Effect of Internal Baffles on Volumetric Utilization of a FWKO – A CFD Evaluation

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ABSTRACT

This paper presents the results of a CFD evaluation on the effectiveness of perforated plate baffles for improving flow and separation performance in a FWKO separator. Using the mixture multiphase model coupled with turbulent interaction, a 3D simulation on two FWKO configurations indicated that with installation of the perforated plate baffles, the short circuiting and recirculation flow in the vessel were substantially reduced. As a result, the mean residence time increased from 630 seconds to 980 seconds for the water phase, and from 520 seconds to 745 seconds for the bitumen phase. Accordingly, the volumetric utilization for the bitumen phase was increased from 46% without the baffles to 66% with the baffles, which corresponds to a 43% improvement. Water phase volumetric utilization was increased from 57% without the baffles to 89% with the baffles, which was increased by 55%. Therefore, an overall 50% improvement on the liquid phase volumetric utilization was achieved due to the introduction of properly designed perforated plate baffles.

I. INTRODUCTION

Performance of the FWKO separators can be greatly improved by introducing appropriate internals into the vessels. Available internals developed at NATCO include the Porta-Test Revolution™ cyclonic inlet device, Performax™ coalescer packing, perforated plate baffles, and other flow modification components. Revolution tubes and perforated baffles were used to enhance the pre-separation and improve the flow distribution in the FWKO vessels used for the diluted bitumen treatment. A good understanding of the flow and separation behaviors within the separator is crucial for identification of design limitations and further design improvements [1]. With the development of computer and numerical methods in the last two decades, Computational Fluid Dynamics (CFD) provides a good option to simulate the complex flow and separation processes within the vessel [2]. The objective of this study was to determine the improved performance of the FWKO from introducing two perforated plate baffles. The flow and separation behaviors in the vessel with and without perforated plate baffles were investigated numerically using the CFD approach.

II. DESCRIPTION OF FWKO VESSEL

Vessel Configuration

Figure 1 schematically shows configuration of the FWKO separator. It was a horizontal vessel with an outside diameter of 5791.2 mm (19 feet) and seam to seam length of 19812 mm (65 feet). To enhance the degassing and pre-separation performances, six pairs of 14" Porta-Test Revolution™ tubes were used as the inlet device. After bulk separation in the revolution tubes, the gas exits from top opening of the revolution tubes and the liquid phase flows out of the bottom opening of the revolution tube device. The pre-separated gas and the liquid streams then flow longitudinally in the vessel. To improve the flow distribution downstream of the revolution tubes, two perforated plates with x% open area and y inch holes were put on a tri-pitch pattern. The normal liquid level was maintained at 4319 mm (14.17 feet) by the level control device, and the interface level was kept at 2858 mm (9.38 feet) by an interface control system.

