16 Numerical Simulation of Fluid Mechanisms and Separation Behavior in Offshore Gravity Separators

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CONTENTS

Abstract

The offshore activities to produce oil and gas have grown rapidly during the last few decades. The equipment used for bulk-separation operations is of considerable size and weight. The most widely used concept to separate bulk flows of water/oil/gas/sand on platforms are vessels in which gravity settling due to the density differences of the fluids takes place. The operation of the separator must provide sufficient time to allow the phases to separate by gravity. Both the operation in the field and the internal devices should make separators efficient and with low maintenance. Computational fluid dynamics (CFD) can provide a valuable insight, and the fluid flow behavior in the liquid bulk zone inside the separator may such be analyzed. Water-in-oil forms unstable emulsion in processing, and the drop-growth in the complex fluid will influence the separation efficiency. Many practical, design, and redesign applications may be performed by CFD modeling and simulations. Examples are (1) the development of the vessel inlet configurations that improve the uniformity of the gas and liquid flows, (2) sensitivity of a separator design to changes in operating conditions, (3) influence of internal equipment on separation performance, and (4) coalescence and breaking of emulsion.

16.1 INTRODUCTION

Separation during petroleum production takes place in a process composed of a number of equipment units. In many fields the process is also composed of a number of separation steps, where the pressure is reduced stepwise and gas flashed off. All oil/gas/water/sand separation is based on differences in density, and most separators are gravity separators, i.e., they utilize the common acceleration of gravity in huge pressurized vessels. Later development has brought compact, reliable high-g equipment to the market, particularly hydro-cyclones and centrifuges for oil and water polishing. The fluid flow behavior of a three-phase separator shows that different physical and chemical phenomena are important in different zones.

Separator sizing must satisfy several criteria for good operation during the lifetime of the producing field:

- Provide sufficient time to allow the immiscible gas, oil, and water phases to separate by gravity
- Provide sufficient time to allow for the coalescence and breaking of emulsion droplets at the oil–water interface
- Provide sufficient volume in the gas space to accommodate rises in the liquid level that result from the surge in the liquid flow rate
- Provide for the removal of solids that settle to the bottom of the separator
- Allow for variation in the flow rates of gas, oil, and water into the separator without adversely affecting separation efficiency.

The simple design methods for gravity separators like those found in Refs. 1 and 2 do not match the complicated multiphase fluid flow behavior through such equipment in any great detail. The design of the separators is not accurate, and the design may be too conservative. This frequently gives oversized vessels, both in volume and weight, and low separation efficiency [2]. Development of design and simulation tools is under way [3–12]. These are based on knowledge of basic hydrodynamic and physicochemical principles, and possibly a combination of these effects. Even at the present stage these tools represent a significant enhancement of the design and redesign of jobs for gravity separators offshore [13,14]. Computational fluid dynamics (CFD) applied to single-phase flow has become more and more important for modeling and design of industrial processes and its components [15–19]. The extension of single-phase CFD techniques to two-phase or multi-phase flow calculations is not easy. Some of the problems and the difficulties have been reviewed by Jayanti and Hewitt [20].

This chapter discusses the characterization of the mixture of oil and water and the distribution of the multi-phase fluid flow in a horizontal gravity separator. CFD can provide valuable insight to develop and demonstrate the technology required for the realization of efficient, compact, low maintenance gravity separators. Water-in-oil will form unstable emulsions in processing and the drop-growth in the complex fluid will influence the separation efficiency. A phenomenological model for drop growth in batch separation is described and a simulation performed. The fluid flow behavior in the liquid bulk zone inside a separator is analyzed. The use of CFD demonstrates how the flow field is related to inlet flow conditions and the performance of internals.

