for liquid-gas two-phase flows (e.g., Yadav et al., 2014). To the best of our knowledge, liquid-liquid two-phase flow has only been addressed by Zhu et al. (2011). However, the density difference between the two fluids they considered was only about 4%, which makes the gravitational forces effect almost negligible. In this research, we propose to study the secondary flows in elbows of liquid-liquid two-phase fluids with marked density differences. A study of oil and brine in a bend was carried on COMSOL 5.1 using the Multiphase Flow Module with an Euler-Euler model. We investigate how the secondary flow develops along bends for: different Reynolds numbers for turbulent regimes, bend radius of curvature, sweep angle of 90 degrees, brine NaCl composition (that affects brine density and viscosity), bend orientation with respect to gravity, and phase volume fractions. For all of the cases in this study, we visualized the secondary flow streamlines, velocity vectors, and looked at the liquid volume fractions.

2. Physical model

The flow consisted of a continuous phase along with a dispersed phase. Since one of the main parameters that affects the fluid flow is gravity, three orientations were proposed by varying the bend direction. The pipe was divided in three segments, upstream, downstream and the bend. For all configurations the pipe is horizontal in the upstream part, but in the downstream could be upward, downward or horizontal.

The pipe had 0.0254m diameter with 1m of entrance length before the bend, to ensure the velocity profile development and volume fraction stratification, and 1m of pipe at the exit. Two curvature ratios were fixed as 6.5D and 10D to evaluate its effect on the secondary flow development. All configurations were simulated with a sweep angle of 90°. For the three different physical configurations of the bend it was proposed 2 different Reynolds number: 10,000 and 100,000 to represent turbulent flow. The fluid enters the pipe with a velocity profile data extracted previously from a simulation of the same fluid flow in a straight pipe to ensure those Reynolds number. The fluids used in the simulations were brine, water and oil. Brine with 20% of NaCl concentration had a density of

1147.8 kg/m³ and a viscosity of 0.001557 Pa.s. Pure water had a density of 999.8 kg/m³ and viscosity of 0.001002 Pa.s. Oil had a density of 762.9 kg/m³ and a viscosity of 0.0011684 Pa.s. On top of that, the effect volume fraction of brine-oil and water-oil mixture was compared for 80% oil and 20% oil for each case.

3. Numerical model

In any computational fluid dynamics, studying the governing equations is based in three fundamental principles: conservation of mass, conservation of momentum and conservation of energy. These are represented by a mathematical equation through mass balance, newton's second law and energy balance. Throughout this study no energy balance was taken into account.

The model chosen to represent the fluid flow was the Eulerian-Eulerian. It was done so assuming that the phases are interpenetrating, incompressible and continuous fluids. This model consists of a set of Navier-Stokes equations and continuity equation for each phase along with Schiller-Naumann drag model to simulate the interchange of momentum between the phases. To avoid that a phase occupies the volume of another one, the introduction of a new concept is required, phase volume fraction. These fractions are assumed to be continuous throughout the domain and their sum is equal to one. The pressure profile is calculated from a mixture-averaged momentum equation.

At the inlet, a predetermined velocity profile was imposed, which was obtained from a long straight pipe simulation. A prescribed value of 0 Pa was set for the simulations at the outlet condition. No slip was set as wall condition meaning that the fluid velocity is zero at the wall. The disperse volume fraction at the inlet was uniform. The gravity will stratify the fluids before entering the bend.

Mesh sensitivity analysis (for both element size and wall resolution) was carefully performed. The normal mesh provided by COMSOL was found to be the most suitable since its results had less than 7% of difference when compared with finer and run much faster. For the turbulent cases, the k-ε model was used. The boundary elements were adjusted in order to decrease wall lift-off to values lower than 20 (viscous unit).

4. Results and discussion

4.1. Plot tables and normalization

For all the simulations, cut planes were done to analyze the two-phase flow in different sections of the pipe bend (see figures 2, 3, 4, and 5). Cut planes were made only in the beginning, at 45º and in the end of the bend. The first types of plots presented are the ones to analyze the secondary flow and volume fraction behavior. On those images, the arrows represent the in plane velocity for each of the phases separately. The colors show the volume fraction also for each phase, dark blue means that there is only water/brine and dark red means that there is only oil. Streamlines are also shown in the plots representing the mixture velocity field.

