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Turbulence predicting criterion based on shear forces at the boundaries in a two-phase flow

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A B S T R A C T

The use of traditional *Re* number turbulence indicator can be extended for a variety of non-pipe flow channel geometries by the use of appropriately defined equivalent diameters. A modified equivalent diameter can be defined also for open channel flow, however, it fails when condensation is present at the open channel interface. This is shown by experimental measurements performed at the LEI (Lithuanian Energy Institute) two–phase test facility for condensing separated flows. It was observed that for such conditions the liquid region can become fully turbulent even when $\mathrm{Re}_f < 1370$. This is documented using axial temperature measurements, and illustrated in more detail by thermo-visual images, obtained with an IR camera. Experimental evidence from other stratified flow facilities is reviewed, which confirm the importance of shear at the vapour-liquid interface for the determination of liquid region turbulence. A turbulence indicator is proposed which takes into account potentially different shear stresses occurring at segments of the flow channel boundaries. It can be used to predict turbulence for separated flows, including flows for which phase change occurs. Compared to the *Re* number indicator it uses additional readily available information to estimate shear magnitude, it can therefore be advantageously applied for single phase flows.

1. Introduction

Horizontal two-phase flow occurs in nature and many industrial processes and the physics of both phases interaction have to be understood. Considerable effort made by various researchers to obtain experimental data on the instantaneous flow phenomena and to develop sophisticated models. However many important fluid dynamical aspects of condensing two-phase flow are still unclear or poorly understood.

The field is developing rapidly, additional test stands and the use of advanced instrumentation techniques has expanded the empirical data base and increased its precision and reliability. Improved measurement precision has made it possible to quantify some of the uncertainties, for example, thermo-vision and PIV (particle image velocimetry) techniques are used to observe the initiation and growth of turbulence in the liquid phase and to measure local turbulence intensity. Different authors presented detailed instantaneous velocity field measurements in stratified horizontal two-phase flows: for laminar, transitional, and turbulent liquid layers [1]; in both gas and liquid phases [2], and subsequently [3] focusing on turbulence structure of the gaseous phase; and for different liquid level and slight inclination [4]. Vestøl et al. [4] explained two-phase flow by analogy to Couette-Poiseuille flow and their measurement results match well. Liquid phase turbulence was large at the wall and at the interface, but low in the middle. Detected gas turbulence maximum at the interface was clarified by measuring secondary downward flow in the gas phase. Similar structures of two-phase wavy flow were observed in Ref. [5]. Additionally, secondary flows were measured not only in gas, but also in liquid phase. Secondary flows modify shear stress and turbulence production: it weakens in liquid near the wall and intensifies in gas near the interface. It is obvious that velocity profile distribution depends on the secondary flow, which is typical for fully undeveloped flows. More light was shed in Ref. [6], where the measurements show that interface waves skew the profile of gas velocity distribution. It was explained by secondary flow dependency on streamwise wave height distribution. In all [6] tests, the waves enhanced turbulent fluctuations in region close to the interface. Interfacial waves also affects the liquid side velocity profiles and turbulence structure. Fernandino et al. [7] demonstrated that small amplitude waves alter near-interface liquid region, analogous to increased shear rate on a flat interface. Large amplitude waves modified the flow structure throughout the whole liquid depth, enhancing turbulence intensity, especially close to the interface.

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The two-phase flow is complicated because of momentum transfer across the interface and feedback interactions. Experimenting with controlled liquid turbulence, Savelsberg et al. [8] found that surface deformations strongly correlates with both vortical and strain events in the liquid velocity field. Other tests of surface roughness link to subsurface turbulence, conducted by Dolcetti at al [9]. Proved that the free surface morphology could be employed for characterisation of underlying turbulence. The linkage model proposed by Nichols et al. [10] and method implemented by Johnson et al. [11]. A year later Valero et al. [12] proposed sophisticated theoretical framework for the prediction of free surface dynamics, related to the subsurface turbulence.

In stratified horizontal two-phase flow the free surface turns into interface between the two fluids of different viscosity and other physical properties flowing together with separate velocity fields and dynamically interacting with each other. Bae et al. [13] provides more insight in the complexity with their experimental investigation of interfacial wave frequency, height and slope dependency on different combinations of gas and liquid *Re*. Study of steady plane-parallel two-layer flow linear stability [15] showed that the critical perturbations can originate at the interface or in the bulk of one of the phases. Fabre [14] highlights that wave generation for low viscosity flows is controlled by the sheltering effect (the pressure in phase with the wave slope) and for high viscosity by the Kelvin-Helmhotz instability (the pressure is in phase with wave height) dominates. Recent theoretical study of the two-phase stratified flow linear stability [16] in many cases of horizontal flows found “sheltering force” having a considerable destabilizing effect.

Condensation plays exclusive role in destabilizing the stratified horizontal two-phase flow as it strongly depends on the liquid side turbulence. Positive feedback between momentum to interface and energy transfer leads to the so called “elliptic sensitivity” in a purely shear driven annular/stratified internal condensing flows. Such flow configuration is sensitive enough for easy switching between regimes of the condensing quasi-steady flow. Experimental evidence of this “elliptic sensitivity” to boundary conditions presented in Refs. [17] and [18] demonstrate large mass flow rate fluctuations triggered by small inlet pressure fluctuations.