16.2 FLOW BEHAVIOR IN HORIZONTAL GRAVITY SEPARATORS

Each separator operates at a fixed pressure. The multiphase fluid flow enters the vessel through the inlet nozzle as a high momentum jet hitting an inlet arrangement such as a momentum

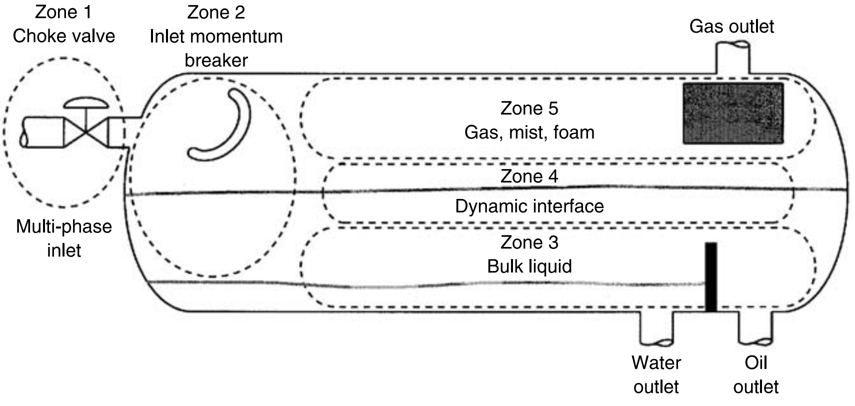

FIGURE 16.1 Typical flow zones in a horizontal gravity separator.

breaker device or cyclones. The liquid is diverted into the liquid pool in the lower part of the vessel. Inside the liquid pool, near the inlet, the multiphase fluid flows as a dispersion with low horizontal velocity. The low-density gas and mist rises, and the oil, water, and emulsion will separate by gravity on the way to the outlet. In the upper part of the vessel, the oil and water particles together with condensed gas will fall down to the liquid interface as the multiphase fluid flows to the outlet. For the modeling and simulation of fluid flow and phase separation behavior inside a gravity separator, it is helpful to characterize the different flow regimes or zones; see Figure 16.1.

16.3 FLUID SYSTEM AND MECHANISMS OF SEPARATION

The mixture of oil, gas, water, and particles that is the inlet stream to a separator train exhibits large variations in both composition and physicochemical properties. The thermodynamic properties, which determine the gas/oil ratio through the various steps of the process, are well known, and will form a well-described system. The properties of the liquid phase, represented by bulk viscosity, emulsification, coalescence, and settling properties, are less well understood, and consequently insufficiently described in terms of realistic mathematical models.

The separation process is dominated by two factors: (1) The emulsification process, which takes place in the choke and other equipment components with high shear, and (2) the coalescence and settling effects, where drops grow and settle or cream to its homo-phase.

16.3.1 DISPERSED MIXTURES OF OIL AND WATER

Normally, the gas is released quickly in the inlet arrangement of the separator, and the water-in-oil or oil-in-water will form an emulsion in between the oil and water. The amount of water, the water cut, and the stability of the emulsion will create the resistance in the flow field. The bulk viscosity is an important parameter in the fluid dynamics and different correlations for apparent viscosity versus water cut for dispersions have been derived and presented in the literature. Some of the models suggested in the literature [21–23] are reviewed and plotted in Figure 16.2 for an oil/water mixture. The plot shows the relative viscosity versus water cut. The relative viscosity for an emulsion is the viscosity for the emulsion divided by the viscosity of the continuous phase.

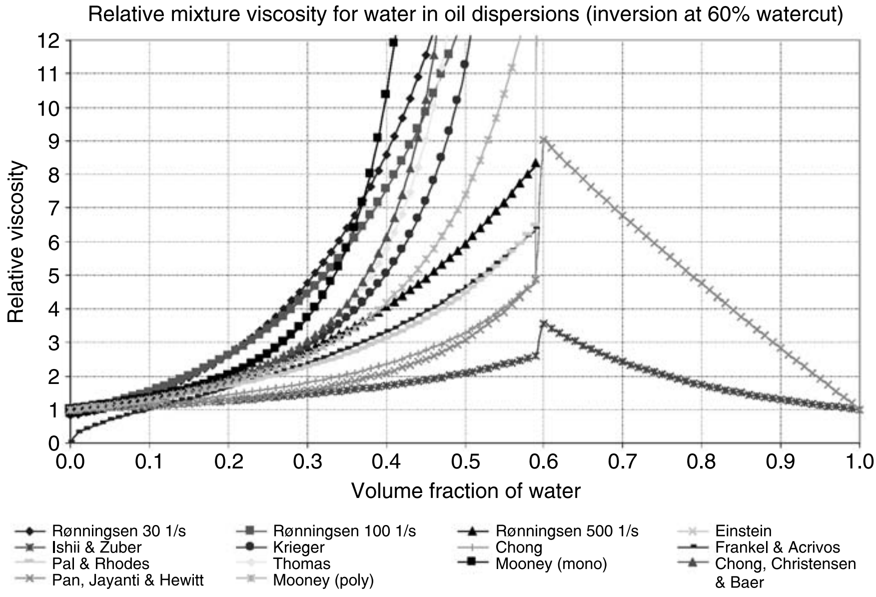

FIGURE 16.2 Relative viscosity correlations for dispersed oil/water mixtures.