The other types of plots presented in this paper were made to analyze the vorticity behavior along the bend (see figures 6 and 7). The streamlines are exactly the same as the previous figures. This time the colors now show the vorticity magnitude for the mixture on that plane.

Figure 1 helps to clarify the orientation of the figures presented in figures 2 to 7, where it can be observed the inner and outer section of the bend for each of the three bend orientations.
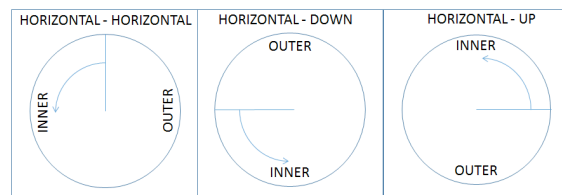
Figure 1: Inner and Outer position for all the plots

It is important to have in mind while analyzing the plots that for Re=100,000 the arrow's scale factor used was 0.005 and for Re=10,000 this factor was 0.05. It means that the arrows in the plots representing the in plane velocities for the first are 10 times bigger than the ones in the second.

4.2. Results

For the case of Reynolds 100,000, the three bend configurations showed the same behavior when looking at in-plane velocity field for both liquids. For instance, the maximum velocity magnitude at a 45° plane was about 4.5% different when comparing the horizontal-horizontal configuration to the others. It seems that the gravitational force had little or no effect on the fluid flow. This behavior is reasonable as the centrifugal acceleration ($\sim u^2/r \sim 120$ and 180 m/s²) is 10 to 20 times larger than the gravitational acceleration (g=9.81 m/s²).

As shown in figures 2 to 5, at the beginning of the bend for all the gravity configurations the flow is similar regardless of the bend orientation. Another important observation is that when changing the NaCl concentration on the fluid flow, no major deviation in flow behavior was observed.

For Re=10,000 the velocity is 10 times lower, and the heavier fluid has time to settle in the bottom part of the pipe represented by the stratification that can be seen in figures 3 to 5, at the beginning of the bend, but not for Re=100,000 (figure 2). In addition, this fluid stratification leads to a smaller buoyancy force due to density difference. On the other hand, centrifugal force is starting to act just as it does for the 100,000 case. The resultant effect of these two phenomena is a diagonal flow that can be seen on the plots of figure 3.

In figures 2 to 5 the size of the velocity vectors for 6.5 curvature ratio are larger compared to 10. Based on the fact that the centrifugal force is inversely proportional to the radius of curvature, when the fluids pass through a bend with a smaller curvature ratio it feels a stronger force due to the turn. Consequently, this force accelerates the fluid proportionally resulting in a higher velocity for 6.5 curvature ratio than 10.

As it can be seen in figures 2 to 5 the water/brine phase vectors size, are larger than the oil phase. For example, in figure 3 for curvature ratio of 6.5 and 80% oil, in the 45° cut planes this phenomenon is recognizable. Since the centrifugal acceleration applied to both phases are roughly the same magnitude, while the density of the water/brine is larger than the density of oil, thus using Newton's Second Law one can infer that the water/brine phase will experience a larger force, thus explaining the phenomena.

While comparing all three configurations presented in figures 3,4 and 5 it is possible to visualize that the H-H cases are the most stratified ones for 45º and end of the bend cut planes, which can be explained by the fact that, gravity is perpendicular to the main direction of the flow which maximizes the stratification. In the H-VU configuration, gravity is acting on the opposite direction of the main flow meaning that the denser fluid (water) will tend to be pushed back towards the bend wall rather than going towards the outlet, resulting in more stratification for the 80% oil cases and less stratification for the 20% oil cases. However, in the H-VD configuration the gravity acts on the same direction as the main flow, causing the water to be pushed towards the bend outlet. Thus, there will be less stratification for 80% oil cases and more stratification for 20% oil cases than if it was H-VU case.

