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Estimation of Wall Shear Stress in Two-Phase Flow Using Hot Film Anemometry

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Abstract. Measurement of velocity gradient near the wall and wall shear stress for air- water two phase flows through pipe is reported. The measurements are carried out using hot film anemometer. Mean and time varying fluctuation of the local wall shear stress and velocity of the horizontal air-water two-phase flow is measured using TSI 1210-20W hot film. Measured wall shear stress distributions are found to be strongly influenced by the condition of gas-liquid interface. Results reveal that an increase in water flow rate increases the wall shear stress while the variation of wall shear stress with air flow rates is negligible. The data collected is utilized to obtain time averaged value of shear stress for the fluctuations. The axial velocity distribution is measured by traversing the probe in radial direction.

Keywords: Two-phase flow; Hot Wire Anemometer; Shear Stress; Reynolds number

1. Introduction

Air-water two-phase flow involves complex shear stress mechanisms which are very difficult to correlate. Shear stress models generally rely on a number of basic assumptions and empirical closure equations. Taitel and Dukler [1] first presented a shear stress model based on momentum balance of the gas and liquid phases. Andritsos and Hanratty [2] reported that liquid-wall shear stress is better predicted via a characteristic stress τC (taken as the weighted average of liquid-wall and characteristic stress). According to the authors, the characteristic stress can be calculated from a dimensionless liquid height, which is a known function of the liquid Reynolds number. Early works for the measurement of shear stress was limited to two-phase flow through the rectangular channels (Davis [3], Fabre et al. [4]).

A variety of techniques have been used to measure wall shear stress. Direct measurements of average wall shear stress by measuring the restoring force are reported by Cravarolo et al. [5] and Kirillov et al. [6]. However, most researchers have used indirect methods based on the analogy between momentum transfer and mass transfer (e.g. Cognet et al. [7]) or heat transfer (e.g. Whalley and McQuillan [8]). These methods however cannot produce the fluctuations in wall shear stress. In order to obtain fluctuating component of shear stress, hot film probes are utilized. Kowalski [9] has presented measurements of the wall shear stress for circular pipe at various radial locations in the gas region, and has concluded that existing models for estimation of the gas wall shear stress seem to be adequate.

The shear stress relation is essential as closure to the analytical model. An experimental investigation to establish the wall shear for air-water two-phase flow through pipe is presented in this paper. The wall shear stress and the velocity gradient in the radial direction in both the phases is measured using hot film anemometer. Experimental values of wall shear stress are plotted as functions of gas and liquid superficial Reynolds numbers and are is then utilized in obtaining two-phase skin friction coefficient.

2. Experimental Methodology

The established experimental setup (Fig 1) is discussed in an earlier paper by the authors [10]. The experimental setup consists of air-circuit, water circuit, flow visualization section and measuring section. The measurement section consists of pressure and temperature measuring sections. Hot film anemometry is utilized in predicting wall shear stress and measuring the velocity profile in radial direction. An attachment is prepared having provision of traversing the probe. The attachment consists of SS pipe with flange

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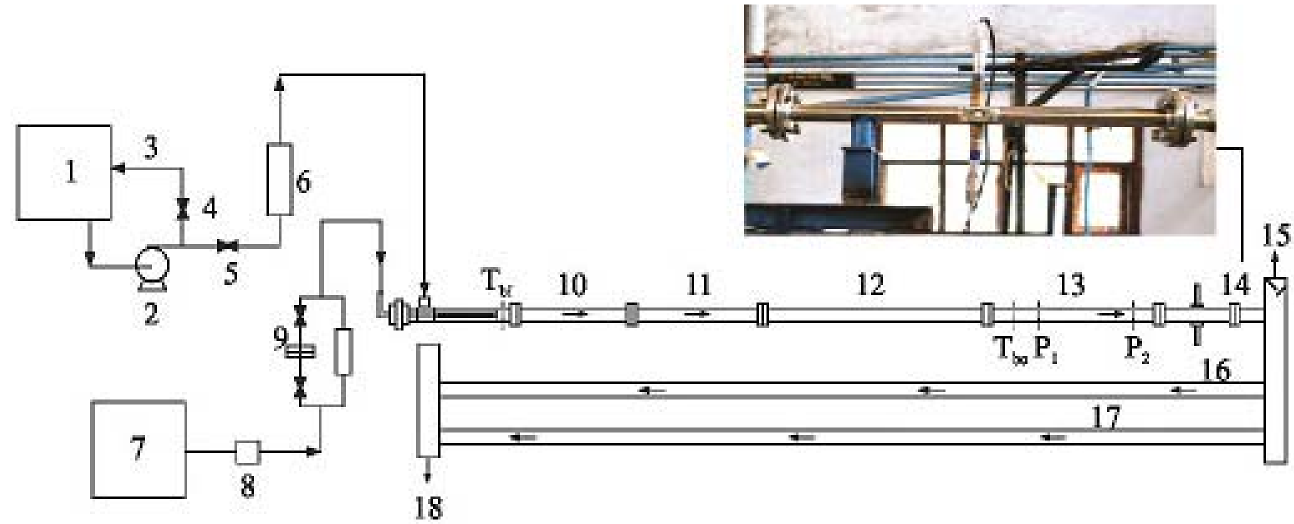
connections at both the ends. Two micrometers are provided, one on the upper side and other on lower side of the pipe through which probe passes. In addition there are glass windows on front and back side (Fig. 1). The Hot film anemometer used here is a Constant Temperature Anemometer (CTA) which works on the principle of fluid convection. Probe voltage is measured by CTA IFA300 manufactured by TSI.