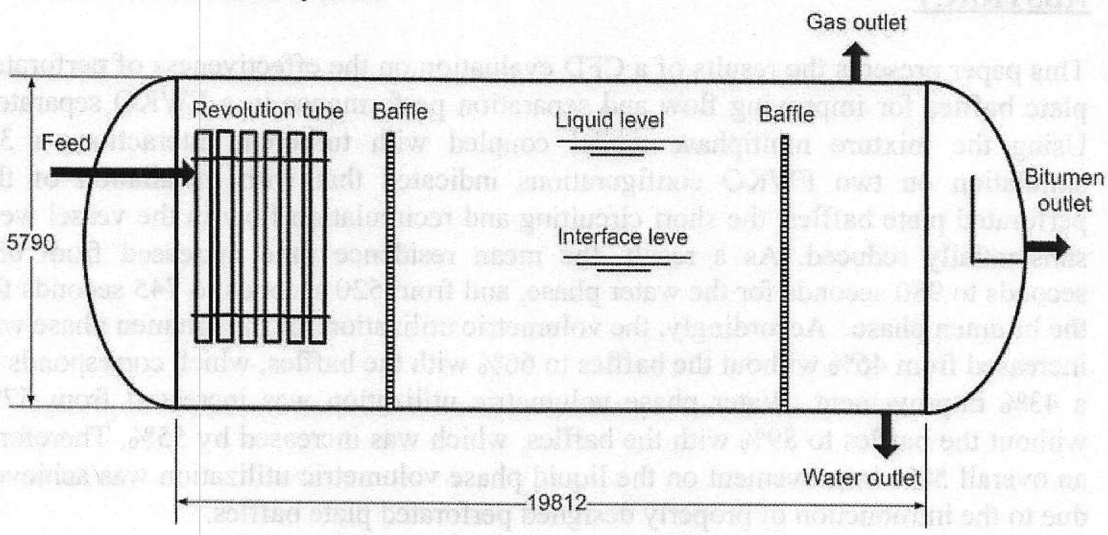

Figure 1 Geometric configuration of the FWKO separator

Operating Conditions

Table 1 summarizes the operating parameters, which includes phase compositions, fluids properties, and related operation parameters. Under the given operating conditions, the designed residence times in the vessel were 18.8 minutes for the diluted bitumen, and 18.4 minutes for produced water.

Table 1 Operating conditions of the FWKO separator

Parameters	Gas	Bitumen	Water
Flow rate (m^3/h)	1415	435	631
Density (kg/m^3)	9.5	874	931
Viscosity (mPa.s)	0.0138	6.9	0.2
Temperature (C)		135	
Pressure (kPa)		1280	

III. MATHEMATICAL MODELING

The governing equations, numerical methods, and initial and boundary conditions have to be defined correctly in order to obtain reliable and meaningful results.

Governing Equations

Operation of the FWKO separator involves simultaneous flow of the released gas, diluted bitumen, and produced water in the same vessel. The dominant flow in the FWKO separator can be described as a stratified flow of the released gas, diluted bitumen, and produced water moving at different rates in the longitudinal direction. Due to the velocity differences, the shear and mixing effects will introduce significant inter-dispersion, which moves perpendicularly to the longitudinal flow. Therefore, actual flow in the FWKO vessel is a combination of the stratified flow and the dispersed flow.

To model the complex flow and separation processes in the FWKO vessel, a mixture model due to Ishii [3] was chosen to predict the overall flow pattern. As a simplification of the full multi-fluid model, the continuity and momentum equations were solved for the mixture. The relative motions of the dispersed phase were approximated by algebraic equations, and concentration fields of the dispersed phase were obtained by tracking their volume fraction equations. Considering that the Reynolds number of the liquid phase at the inlet was up to 58,000 under the operation conditions given in Table 1, flow in the FWKO vessels involved significant turbulence. To account for turbulent effects, a k-ε model due to Launder and Spalding [4] was implemented.

The perforated plate baffles were modeled as porous medium [5] in this study. This significantly reduced the computational time by using coarser mesh, and only affects the flow field near the perforated plate and not the flow throughout the vessel.

Residence Time Distribution

Residence time distribution is typically obtained by conducting a tracer test, in which a tracer is injected at the entrance, and the system response is then measured in time at the exit. In this study, however, a numerical approach based on a particle tracking technique was used to achieve the residence time distribution in the FWKO vessel. Specifically, the Euler-Lagrange approach [7] was used to track the trajectories of fluid particles in a coverage flow field. The time for each individual particle moving from entrance to exit of the vessel was then calculated. If the physical properties of the injected particles were carefully selected to match the fluid phases interested, the injected particles would follow this phase. By releasing a large number of particles at the inlet (outlets of the revolution tubes), the residence times for the fluid particles to escape from the vessel outlets were recorded. Therefore, the retention time obtained for the injected particles can be considered as a representative of the residence time of the matched phase in the vessel.

IV. NUMERICAL METHODS

Flow Domain and Mesh

A 3-dimentional simulation was carried out in this study. Considering the symmetric feature both in geometry configuration and flow regimes involved, only half of the vessel was considered to reduce the computational load without losing flow details. Moreover, the revolution tube was treated as a rectangular block, and the configurations of vessel outlets were simplified to varied extents accordingly. This was a realistic compromise since the objective of this study was to examine the overall performance of the FWKO vessel, particularly the improved hydrodynamics due to the introduction of the perforated plate baffles.

Considering the large flow domain (6m×20m) and complex vessel geometry, a hybrid mesh system was created to divide the flow domain into discrete control volumes by using GAMBIT 2.2 [8], a pre-processor from Fluent Inc. An unstructured grid was used in the elliptical head portion of the vessel, and a structured grid was created in the cylindrical zone. Moreover, a fine grid was utilized in the regions close to the walls and baffles, where the velocity gradients were relatively high. With all of these considerations, a mesh system containing 245,000 computational cells was established for discretization of the governing equations.