As demonstrated in figure 3, the fluid stratification is slightly diagonal. Since the water is denser than the oil, it will be pulled strongly to the outer wall by the centrifugal force. Thus, when the water volume fraction on the pipeline is higher than oil (20% oil cases), the momentum created by the bend on the water pushes the oil upwards forming the diagonal stratification. On the other hand, when oil volume fraction is higher, the momentum created on the water is not strong enough to result in the same stratification shape, however water still pushes the oil in a lightly manner. Another aspect to point out in figure 3 is the in plane oil velocity for H-H when it is the dispersed phase stands out from the other plots by the fact that the velocities are higher close to the wall. It occurs because the centrifugal forces push the water toward the wall, which generate secondary flow and therefore the water carries the oil phase on the same direction. Clearly, there is no oil flow to the inner part of the bend passing by the middle because the interaction with the water that is being pushed by the centrifugal force to the outer part of the bend takes over. In the end, since water is taking place of the outer part of the bend, the oil has to go to the wall.
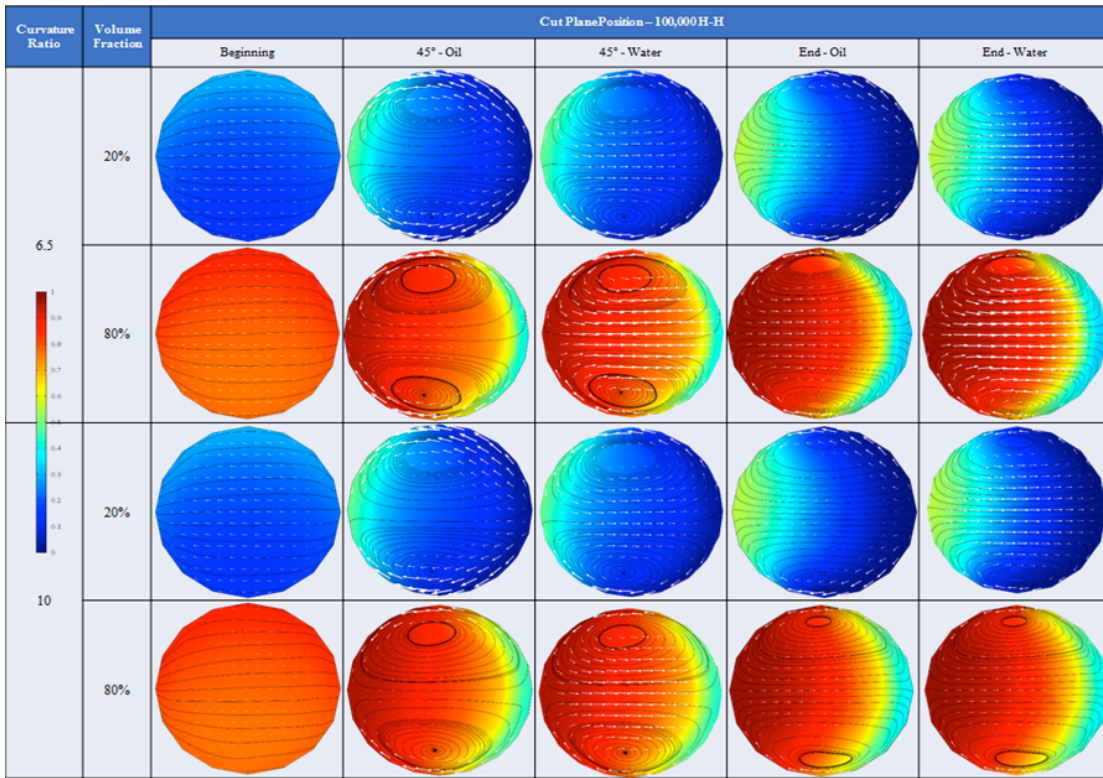
Figure 2: In plane velocities for gravity configuration Horizontal-Horizontal for Reynolds 100,000.
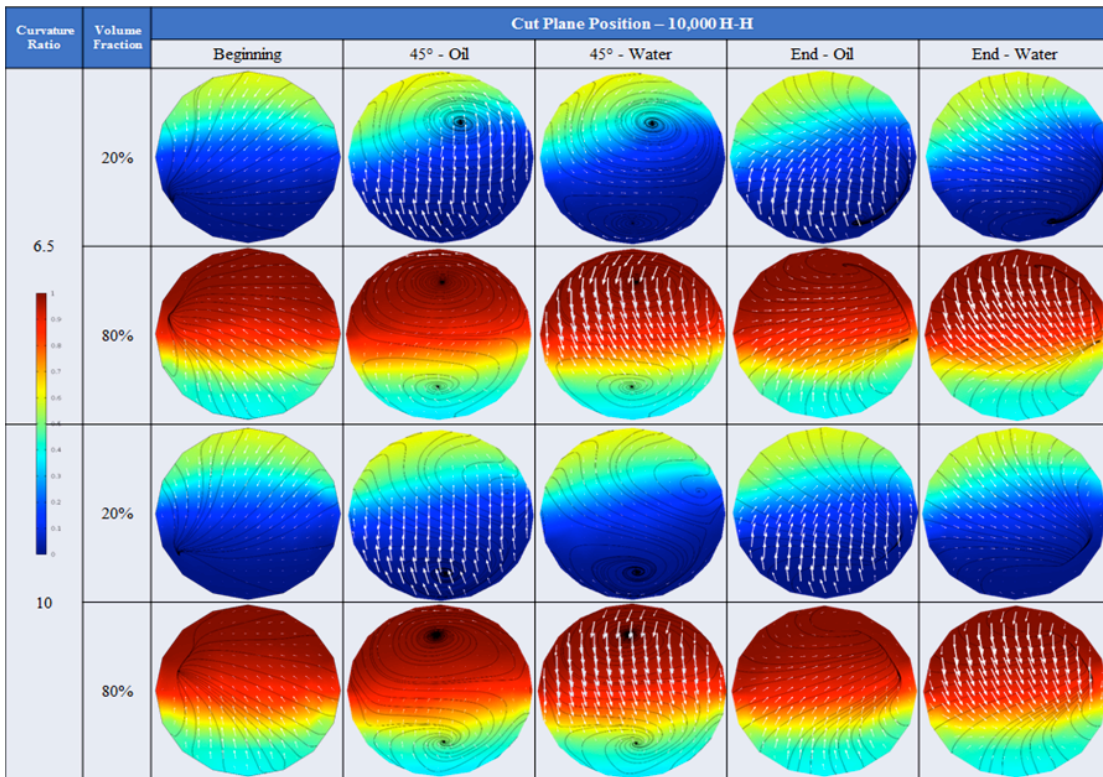

