Improving separation efficiency of two-liquid mixtures

I A Davletshin¹, N I Mikheev¹, O A Dushina¹, A A Paerely¹, V A Fafurin²
¹Federal Research Center “Kazan Scientific Center of RAS”, 2/31 Lobachevskogo str., Kazan, 420111, Russia
²FGUP VNIIR, 7a 2Asinskaja str., Kazan, 420100, Russia

E-mail: davlet60@mail.ru

Abstract. The paper submits a newly developed experimental setup and describes the flow arrangement for the best possible separation of a mixture of two immiscible liquids by a gravitational method. Separation of water and Exxsol D100 solvent has been studied experimentally.

1. Introduction

Recently, measurement of flow rates of multiphase flows has become a relevant problem for oil and gas industry. [1-3]. Such measurements can be considered as simultaneous estimation of gas, oil, and water flow rates combined in a single flow exhibiting constantly variable composition and volume fractions of components. Multiphase flow meters are used for optimization of well operation and in conveying different substances [1, 2].

Oil and gas flow meters and test separators are essential metrological components of oil fields. However, theoretical uncertainty in measurements performed by a multiphase flow meter is usually worse than the one typical of conventional test separators, in which the flow is separated into phases for subsequent metering of each phase individually [4]. In practice, these devices should give reliable information on the flow rates of oil, associated gas and produced water. Their operation is associated with regular calibration of their performance parameters. Such calibration is carried out on special test facilities, in which mixtures of different composition are prepared by mixing “pure” components with their corresponding (measured) flow rates. There are dozens of test facilities across the world intended for calibration of multiphase flow meters and testing of test separators with different working ranges and available flow regimes [1, 2, 5]. Model liquids, Exxsol solvent in particular, are usually used for calibration of flow meters [6, 7].

Continuous operation of test facilities includes the following processes: metering of component flow rates, component mixing, passing the mixture through the tested flow meter (separator), and mixture separation. However, during the long operation times the components become polluted and can no longer be called “pure”. That being said, the design and regime parameters of the test facility should provide complete separation of mixture into components [1]. Among the prerequisites for the latter is prevention of stable finely dispersed emulsions while ensuring the required mixing of components. Nevertheless, reliable operation of the setup is eventually defined by the efficiency of the device that separates the mixture of liquids, i.e. the separator. Besides, when designing a test facility, it is crucial to minimize its dimensions (in particular, the volume of separators, which is currently...
dozens of m\(^3\)) [8-10] and optimize the residence time of the mixture inside the test facility while maintaining the separation efficiency.

2. Experimental setup and procedure

An experimental setup was developed and manufactured to study the process of mixture separation (figure 1). A mixture of two immiscible liquids (water and Exxsol D100 solvent) with different flow rates and proportions was considered. The setup was an open reservoir \(I\) with the length of \(L = 2\) m and a cross section of 0.4×0.55 m\(^2\) equipped with several devices. The reservoir walls, drainage \(2\) and coalescing \(3\) devices made of transparent material (polycarbonate) allowed visual observations of interaction between the mixture components. The coalescing device was a pack of horizontal plates with the vertical spacing of 20 mm. This device provided local separation of the mixture. Autonomous systems of water and Exxsol supply comprising the pumps and flow rate control systems maintained the circulation of liquids inside the setup.

![Figure 1. Experimental setup: Separator: 1 – reservoir; 2 – drainage device; 3 – coalescing device; 4 – channel; 5 – mixer; 6 – check valves; 7 – water supply line (to the mixer); 8 – flow meter of Exxsol supply line (to the mixer); 9 – water flow meter; 10 – Exxsol supply pump; 11 – water supply pump; 12 – flow laminarizing device.](image)

The mixture was prepared as follows: water and Exxsol flows entered the mixer \(5\) downstream of which turbulent mixing of components occurred in the pipe \(4\) with the diameter of 40 mm and the length of 2.5 m. There were no other specific impacts on the mixture parameters.

The mixture consisting of water with the density of 1000 kg/m\(^3\) and Exxsol D100 with the density of 818 kg/m\(^3\) was separated in the gravity field by buoyancy forces. To visualize the mixing and separation processes, Exxsol dyed with oil was used together with a transparent tap water. The experiments were carried out at the ambient temperature and atmospheric pressure.

The quality of mixture separation was estimated depending on the flow pattern for two layouts of the separation setup: with and without the flow laminarizing device. The laminarizing device \(12\) (figure 1) was a vertical pipe bundle of staggered arrangement. Tubes in the bundle had the diameter of 20 mm and were mounted over the whole cross section of the reservoir \(I\) with a spacing of 30 mm. This tube bundle prevented the turbulization and backmixing of separated components downstream of the coalescing device. Note that the design of laminarizing device did not impede vertical stratification of the mixture.