All the models agree well for a dilute dispersion (water cut below 10%), but for higher water cuts the models give quite a scattered result. Thus, the viscosity model used for fluid dynamic calculation in a gravity separator should rely on the emulsion behavior investigated.

16.3.2 The Bottle Test (Batch Separation)

A common method of determining relative emulsion stability of water-in-oil or oil-in-water is a simple bottle test (batch separation test), as described by Schramm [22]. A batch separation test involves agitating a mixture of oil and water to form a uniform dispersion, then removing the agitation to allow the dispersion to settle naturally. These batch sedimentation and coalescence experiments are an attractive method for studying the separation behavior of emulsions because of simple, repeatable, and inexpensive experiments. When the percentage of water in the mixture exceeds about 20% by volume, two "interfaces" become visible as the mixture settles. One is a "sedimentation" interface between the settling dispersion and the bulk oil phase (in which a small amount of dispersed water may remain). The other is a "coalescence" interface between the dispersion and the bulk water phase (which contains a small part of dispersed oil). As time goes on, the thickness of the dispersion layer gets smaller and the two interfaces approach each other.

The mixture in a batch settler behaves as a quasi-homogeneous flow and may be described by an advanced mixture model, such as the drift-flux model [9,24–27]. The drift-flux model is one of the multi-phase flow models in the commercial CFD program FLOW-3D [28].

The settling of drops initiates an upward flow in the container and this dynamic behavior is well defined within the drift-flux model. The model regards the whole mixture as a single flowing continuum, by solving both the volume continuity and the momentum equations for the whole mixture. This mixture has macroscopic properties like the bulk viscosity, previously discussed. The model describes the relative flow of the immiscible fluids with different densities. One of the important variables in focus is the local, instantaneous volume fraction, called the water cut. Furthermore, a drop-system or a drop-size distribution is the resulting macroscopic value called the water cut, in a polydispersed water-in-oil emulsion.

In the separation of the phases, the process is dominated by the coalescence and the settling rates of the dispersed phase. The coalescence rate depends on a number of parameters: drop-size distribution, drop density, shear/turbulence, and interfacial properties. The settling rates are determined by the density difference, and the viscosity of the dispersion, computed by Stokes' law or models for hindered settling. The binary coalescence rate is the product of collision frequency and coalescence efficiency, i.e., the number of collisions that lead to a successful merging of drops, which gives the resulting drop growth in the mixture system. The driving forces in the collision frequency are: the settling of drops, the shear flow, and the turbulence in the flow field.

16.3.3 Modeling and Simulation of Batch Separation

The mathematical modeling of coalescence in unstable oil-in-water emulsions is thoroughly described in the literature [29–32] and by the more fundamental theories in Refs. 33 and 34. Numerical simulations for batch settling of a poly-dispersed water-in-oil emulsion are performed and the results are presented in Figure 16.3. The water cut in the emulsion was 20%, the density difference of the two fluids is 200 kg/m^3, and the height of the settling container was 0.3 m. The drop-size distribution (Figure 16.4) was initially configured in ten different drop classes. The Sautern mean diameter in the distribution is 160 μm. Settling in the batch was simulated with and without a coalescence model, and as seen in Figure 16.3 the separation run faster with the drop-growth model (coalescence model) included. The separation time for the present batch system is 430 sec, calculated by Stokes' unhindered settling equation.