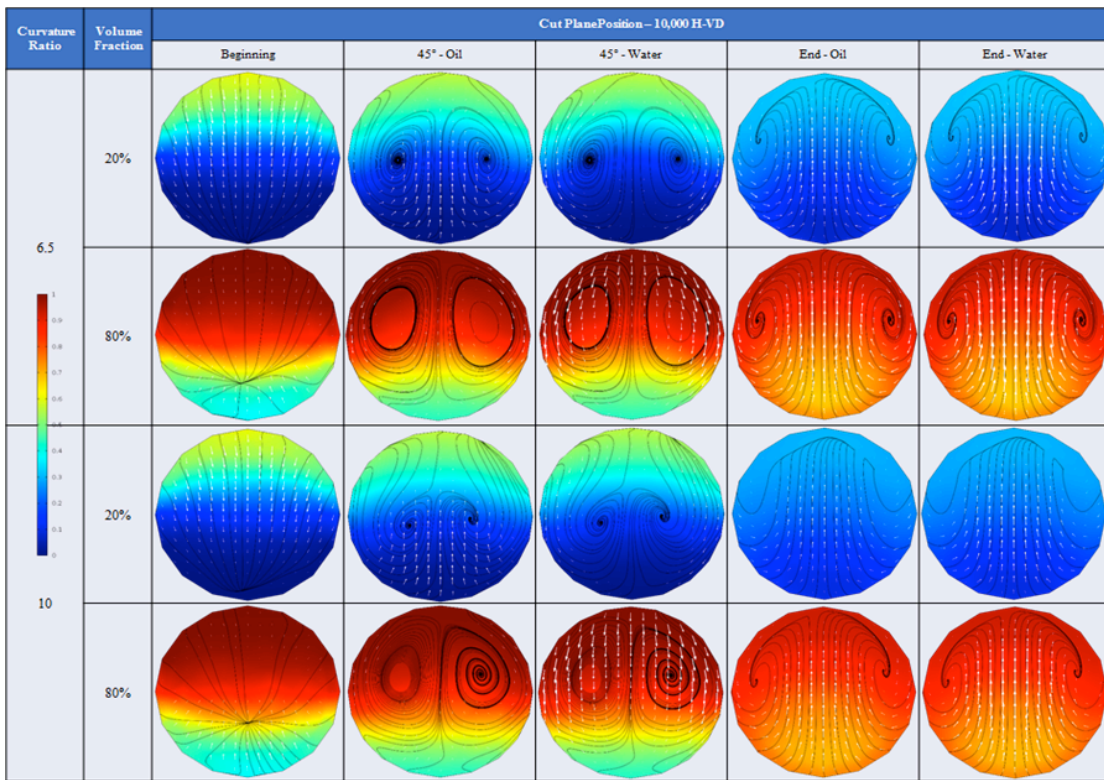**Figure 3**: In plane velocities for gravity configuration Horizontal-Horizontal for Reynolds 10,000.