Initial and Boundary Conditions

To get a meaningful numerical prediction, the governing equations had to be solved in conjunction with the proper initial and boundary constraints. The initial conditions were specified according to the liquid level and the interface level as indicated in section II. The inlet boundaries were specified as plug flow directed vertically upward from top opening of the Revolution Tubes for the gas phase and downward from bottom opening of the Revolution tubes for the liquid phase. The perforated plates were modeled using porous jump boundaries, and all the walls were treated as no slip boundaries.

Numerical Procedure

The governing equations together with the initial and boundary conditions were solved using a solver of Fluent 6.2. At each time step, a control-volume based technique was used to convert the governing equations to algebraic equations that can be solved numerically. The control-volume technique consists of integrating the governing equations about each control-volume, yielding discrete equations that conserve each quantity on a control-volume basis. The set of the algebraic equations, together with the constraints at the flow boundaries, were solved iteratively. The iterative cycle was repeated until the pre-specified convergence criteria were satisfied. Then the calculation moved on to next time step, and so on.

V. RESULTS AND DISCUSSIONS

CFD simulations were carried out for two vessel configurations, with and without the perforated plate baffles. Effectiveness of the perforated plates for improving the flow distribution in the vessels was assessed by comparing the overall flow pattern and residence time distribution in this section.

Overall Flow Patterns

Improved separation could be achieved as the flow distribution in the vessel becomes closer to plug flow. Figures 2 and 3 show the velocity contours predicted for the two FWKO configurations (with and without baffles) at t =56 minutes, colored by the velocity magnitude of the mixture. Basically, the density of the contour lines indicates the velocity gradient. The distribution of the velocity contours is a good indication of the flow pattern occurring in the FWKO vessels.

A close examination of the velocity contour distribution revealed that the introduced gas stream merged into the bulk gas flow immediately after it exits the top of the revolution tubes. The liquid stream showed three stages of flow development downstream of the revolution tubes: (1) the liquid stream flowed downward from the bottom of the revolution tubes into the bulk water phase; (2) reversed its direction and flowed upward along the outer surface of the revolution tubes to the water/bitumen interface; (3) the liquid stream then spread longitudinally.

During the first stage of the flow development, the mixture of diluted bitumen and the produced water emulsion was discharged downward out of the revolution tube into the bulk water phase. It was subjected to an opposite buoyant force immediately due to the density difference between the emulsion stream and the surrounding water. The emulsion stream lost its initial momentum gradually, and its kinetic energy was dissipated during mixing with the surrounding water until zero downward velocity was reached.

During the second stage of the flow development, the emulsion stream flowed upward along the outside surface of the revolution tubes because of the buoyancy force. This process continued until a point of neutral buoyancy was reached. Then a negative buoyant force arose in opposite direction to the rising velocity and the flow decelerated until the upward motion ceased and the maximum height was reached.

During the third stage of the flow development, the introduced emulsion stream stopped rising and flowed longitudinally as a density current whose density matched the surrounding fluid. The introduced liquid stream was eventually located near the interface between the bitumen and the water phases. The third stage of the flow development lasted much longer than the first two stages, and thus formed the major flow pattern that was essential for the separation process in the vessels.

By comparing the velocity contours predicted in the third stage, significant recirculation flows were observed, but different recirculation patterns were noticed in the two vessel configurations. In the vessel without the baffles as shown in Figure 2, the circulation region covered most of the water space downstream of the revolution tubes, and funneled directly to the water outlet. This flow pattern would tend to transport some of the inlet stream from the revolution tube outlet directly to the water outlet. It thus behaves like a short cut flow, and consequently reduces the separation performance of the FWKO separator. In the vessel with the baffles as shown in Figure 3, the circulation flow was broken down into two sections, one section contained between the baffles, and another section located downstream of the second baffle. Consequently, this results in a smaller recirculation region. Therefore, the baffles smoothed the flow distribution and provided better hydraulic conditions for gravity separation.

