Methods for Effective Viscosity of Two Immiscible Liquid Phases

Industry Paper

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Abstract

This paper provides documentation of the methods in Aspen Exchanger Design and Rating® (Aspen EDR) for determining the effective viscosity of a mixture of two immiscible liquid phases. The methods address prediction of the occurrence of the inversion point, at which the continuous phase changes from one liquid to the other. They also address the high viscosities that tend to occur near the inversion point. The methods were introduced in V7.3 to improve accuracy and provide a range of options for handling separate liquid phases and emulsions. There is considerable uncertainty in the prediction of the effective viscosity and in some cases laboratory data may be required.

Introduction

This paper describes the implementation in Aspen Shell and Tube Exchanger of new methods for determining the effective viscosity of a mixture of two immiscible liquid phases. The methods are applied to any such pair of liquid phases, but due to the commercial importance of oil-water mitures in production and refining, the discussion which follows will be based on these applications. Usually the oil phase will have the higher viscosity and water the lower.

The flow is often in the form of an emulsion, which means droplets of one phase are carried along by the flow of the dominant, continuous phase. The presence of such droplets can significantly increase the viscosity of the dominant phase, so effective viscosities higher than either the oil or water often occur.

When one phase is present in relatively small amounts, the situation is straightforward, but there can be significant uncertainties when the amounts of each phase are comparable. As the amount of water in oil increases (their water cut), there is a change from oil being the continuous phase to water being the continuous phase, and the transition is known as the inversion point. There can be a very large increase in effective viscosity in the region of the inversion point

The potential for a high effective viscosity, and the uncertainties associated with its magnitude along with the location of the inversion point, can be the controlling influence in a heat exchanger thermal design.

Oil – Water Viscosity

Corlett and Hall[1] measured the frictional pressure drop in a pipeline running with oil-water mixtures of varying composition and used the pressure drop data to infer the effective liquid viscosity. Figure 1 shows the measured effective viscosity for two different light crude oils for a range of water volume fractions. The oil viscosity for Tests 1 and 2 was 6 cP and for Tests 3 and 4 it was 12 cP.

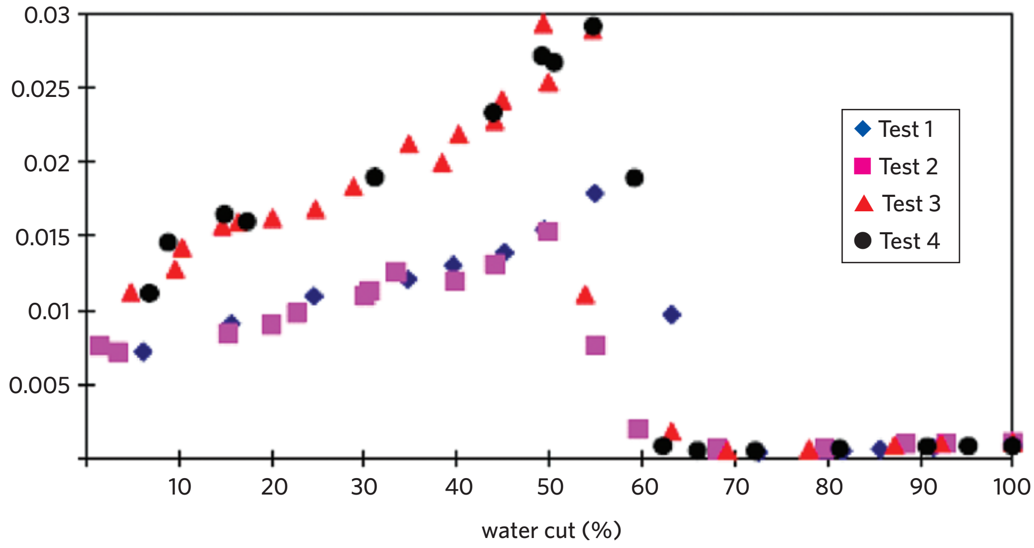

Figure 1: Measured effective viscosity for oil-water mixtures (from Corlett and Hall)

The data show the characteristic behavior of an inversion point near a water cut (i.e. water volume fraction) of 50% and a high viscosity at the inversion point. In the water-continuous region, the viscosity is close to that of water until the water cut falls to about 60%, at which point there is a sudden increase.

Methods for Effective Viscosity

In the Brinkman[2] method it is assumed that the viscosity of the continuous phase is increased by droplets of the other phase. The Brinkman equation for the effective viscosity is:

$$\eta_{eff} = \eta_{cont}\left(1 - V_{disp}\right)^{-k} \quad (1)$$

where V_{disp} is the volume fraction of the dispersed phase.