1. Storage Tank	7. Screw compressor	13. Pressure measurement section
2. Centrifugal Pump	8. Pressure regulator	14. Hot film attachment
3. By-pass line	9. Orificemeter/Rotameter (air)	15. Air vent duct
4. Ball valve	10. Mixing/Calming zone	16 and 17. Return line 1 and 2
5. Gate valve	11. Visualization zone	18. Line to the storage tank
6. Rotameter (water)	12. Heat transfer section	P_1, P_2 Pressure transmitters

Fig. 1 Schematic of experimental setup along with Hot Film Probe

3. Calibration

The calibration program has three steps: (1) Inserting probe data, (2) Generation of auto calibration table and (3) Condition set up. The first step involves specification of probe data related to probe type, cable resistance, operating resistance, wire film, offset and gain. This is followed by the generation of an auto calibration table by selecting the minimum and maximum velocity and number of points. The values of velocity and corresponding value of dP in mm Hg is presented in the auto calibration table. The value of dP is inserted and bridge voltage E is acquired. Calibration curve obtained by this procedure is as shown in Fig 2. Curve fitting is done using polynomial of second order for velocity as shown in figure. Calibration for shear stress measurement is carried out by allowing single-phase (either water or air) in to the test section. Mass flow rate corresponds to the value of shear stress is fixed by controlling the ball valve. Similar to the velocity calibration, the corresponding mass flow rate is calculated and fixed by controlling the ball valve. The probe is maintained at constant temperature by a standard hot-film anemometry circuit. A laminar thermal boundary layer grows on the probe in the direction of flow and the instantaneous average heat transfer coefficient for the probe is proportional to the heat flux which is in turn proportional to the square of the voltage drop, E. In an ideal developing laminar boundary layer, the heat transfer coefficient is proportional to $\tau^{1/n}$. Shear stress calibration curve obtained for the air and water medium is shown in Fig 2 along with the curve fitted equations. In two-phase flow there is a wall liquid film which is sufficient for the wall shear stress probe operation. Therefore, as shown by Martin [12] and Whalley and McQuillan [8], the probe operation in single-phase and in two-phase flows is essentially the same. The instantaneous wall shear stress is determined from the instantaneous bridge output. Mean values of the shear stress can then be obtained by

$$\text{Mean}\,\tau_w = \frac{1}{N}\sum_{i=1}^{N}\tau_{w,i}$$

In order to eliminate uncertainty resulting from the hot film sensor drift, the consistency of single-phase flow anemometer output is frequently checked with the calibration data.