3. Results and discussion

The mixture was supplied to the end part of the reservoir \(I\) (figure 1). While it proceeded through the reservoir between plates of the coalescing device 3, the components were separated locally within the
slots, which were slightly inclined to the horizon in transverse direction. Large-scale segregated jets (drops) of components were observed at the coalescing device outlet. Then they either floated upwards (Exxsol), or settled down (water) within the reservoir. To prevent the mixture turbulization, a vertical pipe bundle 12 was mounted between the coalescing and drainage devices. The opposite (to the mixture inflow) end of the reservoir around the drainage device 2 exhibited mixture stratification: water (heavier liquid) gravitated to the lower part, while Exxsol was observed in the upper part. Separated components proceeded to the corresponding drainage spaces: Exxsol was drained from the upper part while water was drawn from the bottom part of the drainage device. Separated components (water and Exxsol) were sucked by the pumps 10 and 11 and forwarded to the mixer 5. The check valves 6 upstream of the mixer prevented one component from getting into the supply system of the other. Having passed through the mixer, the mixture was transported through the channel 4 to the reservoir 1 for further separation.

Water was pumped through the setup by a centrifugal pump. Its flow rate was controlled by a ball valve and measured by a Pitot tube and static pressure taps. These measurements were performed downstream of the water pump before the mixer. Exxsol was supplied in a similar way. Its flow rate was measured by a Coriolis flow meter.

The following mass flow rates were studied:
- Exxsol $G_{Ex} = (0.5 – 3.3)$ kg/s;
- water $G_W = (0.5 – 3.1)$ kg/s;
- mixture $G_T = G_{Ex} + G_W = (1.0 – 4.1)$ kg/s.

Exxsol content in water appeared to be the most sensitive and representative of the component flow rates in the separator. In general, this value is affected by the mixture flow pattern in the separator and channels of the test facility, i.e. increased flow rate of components leads to nebulosity of liquids. This is primarily relevant to the stream flowing out of the water drainage device. Increased flow rate made the transparent water flow turn into milky liquid. At the same time, the drained Exxsol remained relatively transparent. High flow rate regimes exhibited somewhat nebulous flow of Exxsol to the pump.

When no laminarizing device was installed, large portions of water were regularly entrained into Exxsol drainage starting from some certain flow rates. However, up until some flow rate level they did not deteriorate the composition of Exxsol entering the pump. Flow laminarizing device prevented these negative effects.

Quantitative evaluation of separator efficiency was performed using the volume fraction of Exxsol in water sample. Figures 2 and 3 demonstrate the percentage of Exxsol in water samples in different operating modes. Mixture separation at low Exxsol flow rate $G_{Ex} = 0.5$ kg/s and various water flow rates is illustrated in figure 2. Exxsol percentage in the water sampled from separator is shown in figure 3 depending on the total mixture flow rate at approximately fixed content of water and Exxsol in the mixture.

![Figure 2](image-url)  
**Figure 2.** Volume fraction of Exxsol (%) in water sample at $G_{Ex} = 0.5$ kg/s: 1 – with laminarizing device; 2 – without laminarizing device.
Figures 2 and 3 (line 2) demonstrate that as soon as the total mixture flow rate reaches \( G_\Sigma = G_{Ex} + G_W = 2.5 \text{ kg/s} \) (no laminarizing device), the flow is significantly “deteriorated”. When the laminarizing device (a vertical pipe bundle) is installed between the coalescing device and the drainage, the sample purity becomes somewhat better (lines 1 in figures 2, 3). Furthermore, the volume fraction of Exxsol in water samples at \( G_\Sigma < 2.8 \text{ kg/s} \) did not exceed 0.4 %. Thus, the preferable design of the separator includes the laminarizing device.

Data in figures 2 and 3 were obtained by express analysis of samples. To further examine the separator efficiency at \( G_{Ex} = 1.1 \text{ kg/s} \) and \( G_W = 1.1 \text{ kg/s} \), the samples were analyzed during 2-day settling. Exxsol samples remained transparent. Water samples remained nebulous, and no Exxsol film formed after 15 minutes. After 20 hours, the water sample in the test tube (column height of 250 mm) became mainly transparent. Nebulous liquid was only observed in the ~20-mm high upper part of the column. After another day, the water became fully transparent and a ~0.3-mm thick Exxsol film formed on its surface. Thus, we can conclude that the separator is able to provide the residual content of disperse phase in “clean” components not exceeding ~0.1%.

Hence, when the allowable total mixture flow rate is \( G_\Sigma = 2.8 \text{ kg/s} \), the mean velocity of mixture inside the separator is \( U^* = 0.02 \text{ m/s} \), while the mixture residence time in the separator is \( \tau^* = L/U^* = 100 \text{ s} \). Thus, the proposed separator design is able to provide efficient mixture separation if the conditions of \( U < 0.02 \text{ m/s} \) and \( \tau > 100 \text{ s} \) are met. Estimating the residence time, one should remember that the distance travelled by mixture components also depends on the liquid depth, \( H \), in the separator \( \sim (L^2 + H^3)^{0.5} \).

4. Conclusions

The water-Exxsol interaction, their separation rate as well as the efficiency of the proposed separation method have been studied experimentally. The limits of efficient operation of the separator have been estimated from the flow rates of water and Exxsol.

To enhance the efficiency of gas-liquid mixture separation it is necessary:
- to prevent finely dispersed emulsions of liquids in the setup. To that end, the flow regimes of multicomponent mixtures should be arranged so as to prevent high velocity gradients in them;
- to ensure full separation of components in separators by special devices and provide certain regime parameter ranges inside the separators;
- to install flow laminarizing devices in the free space of the separator to prevent flow turbulization in the process of component stratification.

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