In Aspen Shell and Tube Exchanger V7.2.1, the inversion point is implied by the intersection between the equation (1) for oil-continuous and water-continuous flow, with an upper limit imposed on the higher viscosity. Figure 2 shows the result of this approach for an oil of viscosity 10 cP.

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[1] Corlett, A.E. and Hall, A. (1997), "Viscosity of Oil/Water Mixtures", NEL Report 263/97, TUV NEL Ltd, East Kilbride, UK.

Figure 2 shows that this method tends to give an inversion point at a relatively low water cut, well below 0.3 in the particular case shown. If the actual inversion point is at a higher water cut, the method can significantly under predict the effective viscosity in the range between the predicted and actual inversion point.

Corlett and Hall found good agreement with their data if the parameter k in the Brinkman equation is calculated from the Taylor[3] equation:

$$k = 2.5\left(\frac{\eta_{disp}+0.4\eta_{cont}}{\eta_{disp}+\eta_{cont}}\right) \quad (2)$$

For a dispersion of viscous oil in water, the value of k is very close to the equation used by Aspen Shell and Tube Exchanger V7.2. For water dispersed in a continuous oil flow, the value of k is close to 1.0.

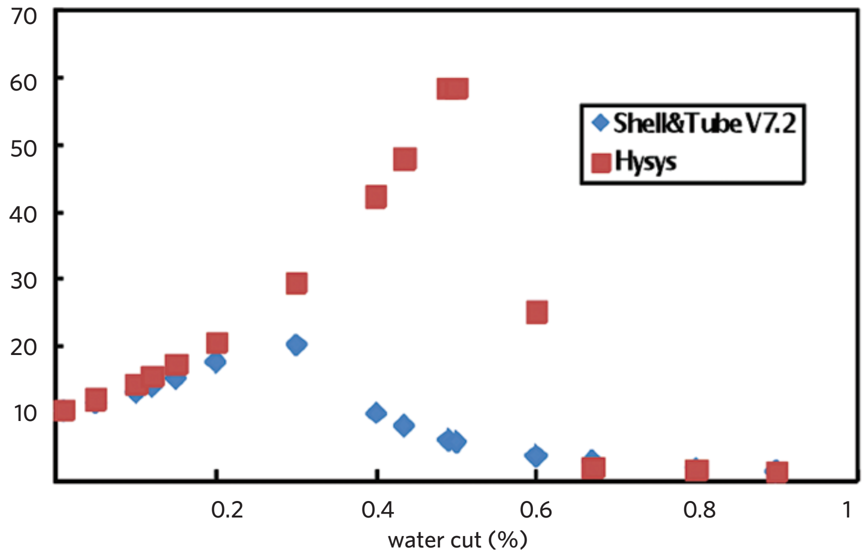

Figure 2: Effective viscosity from Aspen Shell and Tube Exchanger V7.2 and Aspen HYSYS® methods for oil viscosity = 10 cP

An alternative approach to the effective viscosity is the HYSYS emulsion method:

For $V_{oil} > 0.5$: $$\eta_{eff} = \eta_{oil} e^{3.6(1-V_{oil})} \quad (3)$$

For $V_{oil} < 0.3$: $$\eta_{eff} = \eta_{water}\left[1 + 2.5V_{oil}\frac{(\eta_{oil}+0.4\eta_{water})}{(\eta_{oil}+\eta_{water})}\right] \quad (4)$$

In the range $0.3 < V_{oil} < 0.5$ the effective viscosity is a weighted average of equations (3) and (4).

The predictions of the HYSYS method for an oil viscosity of 10 cP are shown in Figure 2. It gives similar results to the Aspen Shell and Tube Exchanger V7.2 method at high oil and water fractions, but the fixed inversion point of 0.5 leads to a much higher viscosity in the water cut range 0.3 to 0.65.

Figure 3 shows the predicted effective viscosities for an oil of viscosity 250 cP. There are clearly much larger differences in the predicted inversion points and in the effective viscosities than in Figure 2.

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[2] Brinkman, H.C. (1952), "The viscosity of concentrated suspensions and solutions", Journal of Chemical Physics, Vol. 20, No. 4, page 371.

[3] Taylor. G.I. (1932), "The viscosity of fluid containing small drops of another fluid", Proceedings of the Royal Society of London, Vol. 138A, pages 41-48.

