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Experimental investigations of the interface between steam and water two phase flows

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ABSTRACT

Hydrodynamic instabilities play an important role in the design of those systems operated at high temperature and pressure. The creation and propagation of Kelvin–Helmholtz (KH) instabilities has been experimentally investigated here for the first time in condensable fluids i.e. steam and water. Generally, in case of these condensable fluids the instabilities are so much short lived that it's very difficult to record them. Here the instabilities occurred in the close vicinity of the steam–water interface, were attributed mainly to the temperature fluctuations of micro scale or less. Supersonic steam was injected inside the subcooled water at inlet pressure varying from 1.5 bar to 3.0 bar by using a specially designed supersonic nozzle, whereas temperature of water inside the vessel was raised from 30 °C to 60 °C at an increment of 50 each. Kelvin–Helmholtz instabilities in the form of minor as well as amplified transient temperature fluctuations were recorded using a specially designed apparatus that uses LM35 sensors and data acquisition system. This system is capable to record temperatures at a rate of one millisecond and was also capable to record the temperatures anywhere inside the vessel. It was also found out that the instabilities created at the interface propagated towards the axis of the geometry as well as these instabilities were strongly affected by change in tank water temperature and inlet pressure.

1. Introduction

Injection of steam jet into subcooled water tank has been the subject of study for the last two decades because of its numerous applications in nuclear and process industry. When steam and water come into direct contact with each other, an interface occurs between the two phases. The phenomenon of steam water interaction becomes very complicated due to the existence of this steam water interface in such flows. The behavior of steam–water interface is difficult to be captured theoretically, experimentally and/or computationally because of its unstable nature. In addition to having unstable nature, occurrence of a transport of heat, mass and momentum across this interface makes the process more complicated.

The study of steam water interface is important because the unstable nature of the interface may result into the formation of hydrodynamic instabilities and the condensation of steam across the interface on macro scale may lead to condensation induced water hammer inside the piping system of a nuclear power plant. The hydrodynamic instability at steam water interface along with water hammering due to condensation may cause a severe impact on the safe operation of nuclear power plant, especially under accidental conditions. Therefore, a detailed study is required to fully understand the behavior of steam–water interface.

The hydrodynamic instabilities in Direct Contact Condensation (DCC) are generally short lived and damped by the surrounding water. As a result the pressure and temperature shocks transform into hydrodynamic fluctuations of micro scale. The interface, at which these instabilities emerge and propagate, is considered a zero thickness surface as discussed by Shah et al. [1]. The fluctuations that occur at the interface and its vicinity are so much higher in amplitude, short lived and complicated that these are almost impossible to be modeled, simulated and difficult to observe experimentally. Therefore, till the date, the theoretical, computational and or experimental efforts to investigate the hydrodynamic instabilities formation and propagation particularly within condensable fluids are scarce. However, the interfacial instabilities of

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non condensable fluids has been studied by a number of researchers prominent among these were Funada and Joseph [2], they theoretically investigated the stability of stratified gas–liquid flow using viscous potential flow. They found that the effect of viscosity on instabilities in fluids with viscosities less than 15 cp is important. Davies and Ting [3] captured the eddy behavior at interface with the help of photography by absorbing CO_2 and H_2 into turbulent jets of water. Woodmansee and Hanratty [4] reveals the mechanism of atomization in co-current flow of air and liquid. They regarded atomization as the removal of small wavelet at interface and highlighted the effect of air stream velocity on atomization. They stated that such instabilities are Kelvin–Helmholtz instabilities (instabilities created due to gradient in velocities of interacting fluids) and airstream pressure is the driving force for causing them. Jeffries et al. [5] measured the mean velocity profile and intensity distribution in vicinity of interface between two phases using hot film anemometry. Results show the total shear, eddy viscosity and turbulent energy distribution. Ishii and Zuber [6] presented the 3D map for the stable and unstable systems, in which they introduce phase change number and subcooling number, Theofanous et al. [7] discussed the role of surface tension and viscosity in stabilizing the turbulence and hence eddies produced at the interface qualitatively as according to them their quantitative role was still uncertain. Van Meulenbroek and Van de Wakker [8] discussed the phenomenon of turbulence and hence temperature fluctuations damping in the water. Podowski [9] regarded the velocity perturbations due to velocity variations rather than mixture density variations. Rizwan [10] studied numerically the Density Wave Oscillations (DWO's) in case of two phase flow systems to get an insight into the physics of DWO's. Main conclusions drawn from this study was that the traveling density waves did not contribute significantly in oscillations and oscillation period is 3–4 times to that of channel transient time, Munoz-Cobo et al. [11] studied boundary conditions during out of phase oscillations when oscillations occurred by the fluctuations in pressure drop and mass inlet to the parallel channel system. They obtained expression for the time dependent common pressure drop in parallel channels, Schlichting et al. [12] presented the analysis on interaction between pressure drop oscillations and density wave oscillations for phase change systems. Transient lumped parameter and compressible volume dynamics models were presented to investigate the interaction of these oscillations; the following researchers [13–15] studied the instabilities in channels on theoretical grounds and try to develop their own models which provided distribution of variables as well as boundaries of instabilities on a plane of subcooling and phase change numbers, Gale et al. [16] investigated the surface instabilities, believed to be Kelvin–Helmholtz instabilities in case of condensation induced water hammer which was further simulated by Strubelj and Tiselj [17]. According to their simulation study no water hammer was observed due to Kelvin–Helmholtz Instabilities, however, entrapment of bubble by water is clearly evident from their simulation, Ambrosini and Ferreri [18] performed a computational study to determine the stability of a boiling channel. They investigate the trends of the ratio of transient time to the period of oscillations in density wave oscillations with low and high subcooling. On the basis of their comparison between the previous work on the linear and the non-linear stability analysis of boiling channels based on a simplified flow model, with the predictions of a well known system code RELAP 5. They concluded that an unstable boiling channel seems to be a non-linear oscillator in which the mass of the fluid and the constant pressure drop constraint contribute in defining the fundamental frequency of oscillations.