The separation time is 1300 sec, calculated by Kumar and Hartland's hindered settling equation (see Ref. 35). The simulated result with a constant Sautern mean drop-size 160 μm (original drift-flux model) gives a long settling time, about 1800 sec. The simulated result with a drop-growth model (coalescence model) shows the approach of the two interfaces after 1150 sec, which

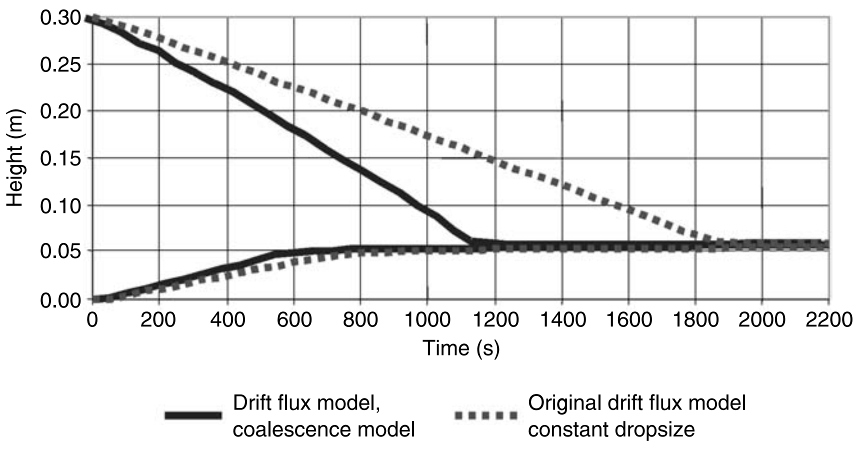

FIGURE 16.3 Simulated results of separation interfaces in batch settling. (From EMU-SIM. Oil/water separation offshore: optimized flow- and separation behavior. JIP, 1999–2002.)

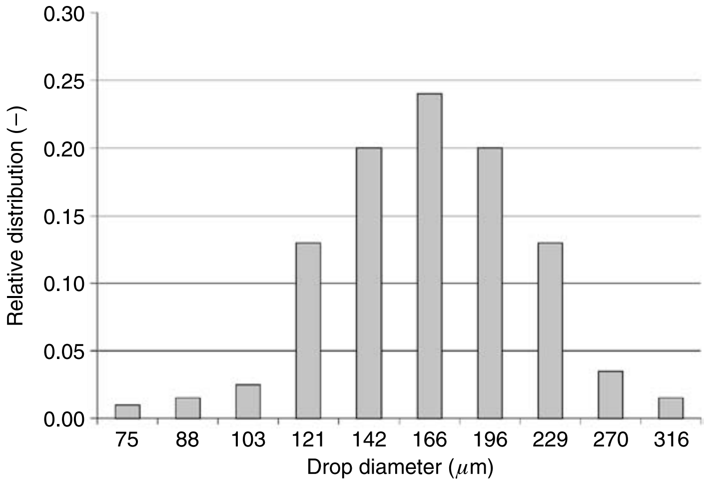

FIGURE 16.4 Drop-size distribution for an oil/water mixture.

is in relatively good agreement with the hindered settling equation. The different simulated results are presented in Figure 16.3.

16.4 HYDRAULIC BEHAVIOR IN A HORIZONTAL SEPARATOR

The gas/liquid and liquid/liquid systems will result in two relatively separated flow systems in pipelines or separators, due to the density differences. Between the two fluids a dynamic interface will form, stratified or annular in pipelines and stratified in separators. The characteristics of such flow systems may be developing flows, entrance flows, co-current flow transition, etc. and the full dynamic interaction between the phases is important.

The gas and liquid flows with rather high velocities enter through pipe and inlet devices to the separator. Inlet devices, such as cup-shaped plates, turbine-vane arrangements, or cyclone arrangements, are normally mounted as momentum breaker devices. The momentum breaker device will lower flow velocities and separate the gas and the liquid phases quickly with a minimum space required in the longitudinal direction. The flow leaving the momentum breaker will further introduce the gas (gas and mist) and liquid phases (water and oil) into gas volume or liquid pool of the separator, respectively. A horizontal three-phase separator is normally about half-filled with liquids (oil/water) to allow the gas to evacuate with a proper retention time in the upper part of the separator.

The modeling and simulation of high momentum multi-phase flow in the complicated inlet momentum breaker region, and further into the three-dimensional gas and liquid bulk flow zones, are beyond the capability of the current CFD programs. The fluid flows leaving the momentum breaker device have to be estimated and introduced as an inlet flow condition to the bulk flow zones in a horizontal separator.