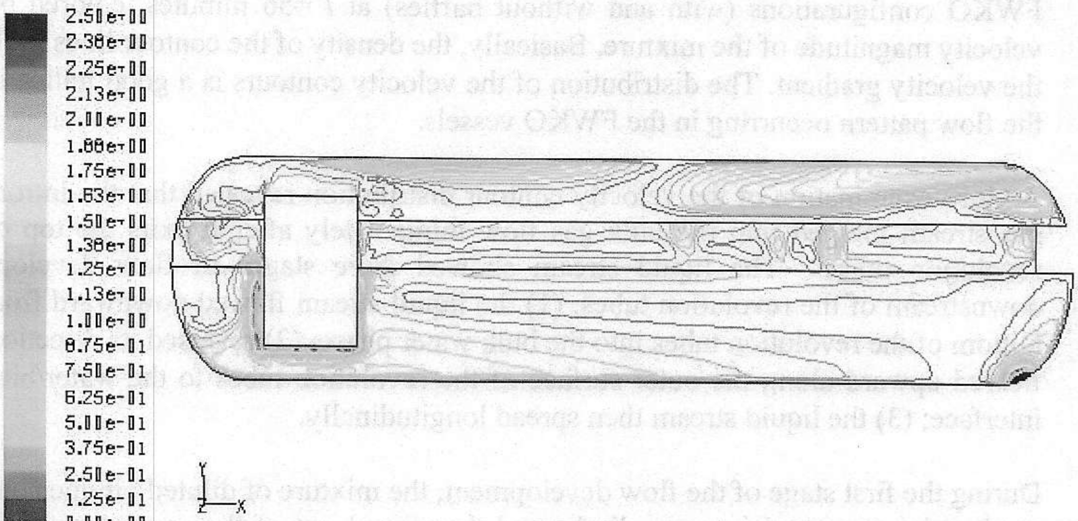

Figure 2 Fluid velocity contour lines in the vessel without baffles.
(Y-axis ranges from 0.0 to 2.5 m/sec.)

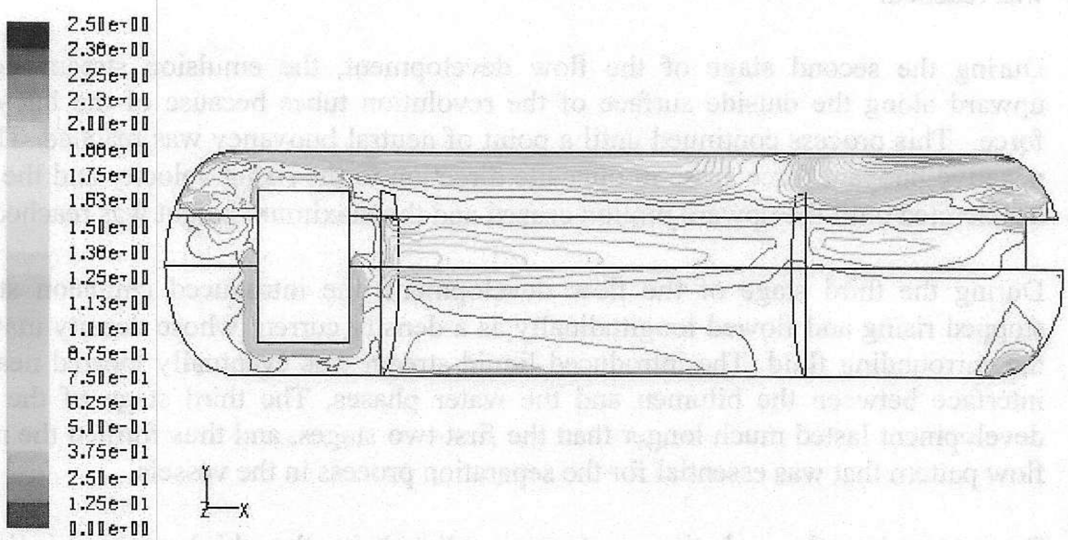

Figure 3 Fluid velocity contour lines in the vessel with baffles.
(Y-axis ranges from 0.0 to 2.5 m/sec.)

Figures 4 and 5 are similar to Figures 2 and 3, except the range of the y-axis is reduced from 0-2.5m/sec to 0-0.5m/sec to enhance the detail of the contour lines of the liquid phase. The channel flow toward the water outlet is more obvious with the detail in Figure 4. Figure 5 shows the vessel with baffles and indicates the more even and slower flow of the water phase.