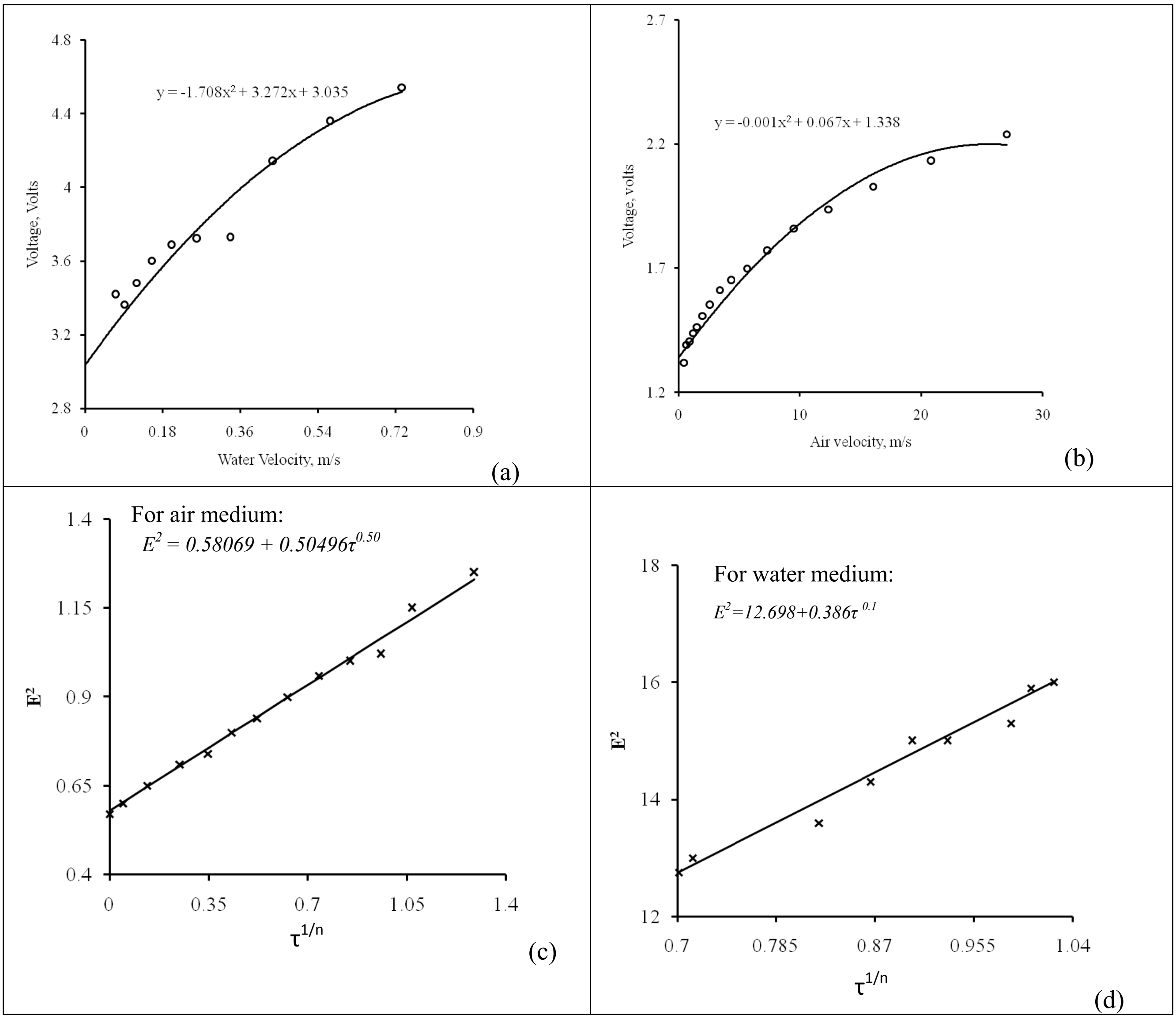
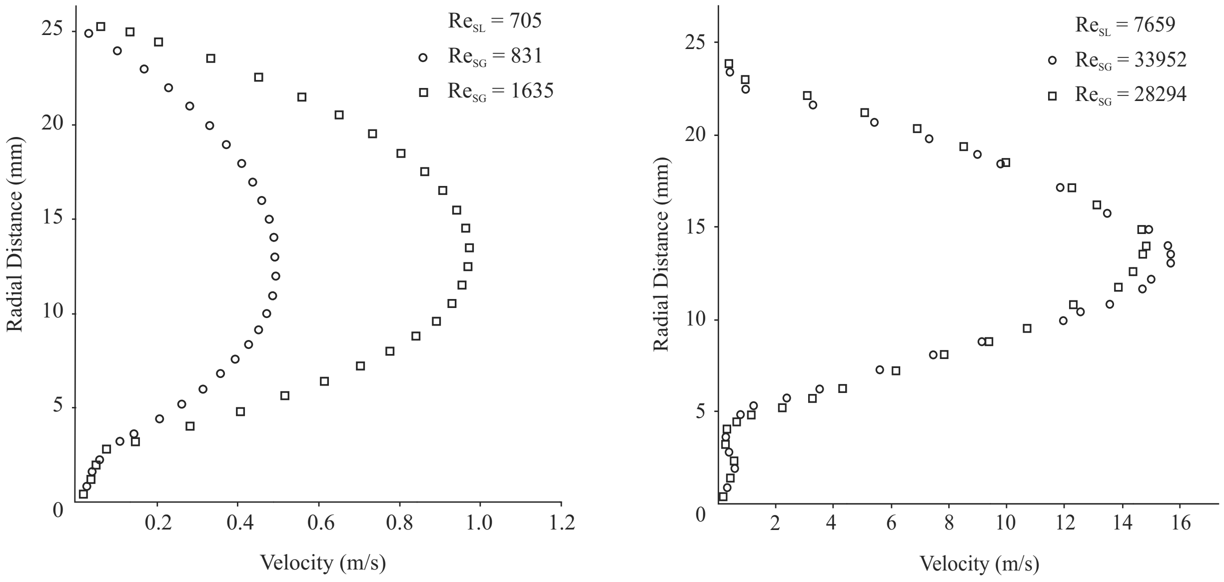