16.4.1 Fluid Flow Modeling and Simulation

CFD simulations are performed to study the fluid flow behavior in the liquid bulk flows in a horizontal separator. The test separator is a conventional horizontal gravity separator with a diffuser and a cascade tray as the inlet arrangement (Figure 16.5). The inlet arrangement, a diffuser and a cascade tray, is mounted on the inlet riser, which is located centrally at the end.

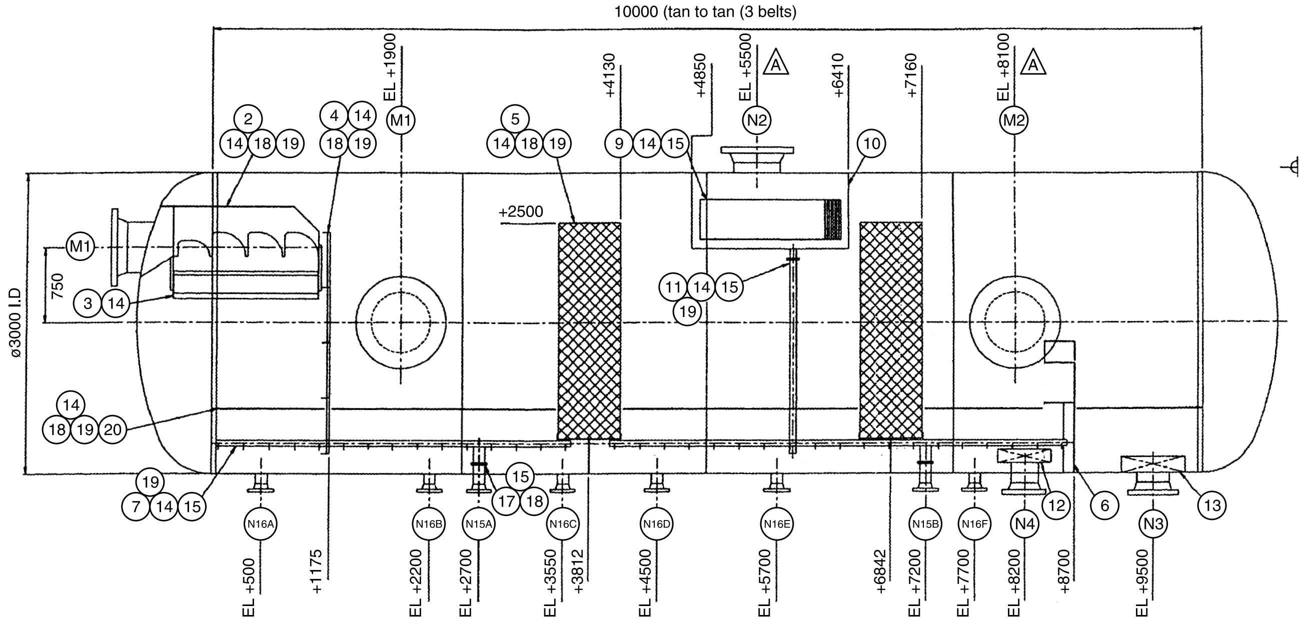

FIGURE 16.5 Sketch of the test separator. (2) and (3) are the inlet diffuser and the cascade tray, respectively. (4) is the distributor plate just downstream of the inlet and (6) is the fixed weir between the water and the oil outlets. A horizontal baffle (20) and the sand wash assembly (7) are in the lower part of the separator. Mellapak, structured packing, is shown as the crosshatched areas in the separator.