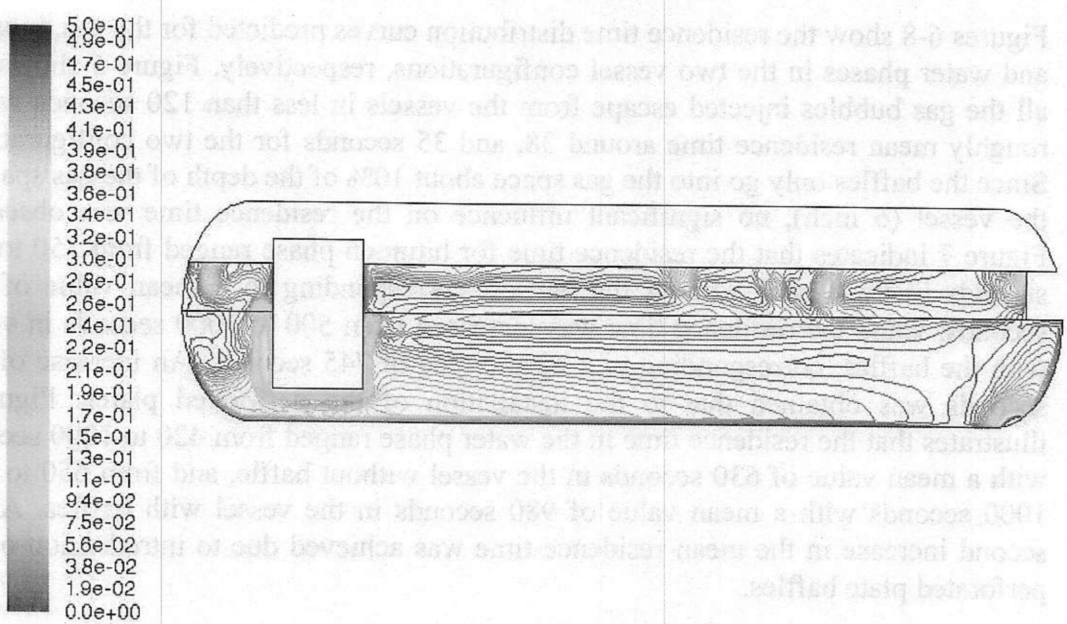

Figure 4 Fluid velocity contour lines in the vessel without baffles.
(Y-axis ranges from 0.0 to 0.5 m/sec.)

