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# Identification and Categorization of Flow-regimes of Counter-current Liquid-liquid Two-phase Flow through Inclined ($45^0$) Conduit of 11 mm Diameter

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## Abstract

Here, rigorous experimental investigations have been made on the flow-regime of counter-current liquid-liquid (kerosene-water) two-phase flow in an inclined ($45^0$) circular conduit with 11 mm diameter. The main objectives of the present experimental investigation are to detect, identify, characterize, and categorize the obtained flow-regimes based on their subjective as well as objective descriptions. Different flow-regimes obtained using different combinations of the superficial velocities of kerosene and water, have been detected and identified through visual observation together with high-resolution photography (using Canon 1300D DSLR camera) and high-speed videography (using PHANTOM high-speed camera). Visual descriptions are subjective in nature and can vary from subject to subject. Therefore, objective descriptions of the obtained flow-regimes have also been collected in the form of transient fluctuations of interfacial distributions and pressure drop across the conduit. In-house fabricated conductivity probes have been used to collect the transient fluctuation of interfacial distributions in terms of time series voltage signal whereas differential pressure transmitter has been used to collect the transient fluctuations of pressure drop in terms of time series current signal. Statistical analyses of the time series voltage and current signals have been performed to identify, detect, and categorize various flow-regimes. It has been found that the obtained signals and the corresponding statistical characteristics are able to successfully detect and categorize the flow-regimes.

## Introduction

Liquid-liquid two-phase flow is the simultaneous flow of two immiscible liquids through a conduit. When two immiscible fluids are flowing together through tubes, due to the topological configurations, flows are characterized in terms of different flow-regimes. Heat, momentum or mass interaction between the phases, pressure drop across the conduit strongly depends on the flow-regimes or interfacial distributions. Proper analysis of flow-regimes is essential to design the safety issues of any multiphase flow system. Liquid-liquid counter current two-phase flow (CCTPF) are observed in crude oil production and transportation processes in petroleum industries, liquid-liquid flows in subsea pipelines in petroleum production facilities, liquid-liquid extraction process, etc.

Most of the investigations on CCTPF have been conducted using gas-liquid two-phase flow [Ghosh et al. 2013; Ami et al. 2014; etc.]. According to best of authors' knowledge, only few investigations [Ullman et al. 2003; Ullman et al. 2006] are available on the flow-regime of liquid-liquid CCTPF in literature. Complex, non-linear hydrodynamics of inclined liquid-liquid CCTPF has been explored up to a very small extent. Therefore, experimental investigations have been conducted here to identify, detect, and categorize the flow-regimes of liquid-liquid CCTPF in an inclined ($45^0$) conduit of 11 mm diameter.

## Experimental Methodology

A Canon-1300D-DSLR-camera has been used to capture the still photographs of the individual flow-regimes. A PHANTOM high-speed camera has been used to capture and record the videos of the highly complex non-linear hydrodynamics of flow-regimes at 1000 fps. Objective descriptions of the flow-regimes have been collected by using in-house fabricated conductivity probes (CP) and differential pressure transmitter (DPT). CP has been used to collect the transient fluctuations of the interfacial distributions in the conduit and DPT has been used to collect the transient fluctuations of the pressure drop across the conduit. The output of the CP and DPT have been collected using respective processing circuits (in-house fabricated) in the form of time series voltage and current signals, respectively. Collection of these signals from the processing circuits of CP and DPT sensors and then recording in a computer have been done using NI data acquisition system with LabView software.

To detect and categorize the flow-regimes, statistical analysis of the normalized time series voltage and current signals have been performed using 'Matlab Coding'. Probability Density Function (PDF) and Cumulative Probability Density Function (CPDF) plots have been made for each of the normalized time series voltage and current signals.

## Results and Discussion

Based on the different combinations of superficial velocities of kerosene ($U_k$) and & water ($U_w$), some unique flow-regimes (shown in Fig. 1) have been obtained through the present experimental investigation. As per the interfacial distributions, these flow-regimes have been classified and named as Kerosene Dominated Thin Water Wavy Stratified Flow Regime (KDTWWSFR), Kerosene Dominated Plugish Wavy Stratified Flow Regime (KDPWSFR), Stratified Plug Flow Regime (SPFR), and Wavy Stratified Bubbly Flow Regime (WSBFR) as shown in Fig. 1.