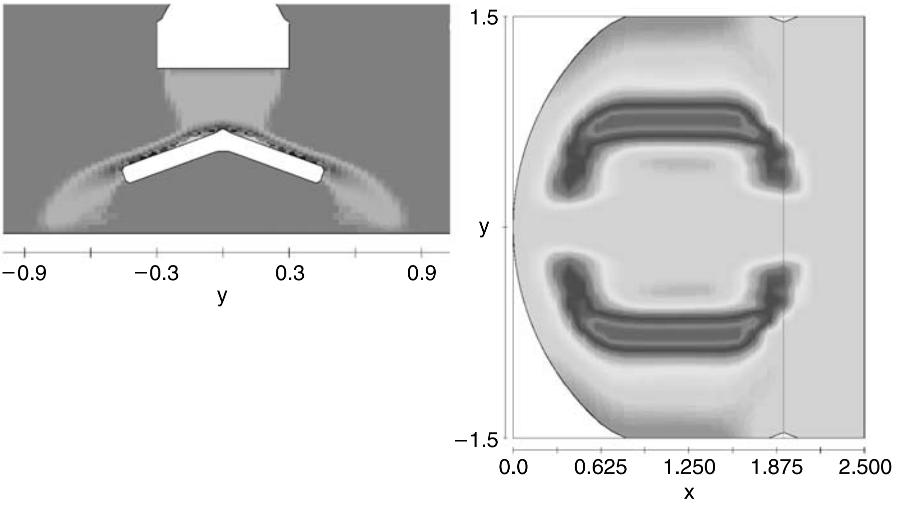

FIGURE 16.6 Left view showing the gas/oil/water-flow (mixture) from the inlet nozzle hitting the cascade tray and flowing further into the oil filled part of the separator. Right view presents the mixture flow, oil/water, diving into the gas/oil interface in the separator.

The separator is a three-phase separator (i.e., separation of gas, oil, and water). The separator is about half filled with liquids in operation. The overall length is 11.5 m and the diameter is 3.0 m. The flow model covers the flow from inlet to the weir plate in the separator. The fluid flows leaving the momentum breaker device have to be estimated and introduced as an inlet flow condition to the bulk flow zones in a horizontal separator. Figure 16.6 presents the inlet flow condition in a cross section in the inlet flow zone at the momentum breaker device and the mixture flow, oil/water, diving into the gas/oil interface in the separator. In most three-phase separators a distributor plate, the porous baffle separating the inlet zone and the bulk flow and separation zones, has a strong impact on the flow pattern in the oil zone and water zone. The distributor plate has a low porosity (fraction of the area that is open to flow) and thus a pressure loss for the flow through. The distributor plate is not extended to the bottom of the vessel and it is important to introduce the water part into a dynamic simulation model of the liquid filled part of the separator.

The normal liquid level is at 1265 mm and the normal interface level at 942 mm. The oil zone thickness is 323 mm; thus most of the liquid volume during operation is filled with water. The water cut in this study is 29.3%. The flow pattern in vertical slices, from the inlet to the weir, is presented in Figure 16.7. The flow upstream of the distributor plate is governed by the flow from the inlet. The flow from the inlet and the restriction of the flow through the distributor plate will increase the pressure and thus push the interface between oil/water somewhat down. The flow of water that is pushed under the distributor plate is also clearly seen in the picture. Relatively high velocities through the distributor plate are visible for both the forward and backward flow through the distributor plate area. High velocities are seen at the free surface between oil and water, especially in the vertical central plane of the separator. In both the oil and the water zones, away from the central plane, backward flows are found in the numerical simulation.

Figure 16.8 gives the velocity fields in horizontal slices, from the inlet to the weir (along the main flow direction). In the oil zone some re-circulation zones are seen just downstream of the distributor plate. In the water zone the re-circulation patterns are more pronounced. The figure

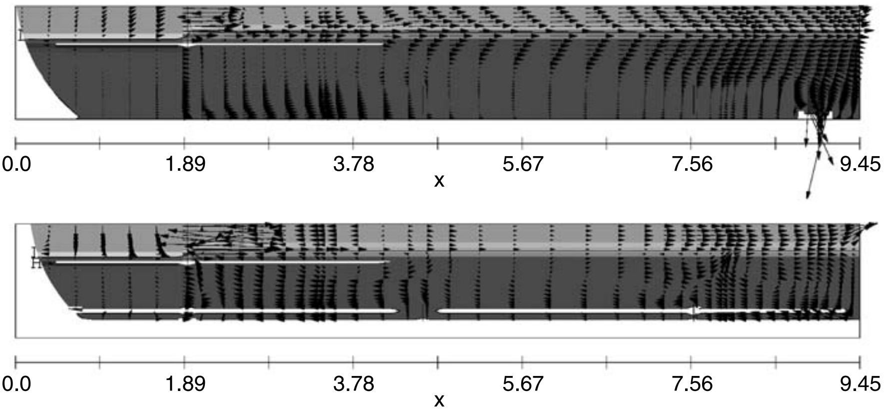

FIGURE 16.7 Numerical simulation of liquid flow in the test separator. Flow patterns are seen in vertical slices, from inlet to weir, along flow direction. Maximum velocity is different in the two different views. Top view is along central plane and max velocity is 59.4 cm/sec. Lower view is about midway between central and wall plane and max velocity is 32.8 cm/sec.

shows both a shorter re-circulation downstream of the distributor plate, and a longer re-circulation pattern from the outlet area back to the distributor plate along the separator wall. The high velocities under the distributor plate govern the re-circulation pattern just downstream of the plate. The Mellapak support plates also govern the re-circulated water in the separator.