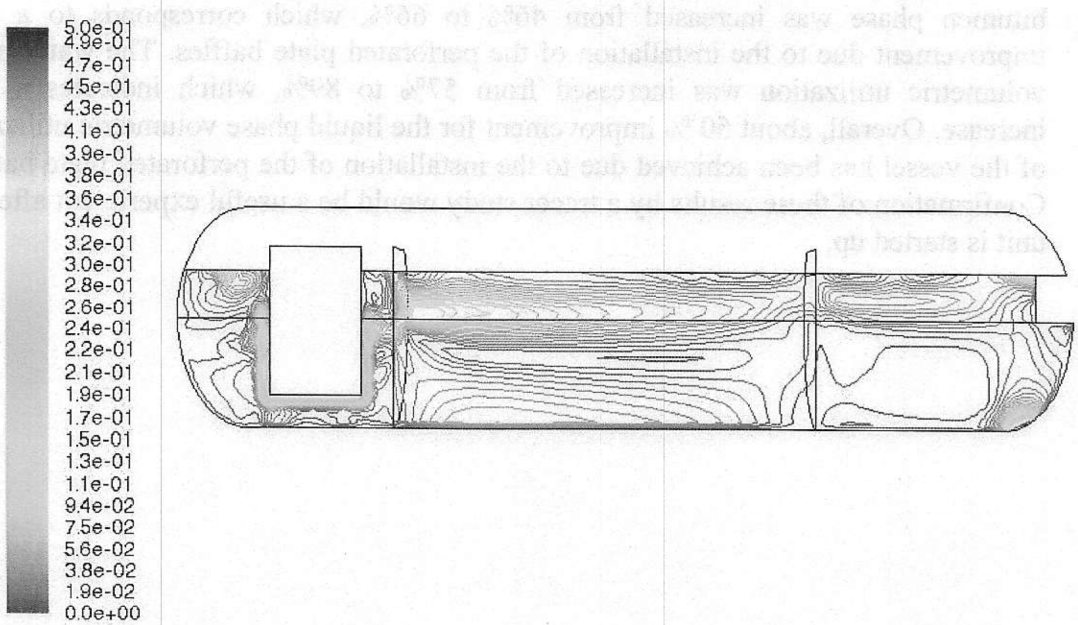

Figure 5 Fluid velocity contour lines in the vessel with baffles.
(Y-axis ranges from 0.0 to 0.5 m/sec.)

Residence Time Distribution

The residence time distribution is a common and simple technique to identify flow and separation conditions in a unit's operation. Normally, diversity of the residence time data indicates the extent of cross mixing or recirculation flow. The discrepancy between the mean residence time and the theoretical retention time based on plug flow imply the degree of short cut flow or dead zone in the vessel.

Figures 6-8 show the residence time distribution curves predicted for the gas, bitumen, and water phases in the two vessel configurations, respectively. Figure 6 shows that all the gas bubbles injected escape from the vessels in less than 120 seconds with a roughly mean residence time around 38, and 35 seconds for the two configurations. Since the baffles only go into the gas space about 10% of the depth of the gas space in the vessel (6 inch), no significant influence on the residence time was observed. Figure 7 indicates that the residence time for bitumen phase ranged from 350 to 800 seconds in the vessel without the baffles, corresponding to a mean value of 520 seconds; while the residence time was increased from 500 to 1000 seconds in vessel with the baffles, corresponding to a mean value of 745 seconds. An increase of 220 seconds was obtained due to the installation of the perforated plates. Figure 8 illustrates that the residence time in the water phase ranged from 420 to 1000 seconds with a mean value of 630 seconds in the vessel without baffle, and from 650 to over 1000 seconds with a mean value of 980 seconds in the vessel with baffles. A 350 second increase in the mean residence time was achieved due to introduction of the perforated plate baffles.

Figure 9 compares the volumetric utilization, defined as a ratio between the actual mean residence time and the theoretical residence time, for the configurations with and without perforated baffles. It was found that the volumetric utilization for the bitumen phase was increased from 46% to 66%, which corresponds to a 43% improvement due to the installation of the perforated plate baffles. The water phase volumetric utilization was increased from 57% to 89%, which indicates a 55% increase. Overall, about 50 % improvement for the liquid phase volumetric utilization of the vessel has been achieved due to the installation of the perforated plate baffles. Confirmation of these results by a tracer study would be a useful experiment after the unit is started up.

