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Example for Determination of the Phase Inversion Point

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Abstract

The phase inversion refers to a phenomenon where with a small change in the operational conditions, the continuous and dispersed phase spontaneously inverts. For instance, in oil-water systems, dispersion (emulsion) of oil drops in water becomes dispersion (emulsion) of water drops in oil, or vice versa. The phase-inversion is a major factor to be considered in the design of oil-water pipelines, since the rheological characteristics of the dispersion and the associated pressure drop change abruptly and significantly at or near the phase inversion.

Key words: *phase inversion, inversion point, spontaneous phenomenon*

Introduction

The inversion point is usually defined as the critical volume fraction of the dispersed phase above which this phase will become the continuous phase. Studies have been carried out in batch mixers, continuous mixers, column contractors and pipe flow, in attempt to characterize the dependence of the critical volume fraction on the various system parameters, which include operational conditions, system geometry and materials of construction [2]. In flow systems, phase inversion will not always occur as the holdup (say of water) is varied continuously from 0 to 1. It will occur only if *Um* is high enough to have a good mixing of the liquids in both the preand post inversion dispersions.

Model for Determination

Similarly to observations made in stirred tanks, also in pipe flows, data on dispersion inversion indicate a tendency of more viscous oil to form the dispersed phase. It was found that the water-cut required to invert a dispersion decreases as the oil viscosity, μ_0 increases. Based on the experimental results of various investigators on phase inversion, [3] proposed the following correlation for the critical water-cut ε_a^I,

$$\varepsilon_a^I = \left(\frac{U_{aS}}{U_m}\right)_f = 0{,}5 - 0{,}1108\lg\left(\frac{\mu_p}{\mu_r}\right);\ \mu_r = 1\,\mathrm{mPa}\cdot\mathrm{s}\ . \qquad (1)$$

The trend is similar to that indicate by the [4] model for the phase inversion point:

$$\varepsilon_a^I = \frac{1}{1+\left(\frac{\mu_p}{\mu_a}\right)^{0,5}} .$$

The later was developed with reference to a configuration of laminar flow in stratified layers, however, its validity was tested against the critical holdup data obtained in a flask (dispersion prepared by manual vigorous shaking of specified volumes of an organic and water phases).

Since phase inversion is a spontaneous phenomenon, it was proposed that its prediction can be based on the criterion of minimization of the total system free energy, [1]. Under conditions where the composition of the oil and water phases and the system temperature are invariant with phase inversion, only the free energies of the interfaces have to be considered. The application of this criterion is, however, dependent on the availability of a model for characterizing the drop size in the initial and post-inversion dispersions, both are usually dense. This approach was recently followed in [2].

According to this approach, when a dispersion structure (say $D_{p/a}$) is associated with higher surface energy than that obtained with an alternate structure (say $D_{a/p}$), it will tend to change its structure, and eventually to reach the one associated with the lowest surface energy. Hence, the phase inversion is expected under the critical conditions where both $D_{p/a}$ and $D_{a/p}$ are dynamically stable and the sum of surface energies obtained with either of these two configurations are equal.

Based on these considerations, the critical oil holdup can be obtained in terms of the liquid-solid surface wet ability angle, α, and the Sauter mean drop diameter in pre-and post inversion dispersions :

$$\varepsilon_p^I = \frac{\left(\frac{\sigma}{d_{32}}\right)_{a/p} + \frac{s}{6}\sigma\cos\alpha}{\left[\frac{\sigma}{d_{32}}\right]_{a/p} + \left[\frac{\sigma}{d_{32}}\right]_{p/a}}, \tag{2}$$

where s represents the surface wetted area per unit volume, $s = \frac{4}{D}$, $0 \le \alpha < 90°$ corresponds to a surface which is preferentially wetted by water (hydrophilic surface), whereas for $90° < \alpha \le 180°$ the oil is the wetting fluid (hydrophobic surface).

The Sauter mean drop size can be scaled with reference to the maximal drop size, $d_{32} = \frac{d_{max}}{k_d}$.

Using such a scaling, models for d_{max} in coalescing, dense $D_{p/a}$ or $D_{a/p}$ can be used in eq. (2) to evaluate the critical oil holdup at phase inversion. Applying the H-Model of Brauner [5], eq. $\left(\frac{d_{max}}{D}\right)_0 = 1{,}88 \cdot \mathrm{We}_C^{-0,6} \cdot \mathrm{Re}_C^{-0,6}$ yields:

$$\bar{d}_p = 7{,}61 C_H \left(\frac{\sigma}{\rho_a D U_m^2}\right)^{0,6} \left(\frac{\rho_a D U_m}{\mu_a}\right)^{0,08} \left(\frac{\rho_a}{\rho_m}\right)^{0,4} \frac{\varepsilon_p^{0,6}}{(1-\varepsilon_p)^{0,2}}, \tag{3}$$

$$\bar{d}_a = 7{,}61 C_H \left(\frac{\sigma}{\rho_p D U_m^2}\right)^{0{,}6} \left(\frac{\rho_p D U_m}{\mu_p}\right)^{0{,}08} \left(\frac{\rho_p}{\rho_m}\right)^{0{,}4} \frac{(1-\varepsilon_p)^{0{,}6}}{\varepsilon_p^{\;0{,}2}}, \tag{4}$$

where d_p and d_a represent the maximal drop size in $D_{p/a}$ and $D_{a/p}$ respectively.