Figure 16.9 presents the velocity field in vertical slices, perpendicular to the flow direction. For the vertical motion in the oil zone the fluid is in general slowing down toward the weir. In the water zone it is demonstrated that the horizontal baffles, above the sand wash assembly, create a vertical circulation flow pattern just below the oil/water interface.

16.4.2 Tracer Response and Hydraulic Efficiency Indicators in Liquid Zones

16.4.2.1 Tracer Response in Oil Zone

The numbers from the tracer simulations performed in the separator are summarized and presented in Table 16.1. A theoretical retention time of 169.7 sec was expected for the oil. The calculated median, or "average," retention time from the tracer response curve is 145.9 sec. The total short-circuiting number is 1.0 for ideal plug flow. For Case 1, the total short-circuiting number is 0.86. The value is reasonably close to unity, indicating little stagnant space in the oil flow. The tail of the tracer response curve indicates the mixing in the oil flow. The hydraulic indicator for the "worst" short-circuiting states that values as low as 0.05 clearly indicate serious short-circuiting. The test separator has an indicator of 0.33. The dispersion index is between 2.5 and 3.0, which is the indicator for mixing in the oil flow. From literature, a "good settling basin" should have a dispersion index of less than 2.0.

16.4.2.2 Tracer Response in Water Zone

The water flow through the separator has a theoretical retention time of 835.1 sec. The hydraulic indicators for the water presents non-favorable separation conditions for oil drops (and small sand particles) in the separator. This number, as well as the re-circulating pattern in the flow field, indicates a high degree of mixing. The most serious short-circuiting clearly indicated a value