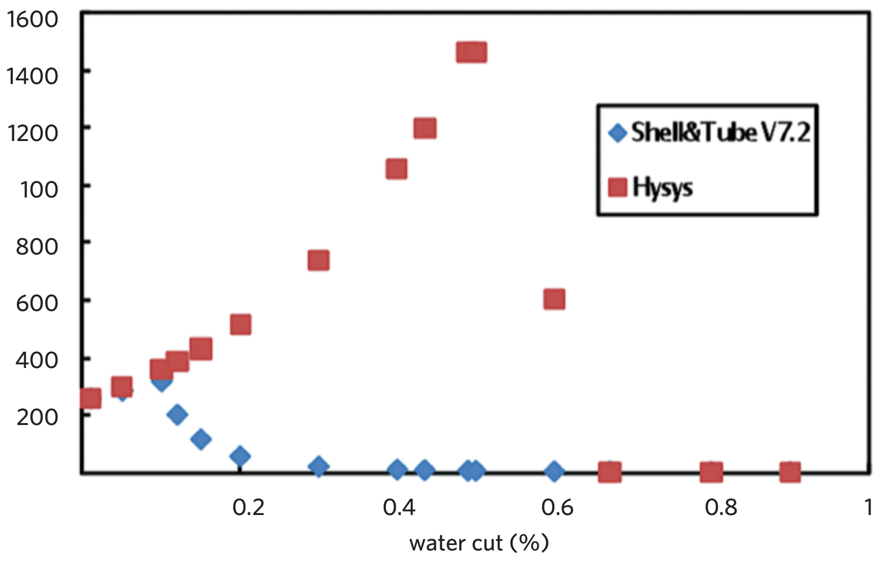
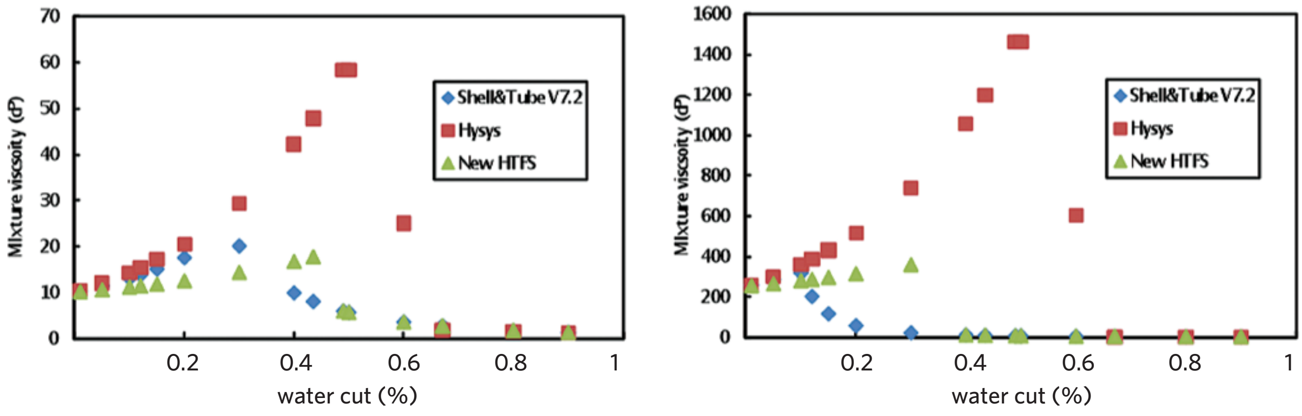


Figure 3: Effective viscosity from Aspen Shell and Tube Exchanger V7.2 and Aspen HYSYS® methods for oil viscosity = 250 cP

Figures 2 and 3 emphasize the importance of accurately predicting the inversion point.

It was decided, therefore, to base a new Aspen HTFS® method for Aspen EDR V7.3 on equations (1), (2) and an HTFS proprietary adjustment. The predictions of this method for oil viscosities of 10 and 250 cP are shown in Figure 4, together with the results from the other methods.



(a) Oil viscosity = 10 cP

(b) Oil viscosity = 250 cP

Figure 4: Predicted effective viscosities

Comparison of Figures 1 and 4(a) confirms that the new HTFS method gives good agreement with the data for the low-viscosity oils. The Aspen HYSYS method appears to over predict the data in Figure 1. Figure 4(b) illustrates the extent of the divergences among the methods for a higher viscosity oil.