Fig. 2: Calibration curve for velocity measurement in (a) water medium (b) air medium and shear stress measurement in (c) air medium (d) water medium

4. Velocity Measurement

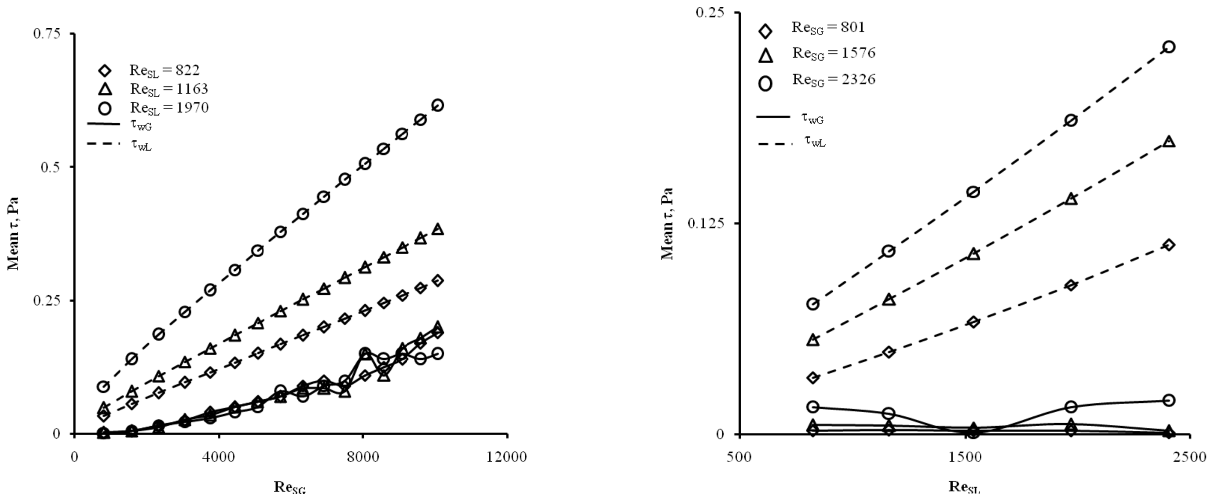
The micrometer facilitates the measurement of radial locations of the probe. Measurements are carried out at number of radial locations for different values of superficial liquid and gas Reynolds number (Re_{SL} and Re_{SG}). Variation of axial velocity profile shown here is limited to stratified and annular type of flow. Fig. 3(a) represents the velocity profile for stratified flow at constant Re_{SL} of 705 and two Re_{SG} of 831 and 1635. This plot is shown here to represent the effect of variation of Re_{SG} on velocity distribution keeping Re_{SL} constant. Fig. 3(a) depicts pronounced effect of Re_{SG} on velocity distribution in the gas phase. Velocity profile in gas phase is symmetric with a maximum which shifts towards upper wall surface with increase in gas superficial Reynolds number. This increases the normal component of the stress. Due to this waves are generated on gas-liquid interface. These waves go on increasing with the Re_{SG}. The liquid phase axial velocity profile shows negligible influence due to increasing Re_{SG} for the range of Reynolds numbers considered here. Fig. 3(b) represents the velocity profile for annular flow at Re_{SL} = 7659 and Re_{SG} = 28294 and 33952. Clear distinction between the annulus of liquid and gas core is observed.