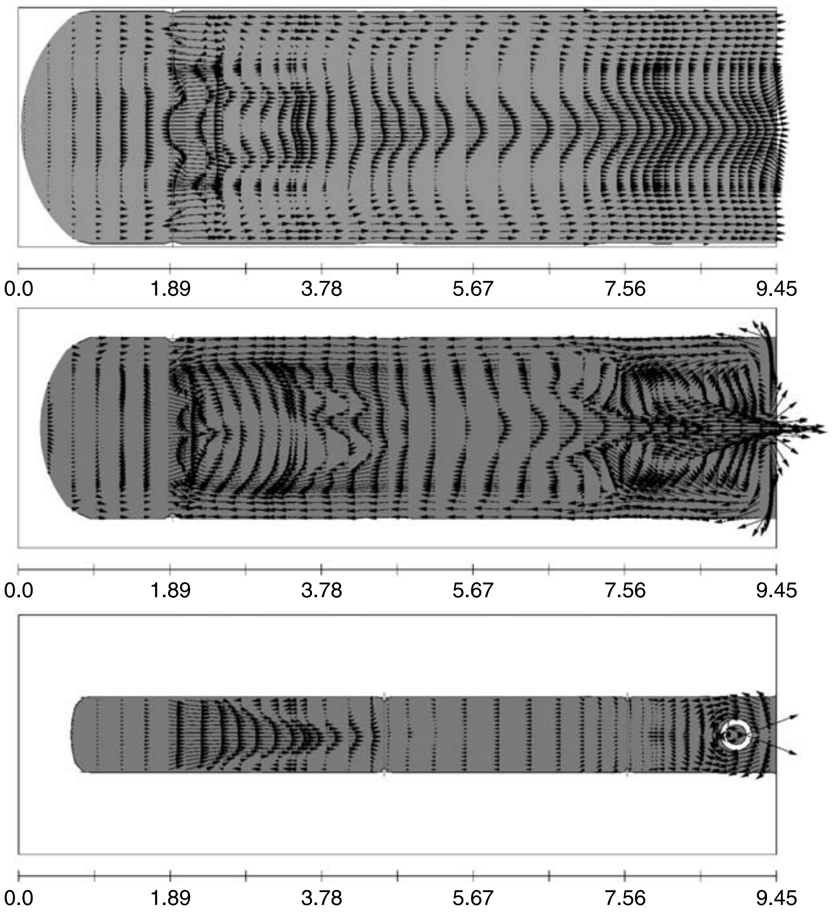

FIGURE 16.8 Case 1 numerical simulation of liquid flow in Test separator. Flow pattern seen in horizontal slices, from inlet to weir, along the main flow direction. Maximum velocity is different in the three different views. Top view is 12.6 cm below oil/gas interface (NLL) and max velocity is 33.6 cm/sec. Middle view is midway between oil/water interface (NIL) and max velocity is 6.98 cm/sec. Lower view is just below distributor plate and max velocity is 17.1 cm/sec.

as low as 0.07, resulting that some flow is passing through the separator much faster than the theoretical retention time.

16.5 CONCLUSIONS

Offshore separators are huge pressurized vessels, in which oil/water/gas/sand are separated. The operation of the separator is to provide sufficient time to allow the phases to separate by gravity. The operation in the field and the internal devices should make efficient and low maintenance separators.

Advanced multiphase flow modeling by the CFD program FLOW-3D can simulate the fluid dynamic effects in a gravity separator. The modeling of flow in separators is based on dividing

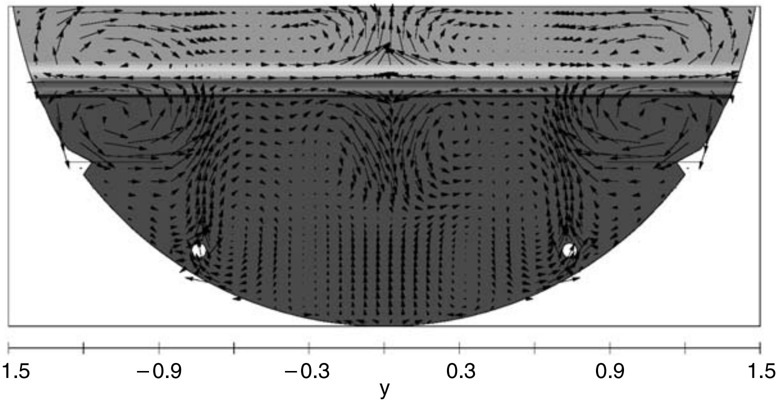

FIGURE 16.9 Numerical simulation of liquid flow in the test separator. Flow pattern is seen in vertical slices, perpendicular to flow direction. The plane view is midway between distributor plate and weir and max velocity is 0.99 cm/sec.

TABLE 16.1
Theoretical Retention Times in Oil and Water Flow Volumes for the Test Separator, Tracer Response Characteristics, and Hydraulic Efficiency Indicators

Flow Volume	Prod. Rates	Theoret. Retention Time, Tr	Init. Appear., Ti	10% Tracer, T10	90% Tracer, T90	Total Short-Circ.	Most Serious Short-Circ.	Disper. Index
	M3/d	s	S	s	s			
Oil	3572	169.7	55.4	88.5	262.0	0.86	0.33	2.96
Water	1479	835.1	62.5	153.6	1909.6*	0.67	0.07	12.43

*T88: 88% of tracer particles counted at outlet.

the separator in different zones, and limiting the study to two phases at a time; the entire separator can be analyzed. FLOW-3D has been used in a number of studies and engineering jobs.

The rheology of oil/water emulsions is described mathematically. The bulk viscosity models generally lack validation towards relevant field or pilot scale model experiments. The drop-growth (coalescence rate) modeling implemented in a drift-flux flow model gives realistic separation and the behavior of the dispersion interfaces. Simulations of oil/water separation in a typical batch settler are performed.

The coalescence can be modeled with semi-empirical relations, but the relation between the coalescence rate and the mixing/turbulence in bulk flow zones in a separator is not yet sufficiently described.

Computational fluid dynamics and numerical simulations represent a significant enhancement of design jobs and the great challenge is to combine the chemical and the fluid dynamic effects.

Many practical, design, and redesign applications may be performed by CFD modeling and simulations. Examples are (1) development of vessel inlet configurations that improve the uniformity of the gas and liquid flows, (2) sensitivity of a separator design to changes in operating conditions, (3) influence of internal equipment on separation performance, and (4) coalescence and breaking of emulsion.

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