Also, condensation may contribute to steam turbulence because of interface suction. Although there was considerable interest in using wall suction to increase boundary-layer stability, recent stability analyses suggest that porous walls are inherently destabilizing. Tilton et al. [19] found that small amounts of wall permeability destabilize the Tollmien–Schlichting wave and cause a substantial broadening of the unstable region. High resolution direct numerical simulation of turbulence in the asymptotic suction boundary layer [20] suggest complete turbulence collapse at *Re* below 270 only.

Moreover, heat transfer between phases because of condensation, particularly in horizontal vertically stratified two-phase flow configuration, promotes vertical density gradient build up in the liquid. Direct numerical simulation of temperature dependent variable viscosity near the heated wall [21,22] showed that it enhances heat transfer between the fluid and the heated wall, but reduces turbulent drag. Very recently Boutrouche et al. [23] reviewed database of relevant direct numerical and large eddy simulations and investigated the ability of different Reynolds-averaged Navier–Stokes models to reproduce the asymmetry of the flow and the tendency toward relaminarization close to the hot wall due to the variations of molecular viscosity and density. Such phenomena can facilitate subsurface turbulence, but restrict its spreading to water bulk, as condensation causes the very step viscosity gradient in the beginning of developing two-phase flow with horizontal interface.

Pipe flow is a well-studied case, nevertheless there are difficulties using the Reynolds number to determine the flow is ultimately laminar or persistently turbulent. Turbulence first appears as localized puffs and slugs. They propagate downstream and may decay or split. Barkley [24] explains the route to turbulence as process of transition from excitability to bistability and points out that turbulent puff could travel for 10^7 diameters before decaying completely. Turbulence is highly fluctuating state itself as many local effects and interactions are driving to the large-scale phenomena. Numerical and laboratory experiments in a circular pipe [25] showed that transient low *Re* turbulence becomes sustained (puff splitting rate exceeds decaying) at a distinct critical $Re = 2040 +- 10$. However, their data indicate that there is no critical point at which the turbulence suddenly spreads. Even at low *Re* the tendency to split was inherent to turbulence. Extensive following-up experimental and computational studies [26] for the example of Couette flow confirmed that the complex laminar–turbulent patterns are result of interactions between turbulent regions. Direct subcritical transition to turbulence was demonstrated in their recent experiment [27] of Couette–Poiseuille water flow with zero mean velocity and stable velocity profile for all *Re* (because of dead channel end).

Instead of generally accepted stochastic interpretation, Budanur at al [28]. applied the complementary deterministic approach. They unravelled details of puff formation by providing new dynamical understanding of bifurcation phenomenon. Structural stability of such a dynamical system demonstrated from bifurcation at $Re \approx 1430$ up to $Re = 1900$. Physical experiments of laminar–turbulent transition in stratified horizontal two-phase flow [29] showed that transition can begin at $Re = 1500$. One-phase flow tests with continuously excited turbulence at the channel entry [30] was achieved sustained turbulent flow from $Re > 900$. Summarising the different processes and transitions in parallel shear flows, the upgraded sequence of Reynolds numbers staged by Eckhardt [31]: “energy stability $Re = 81.5$; appearance of the first critical states near $Re = 773$; first indications of turbulence in experiments near $Re \approx 1600$; critical Reynolds number from balance between splitting and decay $Re \approx 2040$; weak spreading of slugs above $Re \approx 2250$; and finally transition to strong spreading near $Re = 2900$”. However, Eckhardt [31] admits that local *Re* variation has to be taken into account in the case of spatially developing flow.

The *Re* criterion as indicator of transition from laminar to fully developed turbulent flow, was derived on the basis of experimental measurements of single phase flow in a pipe. Its application has been extended to other channel flow geometries using definition of an “equivalent diameter”. In the evaluation of a D_{eq} for two phase flows a decision has to be made regarding the common interface between the fluids. One of the recommended choices is not to consider the interface when evaluating D_{eq} for more viscous phase, it is then included when evaluating D_{eq} for less viscous phase.

For flow channels which depart from the cylindrical pipe flow geometry definition of an appropriate D_{eq} introduces a measure of uncertainty. The cylindrical geometry has the unique characteristic that the entire boundary influences the conditions of internally flowing fluid uniformly. This is no longer true for other flow geometries and for stratified flows. For the cases when evaporation or condensation occurs in stratified flows there is no possibility to account for their potential effect on turbulence of either phase. In a fairly recent assessment of all available empirical correlations for co-current and counter-current condensing flows Park et al. [32] reached the conclusion that for condensing flows, - “there are no reliable correlations to accurately predict the co-current experimental data”.

All the advanced measurements show that for a range of stratified flow conditions “classical” *Re* number restricts prediction of the transition from laminar to turbulent flow. Experiments conducted at the LEI facility [33,34], investigations in the HOCO test loop in Korea [35], and in the test loop at Delft University in Netherlands [1] have shown that for condensing stratified two-phase flows, the liquid region can become fully turbulent when the liquid phase *Re* number is below 2000. Recent review of the theoretical issues and modelling perspectives of laminar-turbulent patterning in transitional flows [36] highlights that Kelvin-–Helmholtz instability is mostly responsible for liquid turbulence at low *Re* after a gas/liquid splitter plate because of an inflectional velocity