Under conditions where the oil-water surface tension in the pre-inversion and post-inversion dispersions is the same (no surfactants or surface contaminants are involved), $(k_d)_{p/a} \cong (k_d)_{a/p}$ and solid-liquid wettability effects can be neglected ($\alpha = 90°$ or $s \to 0$, as in large diameter pipes, where $d_a, d_p << D$), eqs. (2 - 4) yield:

$$\varepsilon_p^I = \frac{\tilde{\rho}\tilde{\nu}^{0{,}4}}{1+\tilde{\rho}\tilde{\nu}^{0{,}4}}\ , \tag{5}$$

where $\tilde{\nu}$ is the cinematic viscosity ratio, $\tilde{\nu} = \dfrac{\nu_p}{\nu_a}$.

Equation (5) provides an explanation for the observation made in many experimental studies, which the more viscous phase tends to form the dispersed phase. For a given holdup, and in the case of viscous oil, the characteristic drop size in $D_{p/a}$ is larger than in the reversed configuration of $D_{a/p}$. Hence, a larger number of oil drops must be present in order that the surface energy due to the oil-water interfaces would become the same as that obtained with the water dispersed in the oil. The larger is the oil viscosity, the wider is the range of the oil holdup, $0 \le \varepsilon_p \le \varepsilon_p^I$, where a configuration of oil drops dispersed in water is associated with a lower surface energy. In this range of holdups, the flow pattern will be $D_{a/p}$ if the operational conditions are in range a the dynamic stability criterion is satisfied. Whereas, $D_{p/a}$ will be obtained in the range of $\varepsilon_p^I \le \varepsilon_p \le 1$, provided such a dispersion is dynamically stable.

Thus, when only the liquids' interfacial energy is involved, and the hydrodynamic flow field is similar in the initial and post inversion dispersions, the details of the flow field and the system geometry are not required for predicting the critical holdup at inversion.

Figure 1 shows a comparison of the critical oil holdup predicted via eq. (5), with experimental data of phase inversion in pipe flow which were used by Arirachkaran et al [3] to obtain their experimental correlation, eq. (1) (line 2 in figure 1). A lower variance is however obtained by correlating the data using the form of eq. (5).

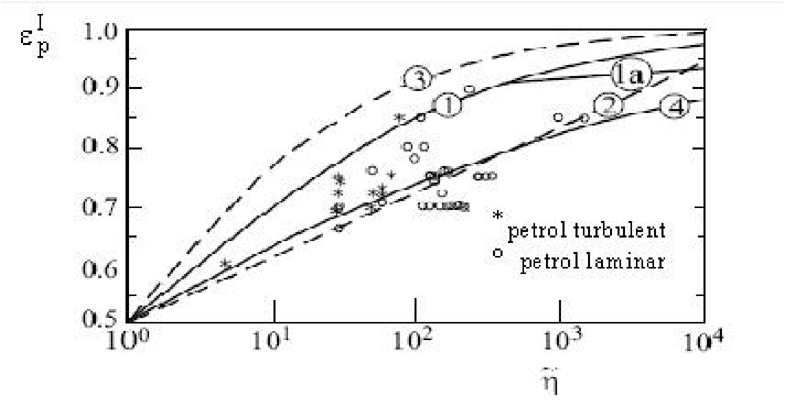

Fig. 1. The critical oil-cut for phase inversion in pipe flow comparison of models/correlations with experimenal data

This phase inversion model was shown to be useful for explaining various experimentally observed features related to phase inversion in pipe flow and in static mixers. These include the effects of the liquids physical properties, liquid/surface wet ability (contact angle), the existence of an ambivalent region and the associated hysteresis loop in pure systems and in contaminated systems [1]. Impurities or surfactant, and even entrained air bubbles, may have prominent effect on the critical holdup. Therefore, in many applications it is practically impossible to predict the conditions for phase inversion.

Conclusion

From the practical point of view, the main issue in predicting the pressure drop in homogeneous liquid-liquid dispersed flow is the modeling of the effective (apparent) mixture viscosity, μ_m. To this aim, the first decision to be made concerns the identity of the continuous phase. This decision is related to the phase inversion phenomenon. The second decision concerns the appropriate model to represent the variation of μ_m with the holdup in the particular system under consideration. The latter depends on the extent of mixing (emulsification) of the dispersed phase, which is a result of a combined effect of many factors (e.g. flow field, liquids physical properties, impurities and/or surfactant, liquid/wall wetting). These factors affect also the critical conditions for phase inversion.

In any case, at the phase inversion point the liquids must be at intimate contact and models for emulsion viscosity are applicable to evaluate the pressure drop peak. However, so far, there are no general models or correlations for predicting the effective mixture viscosity for the variety of systems and operational conditions and much empiricism is still involved.

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Exemplu pentru determinarea punctului de inversie de fază

Rezumat

Inversiunea de fază este un fenomen în care cu o mică schimbare a condiţiilor de operare, fazele continuă şi dispersă, se inversează spontan. De exemplu în sistemele petrol - apă, o dispersie (emulsie) a picăturilor de petrol devine o dispersie (emulsie) a picăturilor de apă în petrol, sau viceversa. Inversarea de fază este un factor major care trebuie luat în considerare la proiectarea conductelor petrol - apă, deoarece caracteristicile reologice ale dispersiei şi scăderea de presiune se asociază în mod semnificativ la punctul inversiunii fazei sau în apropierea acestuia.