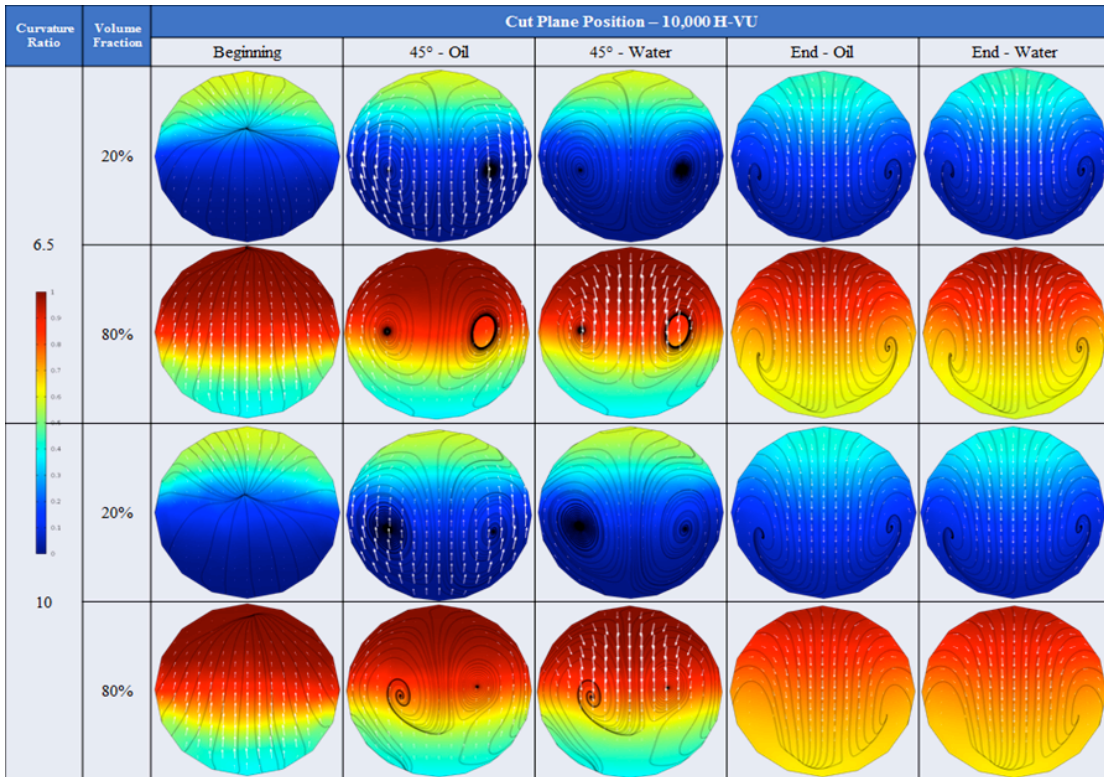**Figure 4**: In plane velocities for gravity configuration Horizontal-Down for Reynolds 10,000.

Figure 5: In plane velocities for gravity configuration Horizontal-Down for Reynolds 10,000.

In figures 6 and 7 the vorticity fields are shown at the same plane cuts used in previous figures. The color range shows the nondimensional vorticity (D/Umean*Vorticity).