Method Selection

In Aspen EDR V7.3 it is possible to select one of five different methods for prediction of the oil-water effective viscosity:

1. The HTFS selected method (new HTFS method for single phase and boiling, higher viscosity for condensing)
2. The new HTFS method
3. The HYSYS emulsion method
4. Use higher viscosity
5. The old HTFS method (the only option in V7.2.1 and earlier)

Method 4 has been a traditional approach in some companies and is primarily made available for the convenience of users who may wish to set the effective viscosity equal to the oil viscosity. It is also appropriate for film wise condensation and falling film evaporation, when the phases will usually flow separately rather than being intimately mixed.

The behavior of oil-water emulsions can be very difficult to predict and the presence of trace concentrations of certain materials can significantly affect the behavior. In practice, it is preferable to obtain laboratory data for a specific mixture, particularly when the phase composition is in the region of the inversion point. Figure 4(b) shows that it may be particularly important to obtain laboratory data with higher viscosity oils.

Nevertheless, the effective viscosity of an emulsion is known to depend on its stability. Static laboratory data may not reflect the actual behavior of the emulsion under flow conditions.

The limited data available in Corlett and Hall (1997) suggest that the new HTFS method is appropriate for relatively light oils. The HYSYS method reflects some oil industry experience with emulsions, and it may be more appropriate for heavier oils that are more likely to form stable emulsions. It can generate very high viscosities, especially close to a water cut of 50%, which can lead to very high predicted pressure drops.

Whichever method is selected for determining the effective viscosity, the Aspen EDR program will issue warnings when significant uncertainties exist. One warning is issued when the predicted viscosity is more than 50% higher than either of the pure fluid viscosities. Another gives the temperature range over which viscosities are in or near the transition region. The temperature range may extend beyond the stream bulk temperature range, since viscosities are also evaluated at wall temperatures. The criteria for issuing these messages are difficult to define precisely, so absence of a message is not necessarily a guarantee of accuracy.

Case Study - 1

Aspen Shell and Tube Exchanger V7.3.1 was used to design a heat exchanger using two methods to determine the impact that the viscosity of the light oil/water mixture has on the sizing and corresponding estimated cost of the exchanger. The first run used the new HTFS method, the second run used the HYSYS emulsion method.

Details for the process for the case study are included in the table below:

Fluid	**Light oil (shell side)**	**Light oil / water (tube side)**	**Units**
Total Flow Rate	52	61	kg/s
Temperature (In / Out)	140 / 55	42 / 80	C
Viscosity (In / Out)		14 / 2.5	cP
Water Mass Fraction		0.4	

Results from the case study using the two viscosity methods:

		HTFS Method	**HYSYS Method**
Shell size	mm	1117.6	1193.8
Tube number		1896	2234
Tube length – actual	mm	6096	6096
Tube length – required	mm	6064.6	6095.7
Area reqd., dirty	m2	2155.4	2560.4
Film coef overall, TS	W/(m2 K)	237.8	187.2
Pressure drop, TS	bar	0.986	0.48666
Number of units in series		3	3
Number of units in parallel		1	1
Total price	Dollar (US)	$862,158	$1,006,977

The new HTFS method for prediction of the viscosity of a light oil / water mixture resulted in a design that was approximately $144k less than with the HYSYS emulsion method.

Case Study - 2

Aspen Shell and Tube Exchanger V7.3.1 was used to check rate a heat exchanger using the highest viscosity determined from either the HTFS method or the HYSYS emulsion method. The operation of the heat exchanger was then simulated using the more accurate HTFS method for determining the actual operation in an existing process.

The flow rate on the tube side was iterated with the second run until the actual tube side pressure drop was equal to the allowable tube side pressure drop of 1 bar.

Results from the case study using the two viscosity methods:

Case	Heat Load (MW)	Outlet Temp Deg C	Tube Side Flow Kg/s	Tube Side DP bar
Design with high viscosity	10.0	80	60.8	0.88
Simulation with HTFS viscosity	8.8	79.7	54	1.0

The result suggests a reduction in throughput of 11% could be expected, based on the more accurate HTFS method.

This amounted to an oil flow reduction of approximately 5,200 barrels of oil/day or a loss of $300,000/day.

Conclusions

Aspen Shell and Tube Exchanger V7.3 provides a range of methods for prediction of the effective viscosity of an oil-water mixture. The new HTFS method gives good agreement with some available data obtained from pressure drop measurements for low viscosity crude oil-water mixtures. However, there are large divergences between the new HTFS method, the previous (V7.2.1) HTFS method and the HYSYS emulsion method.

It is emphasized that prediction of the effective viscosity of an oil-water mixture is often highly uncertain, particularly with higher viscosity oils and in the vicinity of the inversion point. In many cases, use of laboratory data will be advisable to mitigate the consequences of this uncertainty on a heat exchanger thermal design.

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