(a) (b)

Fig 3: Axial velocity profile along radial direction for (a) Stratified flow (b) Annular flow

5. Prediction of Shear Stress



(a) (b)

Fig. 4: Variation of liquid-wall shear stress with (a) Re_{SG} and (b) Re_{SL}

For intermittent type of flow patterns, it is very difficult to predict which phase come in contact with inner surface of the pipe. Hence, investigation here is restricted to stratified, wavy and annular type of flow regime only. Range of Re_{SG} and Re_{SL} considered here are 801-11858 and 822-5080, respectively. Fig. 4 represents the variation of liquid-wall shear stress as function of Re_{SG} and Re_{SL}. Careful observation of figure reveals that there is an increase in mean value of liquid-wall shear stress with the increase Re_{SG} as well as Re_{SL}. It is also observed that the variation of gas–wall shear stress (τ_{wG}) is not significant as compared to liquid wall shear stress (τ_{wL}) as is depicted in Fig. 4(a). Moreover there is negligible effect of variation of liquid superficial Reynolds numbers on variation of gas wall shear stress (τ_{wG}). Same is clearly visible in Fig. 4(b).

Mean wall shear stresses obtained experimentally are plotted against two-phase friction factor f_{TP} in Fig. 5. The curve fitting of the experimental date results in the following expression for the two-phase friction factor f_{TP}:

$$f_{TP} = 0.046\,\mathrm{Re}_m^{-0.2}$$

where, f_{TP} is two-phase friction factor; Re_m is the mixture Reynolds number = $\rho_m v_m d/\mu_m$; ρ_m is the mixture density = $(1-\alpha)\rho_L + \alpha\,\rho_G$; μ_m is the mixture viscosity = $(1-\alpha)\mu_L + \alpha\,\mu_G$, v_m is the mixture velocity = $v_{SL} + v_{SG}$ and α is the volume fraction = $v_{SG}/\,v_{SL} + v_{SG}$.