The work related to Direct Contact Condensation (DCC) include contributions from Hughes and Duffey [19] that introduced a "surface renewal theory" for DCC in turbulent separated flow, which points to an important role of the turbulence in the liquid layer. Strubelj and Tiselj [20] experimentally investigated the direct contact condensation and condensation induced water hammer in a horizontal pipe at PMK-2 test facility of the Hungarian Atomic Energy Research Institute KFKI. Comparison of results with simulation studies reveals a disagreement which may largely be owing to the effect of wire mesh sensor due to its physical size that they used and water hammer on turbulence. Along with this inflow water turbulence characteristic and used turbulence model are also among main factors responsible for this disagreement, Henry and Bartosiewicz [21] investigates the capability of the CATHARE 3 system code to predict growth and propagation of interfacial waves of a gas–liquid horizontal stratified flow. They recorded amplified wavelengths in case of small diameters with low fluid velocity but at large diameters within actual reactors these will be similarly amplified. Guo et al. [22] discussed the behavior of two-phase flow instabilities in a twin channel system, these are observed against system pressure, inlet resistance coefficient and non-uniform heating conditions. Results included the instability boundary drawn against plane of subcooling and phase change number, Wu et al. [23–27] investigates the variation of axial temperature in case of sonic and supersonic steam injection into subcooled water; their results included the shapes of the plume and condensation heat transfer coefficient, axial and radial temperature distribution, but their distribution of temperature contained coarse data with only few points used to draw the temperature profiles. Gulawani et al. [28] conducted a CFD analysis of direct contact condensation. They drew temperature profiles along axial and radial direction as well as drew a correlation for the interfacial area measurement across steam plume. Chun [29] investigated the direct contact condensation phenomenon by which measurements of dynamic pressure with visual observations revealed six regimes of direct contact condensation, identified on a condensation regime map, the regime boundaries showed stable condensation, and interfacial oscillation condensation. The regime boundaries were quite clearly distinguishable except the boundaries of bubbling condensation oscillation and interfacial oscillation condensation. Song et al. [30] investigated the thermal mixing and thermo-hydraulically induced mechanical loads produced as a result of steam injection into a pool of water thus defining the physics behind it. There are numerous other researchers [31–36], whom put their contributions in studying the phenomenon of direct contact condensation.

The scope of this work is to develop an experimental setup of steam jet injection into subcooled water tank, to study the behavior of interface between the two phases. The interface behavior, being highly fluctuating requires an experimental setup with high spatial resolution as mentioned by Song et al. [30]. The experimental setup could have multifarious applications depending on the type of the sensors along with data acquisition system used for multiphase flow diagnostics, however here is used for observing the short lived Kelvin–Helmholtz Instabilities arise in the case of condensable fluids i.e. steam and water. These instabilities are observed by measuring the temperature fluctuations across interface. The system is capable to record temperature data at a rate of 1000 samples/s so this setup is a way forward to study the Kelvin–Helmholtz interfacial instabilities.

2. Experimental setup

Our experimental system is composed of a cylindrical Perspex vessel (height 610 mm, inner diameter 330 mm) as shown in Fig. 1. Three inlet flow ports exist at the base of the vessel water injection and one outward flow port is located at the side wall of the vessel. The unique feature of this setup is the temperature