The vortical structure is a region where the flow is rotating along an axis line; meanwhile the vorticity is a local rotary motion of a fluid particle. They both somehow related. The vortices act in its on axis it can act upon the rotation of fluid particle in the vortex region, therefore enhancing the vorticity of the fluid particles. This explains how intense vortical structures in the 45° plane of the bend produces in the end of the bend strong vorticity, however with low-energy vortical structures. This phenomenon can be seen in figure 7. For the H-H configuration (figure 6), this does not occur as gravity acts parallel to the plane where the vortical structures appear. The gravity changes the momentum of the fluid particles helping the dissipation of such vortices, therefore not vorticity enhancement is observed.

For each configuration the vorticity at the wall shows a different direction of rotational spin when comparing it to the main vorticity region, this is showed by the instant change of color near the wall. While a fluid particle rotates in the main vortical region in a positive direction, the wall presence forces fluid particles near it to rotate in the opposite rotational direction. So, if the fluid particles in the core of the main vortical structure have a negative spin direction than the fluid particles near the wall will have a positive spin direction.

As it can be seen in figure 6 and 7 the vorticity is stronger when the curvature ratio is 6.5. This is attributable to the same reason mentioned before when explaining the arrows size for different curvature ratios, the centrifugal acceleration is stronger for 6.5 curvature ratio.

5. Conclusions

In this paper it was analyzed the influence of Reynolds number, oil volume fraction, salt concentration, curvature ratio and bend configuration with respect to gravity on the two-phase liquid-liquid flow. Throughout this study, it was possible to infer that salt concentration plays little or no role on the fluid flow behavior. Additionally, from the gravity direction point of view, even though two different Reynolds

numbers were simulated for each bend configuration, only for Reynolds 10,000 the configurations present a distinctive behavior.

As the flow passed through the pipe, and entered the bend, various vortical structures appear, meaning that there is a secondary flow emerging.

Also while the flow is in the bend gravity forces affect distinctively its behavior as long as the centrifugal force is not greater.

From this study, it appears that the fluid behavior on the pipe bend is strongly related to gravitational and centrifugal force ratio.

Further studies should be considered to analyze the effect of this ratio and the effect of laminar Reynolds number on the fluid flow. Therefore, a study carrying out a gravitational to centrifugal ratio of 1 might be pursued, since more conclusions can be taken to even better understand the two-phase flow on pipe bends.

6. References

1. Zhu et. al., Numerical Simulation of the Oil-Water Two-Phase Flow in Horizontal Bend Pipes, Communications in Computer and Information Science, 158, 75-82 (2011).
2. Yadav et al, Experiments on Geometric Effects of 90-degress vertical-upwards Elbow in Air Water Two-phase Flow, 65, 98-107 (2014).