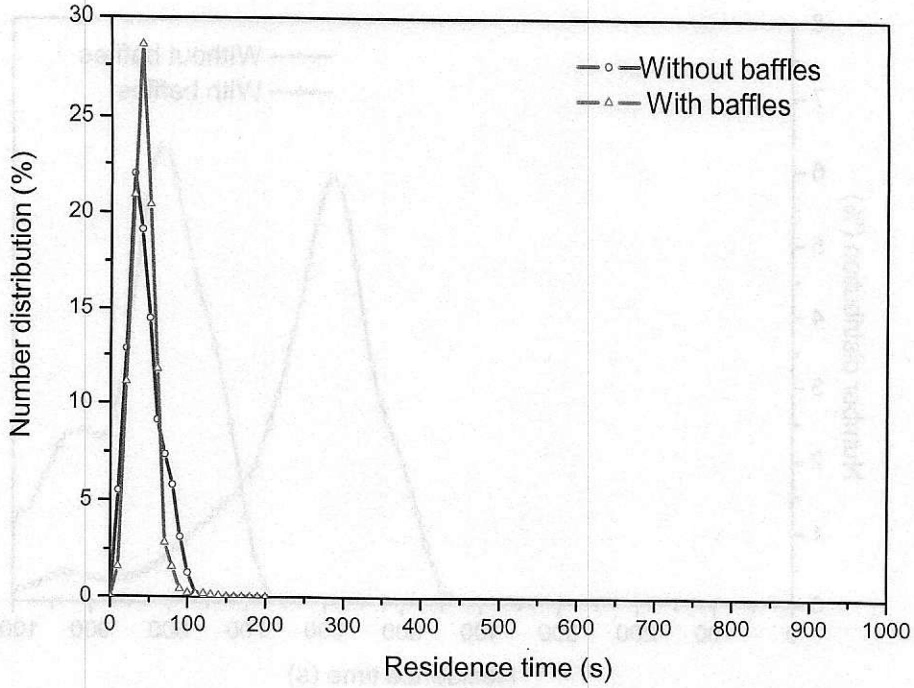

Figure 6 Residence time distributions in the gas phase

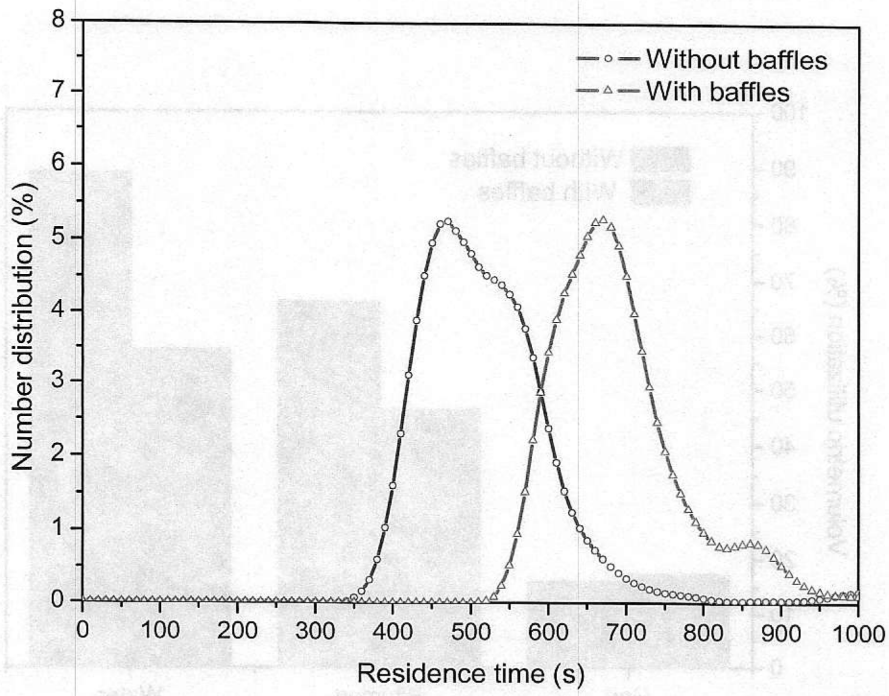

Figure 7 Residence time distributions in the bitumen phase

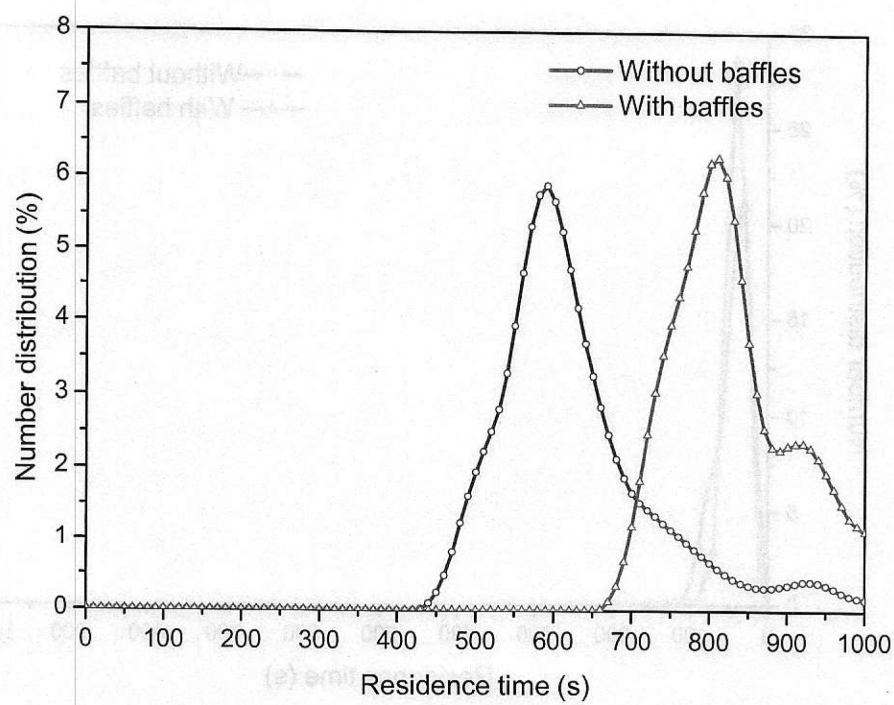

Figure 8 Residence time distributions in the water phase

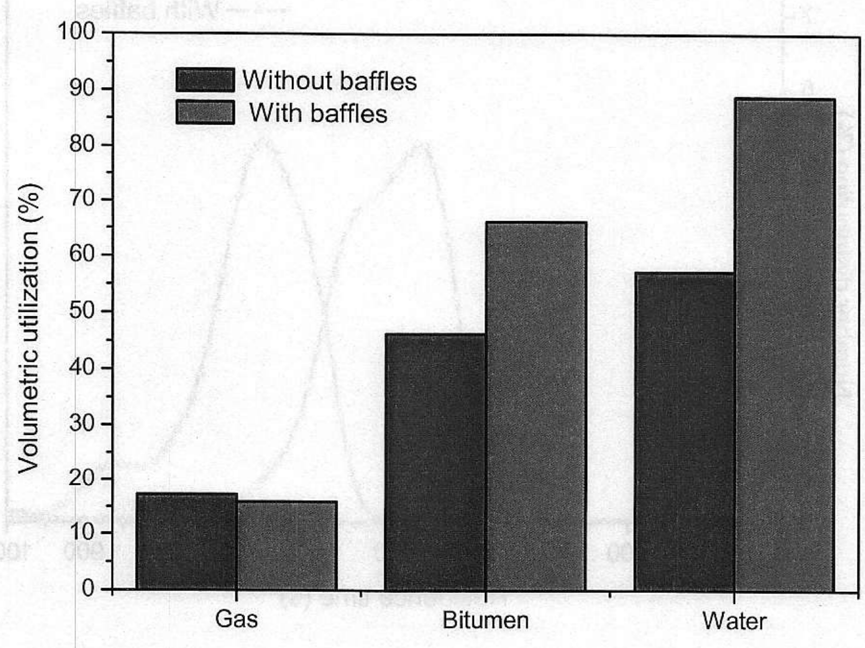

Figure 9 Volumetric utilization of the separator vessel

VI. CONCLUSIONS

1. The overall flow pattern in a vessel without baffles showed significant recirculation or reverse flow in the settling region. This flow regime could reduce the volumetric utilization of the vessel and could carry the separated bitumen into the water phase, thus reducing separation performance.

2. With the introduction of properly designed perforated plate baffles, the recirculation flow in large scale was broken into smaller ones, and the short circuiting of the vessel was substantially reduced. The separator performance could be significantly improved.

