

Phase inversion in dispersed liquid–liquid flows

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Abstract

Phase inversion and its effect on pressure gradient during the dispersed flow of two immiscible liquids have been studied for two pipe materials (steel and acrylic) and two pipe sizes (60 and 32 mm ID). Water and oil (796 kgm⁻³ density and 2.19 mm²s⁻¹ viscosity) were used as test fluids while the appearance of phase inversion in the acrylic pipes was confirmed with the use of impedance ring probes. In the large pipes (steel and acrylic with 60 mm ID) it was found that the *phase inversion point* (oil volume fraction where inversion appears) depended on whether the inversion was from oil to water continuous mixture or from water to oil. The difference in the phase inversion points between the two dispersion initialisation conditions increased with increasing mixture velocity. No effect of initial conditions on the inversion point was found for the small acrylic pipe.

Phase inversion was in all cases preceded by a large increase in pressure gradient, which was sharply reduced immediately after the new continuous phase was established. The pressure gradient peak was sharper and larger at high mixture velocities than at low ones and in the acrylic pipe compared to the steel one. The change in phase continuity lasted a few minutes and was accompanied by large fluctuations in pressure gradient and mixture impedance.

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1. Introduction

Two-phase flow of immiscible liquids, an organic and an aqueous, appear in many chemical and petrochemical processes. In the petroleum industry, water can be present in oil reservoirs as formation water or it can break through from adjacent sources, particularly at the later years of production. Oil and water are therefore frequently transported together in wells and surface pipelines. Knowledge of the behaviour of oil–water mixtures would be applicable to the design of pipelines, downstream separation facilities and pumps, and in the areas of corrosion prediction and production instrumentation interpretation. A sound understanding of oil–

water systems is also a platform to the understanding of more complex flows, such as the oil–water–gas ones.

At high flow velocities dispersions will form, where either the organic or the aqueous phase can be the continuous one. At a particular volume fraction, *phase inversion* will appear, which is defined as the change of the continuous phase to become dispersed and vice versa. The critical volume fraction of the dispersed phase where inversion occurs is the *phase inversion point*. The change of the continuous phase will lead to a system with different properties which can be desirable in some cases (i.e. production of margarine [1]) but in other cases are unwanted (i.e. in exothermic aromatic nitrations phase inversion can cause a sudden increase in the reaction rate and produced heat [2]). In pipeline flows a maximum in pressure gradient at phase inversion point has been observed [3,4], which has implications for the flow-rates in multiphase pipelines.

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Nomenclature

\tilde{C}_H	constant in Eq. (3)	ε_o^I	critical oil fraction at phase inversion
d_{32}	Sauter mean drop diameter (m)	η_o	oil viscosity (mPa s)
d_{\max}	maximum drop size diameter (m)	η_r	water viscosity, $\eta_r = 1$ mPa s
D	pipe diameter (m)	θ	liquid–solid contact angle (degrees)
f	wall friction factor	$\tilde{\nu}$	kinematic viscosity ratio, $\tilde{\nu} = \nu_o/\nu_w$
k_d	constant ($k_d = 1.5–5$, $d_{32} = d_{\max}/k_d$)	$\tilde{\rho}$	density ratio, $\tilde{\rho} = \rho_o/\rho_w$
s	solid surface area per unit volume (in smooth pipes $s = 4/D$) (m^{-1})	ρ	density ($kg\ m^{-3}$)
U_{ws}	water superficial velocity ($m\ s^{-1}$)	σ	oil–water surface tension ($mN\ m^{-1}$)
U	velocity ($m\ s^{-1}$)		
<i>Greek letters</i>		<i>Subscripts</i>	
ε_d	dispersed phase holdup	c	continuous phase
ε_w^I	critical water fraction at phase inversion	m	oil/water mixture
		o	oil phase
		w	water phase