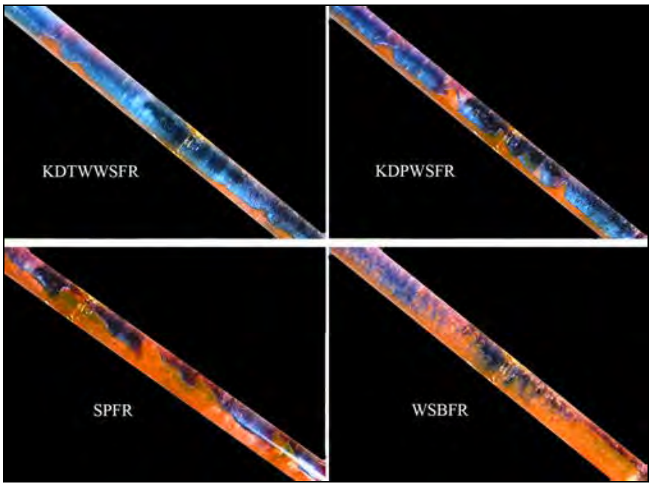


**Figure 1**: Digital photographs of the obtained flow-regimes (Here, $U_k$ = 0.420 m/s, $U_k$ = 0.018 m/s for KDTWWSFR; $U_k$ = 0.455 m/s, $U_k$ = 0.070 m/s for KDPWSFR; $U_k$ = 0.420 m/s, $U_k$ = 0.105 m/s for SPFR; and $U_k$ = 0.455 m/s, $U_k$ = 0.175 m/s for WSBFR).

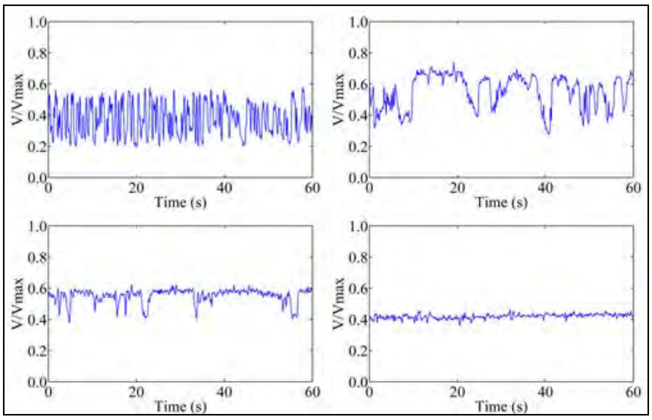


**Figure 2**: Time series voltage signals of the in-house fabricated CP.

Gravitational force has played an important role for the obtained flow-regimes. The normalized time series voltage signals from CP for these flow-regimes are shown in Fig. 2. By analyzing this figure, it is clear that time variation of the magnitude and nature of fluctuation for these voltage signals strongly depend on the phase distributions in the conduit for the respective generated flow-regimes. The PDF and CPDF of the voltage signals have been plotted through statistical analysis. Shape and size of these plots differ for different flow-regimes. Similarly, the normalized time series current signals obtained from the DPT and its PDF and CPDF plots look very different for different flow-regimes. Some statistical parameters (like mean, standard deviation, skewness, and kurtosis) have been extracted to parameterize the PDF plots of the CP and DPT signals.

## Conclusions

It has been found that time variation of the magnitude and nature of fluctuation of the signals (collected from CP and DPT) for different flow-regimes are different. Consequently, different statistical characteristic-plots (PDF and CPDF plot) have been found for different flow-regimes and subsequently they are able to identify and categorize the generated flow-regimes successfully. Methodologies can be developed by using the statistical parameters of PDF and CPDF for automatic identification and classification of the flow-regimes. Some unique flow-regimes (which have not yet been reported earlier in literature) have been obtained through the present experimental study. Good agreement has been found between the flow-regime clusters obtained through visual observation and that obtained through objective descriptions.

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