3. The CFD predictions of residence time distribution indicate that with installation of the two perforated plate baffles, the mean residence time (or volumetric utilization of the vessel) for the water phase was increased from 57% to 89% and from 46% to 66% for the bitumen phase.

4. Confirmation of the above results by a tracer study is recommended after the unit is started up.

VII REFERENCES

1. Souder, J.M. and Briown G.G., *design and fractionating columns. 1. entrainment and capacity*, Ind. Eng. Chem., Vol. 26, No. 1, 1934.
2. Oliemans, R.V.A, *Computational fluid dynamics for the petrochemical process industry*, Kluwer Academic Publishers, Dordrecht, 1991
3. Ishii, M., *Thermo-fluid dynamics theory of two-phase flow*, Paris: Eyrolles, 1975.
4. Launder, B.E and Spalding, D.B., *Lectures in Mathematical Models of Turbulence,* Academic Press, London, England, 1972.
5. Fluent user manual 6.2, Fluent Inc, 2003.
6. Daugherty, R.L and Franzini, J.B., *Fluid Mechanics*, McGraw-Hill, New York, 1965.
7. Crowe, C. Sommerfield, M. and Tsuji, Y, *Multiphase Flows with Droplets and Particles,* CRC Press, New York, 1998.
8. Gambit 2.2 Modeling Guide, Fluent Inc, 2003.