Most of the available information on the phenomenon originates from work in stirred vessels. This revealed that for two immiscible liquids, there is a range of volume fractions, the *ambivalent range*, over which either phase can be the continuous one [5–7]. For a particular system the exact phase inversion point within the ambivalent range will depend on a number of parameters, such as fluids' properties, operational (i.e. impeller speed) and initial (i.e. position of impeller, aqueous or organic continuous initial dispersion) conditions and wetting characteristics of the vessel material. From the physical properties, viscosities of the two phases seem to have the greatest effect. Selker and Sleicher [5] found that as the viscosity of a phase increases both the minimum volume fraction that this phase can be continuous and the maximum fraction that it can be dispersed also increase, while Norato et al. [8] found that an increase in the viscosity ratio will in general widen the ambivalent range. There is some disagreement on the effect of interfacial tension [5,9] and according to Norato et al. [8] ambivalent range widens with decreasing interfacial tension.

A few investigators have suggested models for the prediction of the phase inversion point. Based on a number of experimental studies on oil–water dispersed flows that covered a wide range of oil viscosities, the empirical model suggested by Arirachakaran et al. [10] (Eq. (1)) confirms the importance of viscosity on phase inversion:

$$\varepsilon_w^I = \left(\frac{U_{ws}}{U_m} \right)_I = 0.5 - 0.1108 \log_{10}(\eta_o/\eta_r) \quad (1)$$

where ε_w^I is the critical water cut for phase inversion, $\eta_r = 1$ mPa s, η_o is the oil viscosity, and U_{ws} and U_m are the water and mixture superficial velocities respectively.

Phase inversion has been suggested to occur at the point where the surface energies of the two possible dispersions, oil continuous or water continuous, within the

ambivalent range, are equal [11–13]. Based on this, the critical oil hold up for phase inversion can be given by the following correlation [13]:

$$\varepsilon_o^I = \frac{[\sigma/d_{32}]_{w/o} + \frac{\sigma}{6} \cos \theta}{[\sigma/d_{32}]_{w/o} + [\sigma/d_{32}]_{o/w}} \quad (2)$$

where θ is the liquid–solid surface contact angle with $0 \leq \theta < 90^\circ$ denoting a surface preferentially wetted by water (hydrophilic surface) and $90^\circ < \theta \leq 180^\circ$ denoting a surface wetted by oil (hydrophobic surface); $s = 4/D$ is the solid surface area per unit volume and D is the pipe diameter, σ is the interfacial tension and d_{32} is the Sauter mean drop diameter. The subscripts w/o and o/w denote a water-in-oil and an oil-in-water dispersion respectively. The Sauter mean diameter can be found from the maximum drop size, d_{\max} , and $d_{32} = d_{\max}/k_d$ where k_d is a constant that depends on the fluid system used and $k_d = 1.5–5$. d_{\max} in a dense dispersion can be found from the following correlation [13]:

$$\frac{d_{\max}}{D} = 2.22 \tilde{C}_H \left(\frac{\rho_c U_c^2 D}{\sigma} \right)^{-0.6} \left[\frac{\rho_m}{\rho_c (1 - \varepsilon_d)} f \right]^{-0.4} \left(\frac{\varepsilon_d}{1 - \varepsilon_d} \right)^{0.6} \quad (3)$$

where \tilde{C}_H is a tunable constant and f is the wall friction factor, ρ_c and ρ_m are the continuous phase and mixture density respectively, U_c is the continuous phase velocity and ε_d is the dispersed phase holdup.

For systems where the surface energy between the solid wall and the continuous phase contacting it can be ignored, the phase inversion point is given by [13]:

$$\varepsilon_o^I = \frac{\tilde{\rho} \tilde{\nu}^{0.4}}{1 + \tilde{\rho} \tilde{\nu}^{0.4}} \quad (4)$$

where $\tilde{\nu} = \nu_o/\nu_w$ is the kinematic viscosity ratio (oil over water) and $\tilde{\rho} = \rho_o/\rho_w$ is the density ratio (oil over water).

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