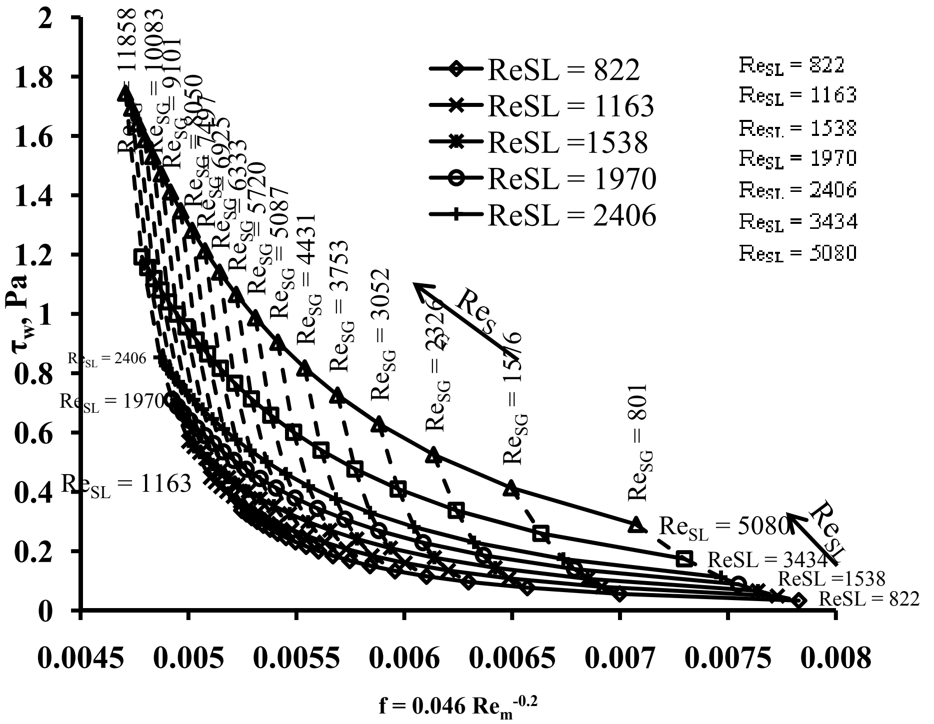


Fig 5: Variation of mean τ_w with f for different Re_{SG} and Re_{SL}

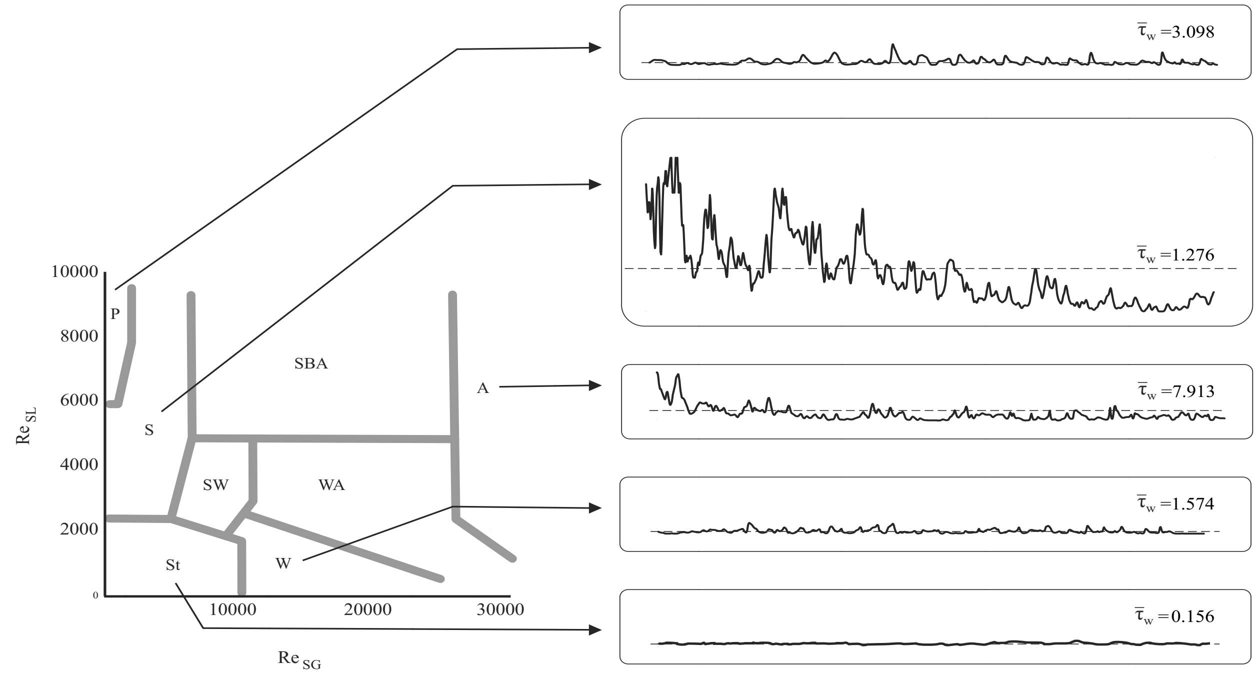


Fig 6: Time variation of shear stress signal

Time history of temporal fluctuations of the shear stress on the wall is captured for different combinations of gas and liquid superficial Reynolds numbers. These are illustrated in Figure 6. Representative shear stress signals are shown in the figure. These represent the overall behavior of wall shear stress in that particular flow regime. For the stratified flow regime fluctuations in shear stress are absent. These fluctuations are clearly observed in other type of flow regime. Pulsations at regular interval are observed in wavy, annular and plug flow patterns, while slug flow exhibits chaotic nature of irregular pulsation. Mean shear wall stress obtained from these fluctuations depicts that annular flow has higher drag compared to slug flow. It is also observed that the peak value of shear stress pulsation in slug flow regime is higher compared to the peak values in annular regime, although the mean value of shear stress in annular flow is large compared to the mean value of shear stress in slug or any other type of flow patterns for the considered range of Reynolds numbers.

6. Closure

Hot film anemometry is utilized to measure wall shear stress and axial velocity at discreet radial distances. Axial velocity distribution for the considered Reynolds numbers shows symmetric variation in gas phase. Maxima of gas phase axial velocity shifts toward the upper surface with the increase in gas superficial Reynolds number. This causes the formation of small waves on the gas-liquid surface. Transient fluctuations of wall shear stress observed for various flow patterns represent the behavior of different flow regime. Significant enhancement in mean liquid wall shear stress compared to gas wall shear stress is observed for stratified and wavy flow regime with the increase in gas and liquid superficial Reynolds number. This is due to the viscosity difference between the fluids. These time averaged wall shear stress of stratified, slug and wavy flow (limited Reynolds numbers) are utilized in obtain the variation of wall shear stress with two-phase friction factor for different gas and liquid superficial Reynolds numbers. For the annular flow, wall shear stress variations follow a linear behavior with gas superficial Reynolds number and a non-linear pattern with liquid superficial Reynolds number.

7. References

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