7. Acknowledgements
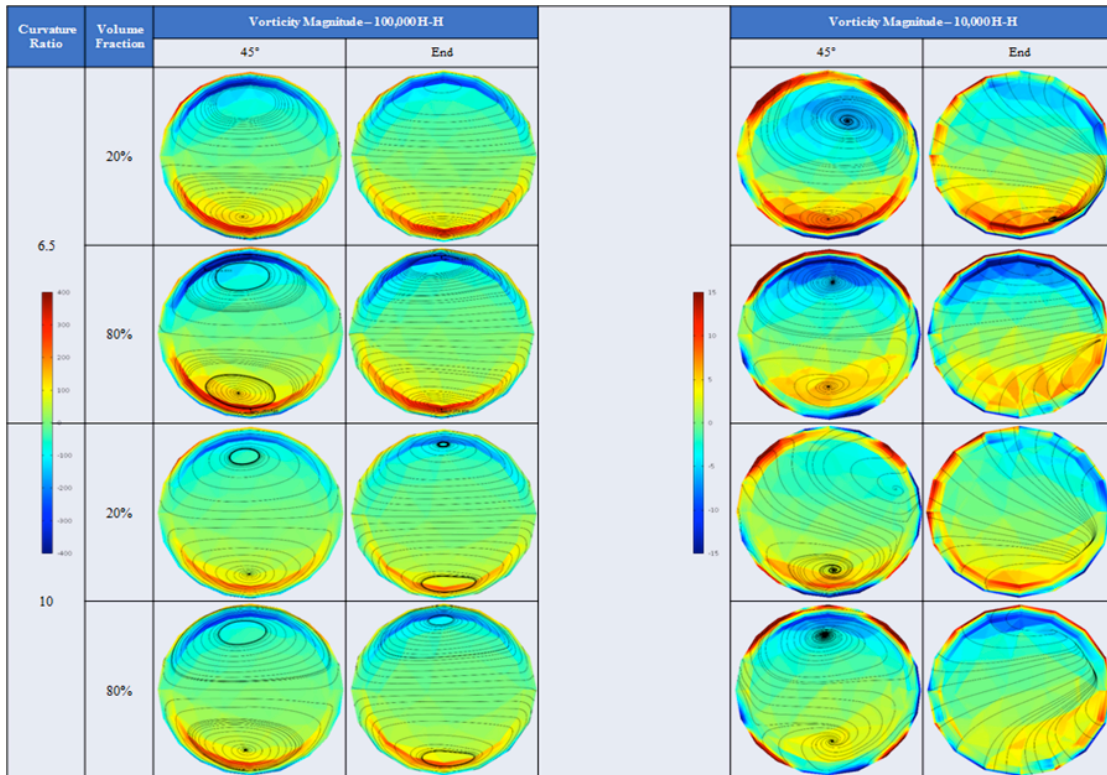
Figure 6: In plane vortices for gravity configuration Horizontal-Horizontal for Reynolds 100,000 and 10,000.
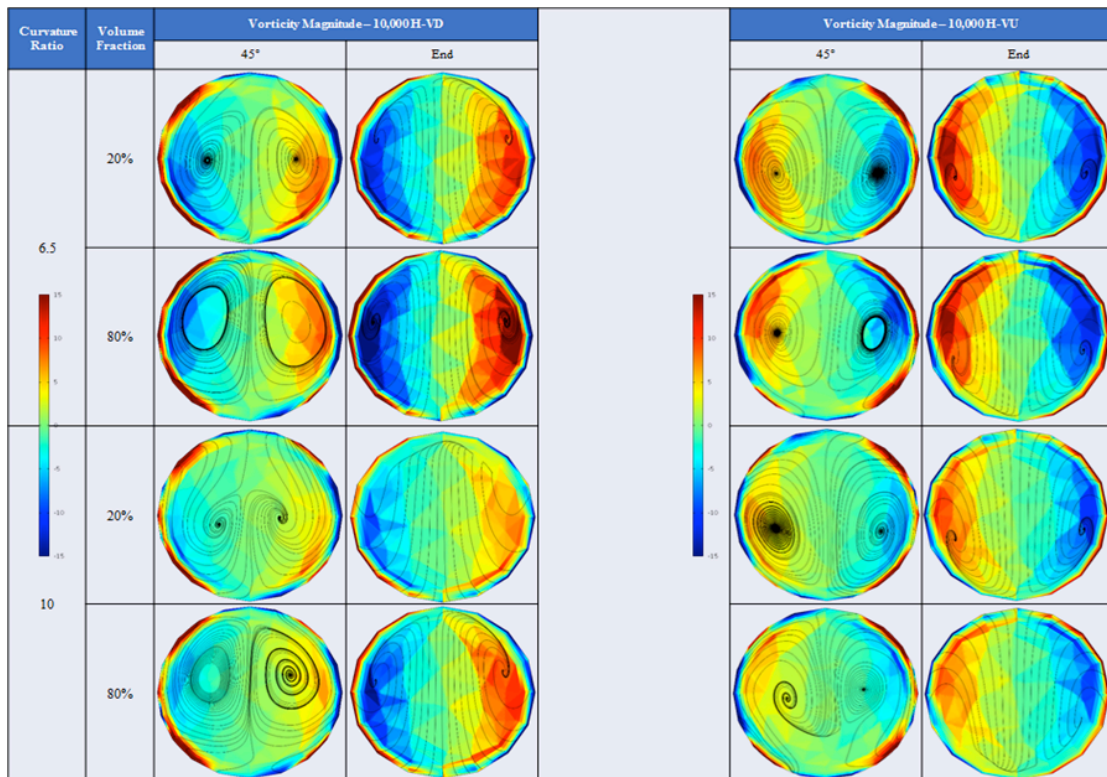
Figure 7: In plane vortices for gravity configuration Horizontal-Down and Horizontal-Up for Reynolds 10,000.