Nucl Eng Technol 47 (2015) 267–283

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.journals.elsevier.com/nuclear-engineering-and-technology/

Original Article

QUANTITATIVE OBSERVATION OF CO-CURRENT STRATIFIED TWO-PHASE FLOW IN A HORIZONTAL RECTANGULAR CHANNEL

SEUNGTAE LEE [a,b], **DONG-JIN EUH** [a,b], **SEOK KIM** [b], and **CHUL-HWA SONG** [a,b,*]

[a] *Department of Advanced Nuclear System Engineering, Korea University of Science & Technology (KUST), Gajungro 217, Yuseong-Gu, Daejeon, 305-350, Republic of Korea*

[b] *Thermal Hydraulics Safety Research Division, Korea Atomic Energy Research Institute (KAERI), Daedeok-Daero 989-111, Yuseong-Gu, Daejeon, 305-353, Republic of Korea*

ARTICLE INFO

Article history:
Received 19 September 2014
Received in revised form
10 November 2014
Accepted 17 November 2014
Available online 22 January 2015

Keywords:
Direct-Contact Condensation
Flow Visualization
Horizontal Stratified Flow
Laser Induced Fluorescence
Particle Image Velocimetry
Ultrasonic

ABSTRACT

The main objective of this study is to investigate experimentally the two-phase flow characteristics in terms of the direct contact condensation of a steam–water stratified flow in a horizontal rectangular channel.

Experiments were performed for both air–water and steam–water flows with a co-current flow configuration. This work presents the local temperature and velocity distributions in a water layer as well as the interfacial characteristics of both condensing and noncondensing fluid flows.

The gas superficial velocity varied from 1.2 m/s to 2.0 m/s for air and from 1.2 m/s to 2.8 m/s for steam under a fixed inlet water superficial velocity of 0.025 m/s. Some advanced measurement methods have been applied to measure the local characteristics of the water layer thickness, temperature, and velocity fields in a horizontal stratified flow. The instantaneous velocity and temperature fields inside the water layer were measured using laser-induced fluorescence and particle image velocimetry, respectively. In addition, the water layer thickness was measured through an ultrasonic method.

1. Introduction

The direct-contact condensation (DCC) occurring in a steam–-water stratified flow is an important thermal–hydraulic phenomenon relevant to the safety of nuclear reactor systems. For a pressurized thermal shock with a partially water-filled cold leg, the mixing of hot and cold water and the DCC heat transfer in a horizontal flow zone can be frequently encountered in postulated accident situations. A condensation-induced water hammer in horizontal pipes, which initially occurs by a DCC of steam on the subcooled water in a horizontal stratified flow, is another well-known engineering safety issue. The modeling of

---

[*] *Corresponding author*. Thermal Hydraulic Safety Research Division, Korea Atomic Energy Research Institute (KAERI), Daedeok-Daero 989-111, Yuseong-Gu, Daejeon, 305-353, Republic of Korea

E-mail address: chsong@kaeri.re.kr (C.-H. Song).

http://dx.doi.org/10.1016/j.net.2014.11.007

DCC in a steam–water stratified flow is particularly important in the analysis of pressurized thermal shock and condensation-induced water hammer.

A number of experimental studies have been previously performed to investigate the DCC phenomena for a stratified two-phase flow in a horizontal flow channel. Empirical correlations of DCC heat transfer in the form of a power–law relationship of the parameters were derived from the experimental measurements.

Segev et al. [1] and Kim et al. [2] investigated an interfacial condensation heat transfer for a counter-current steam–water stratified flow in an inclined rectangular channel. Kim et al. [2] found that for the given flow conditions, the heat transfer coefficient increases as the water layer thickness decreases (or, equivalently, the inclination angle increases), and that the Froude number is a better correlating parameter than the gas Reynolds number. Lim et al. [3] investigated the condensation of steam on a subcooled water layer for a co-current flow in a horizontal rectangular channel. They found that the condensation heat transfer coefficient increased with the increase of steam flow rate and water flow rate. Chu et al. [4] and Lee et al. [5] investigated an interfacial heat transfer for counter-current steam–water stratified flow in a horizontal circular pipe for a smooth and wavy liquid flow, respectively. They investigated the parametric effects of the flow rates of steam and subcooled water and the degree of subcooling on the condensation heat transfer. In addition, they showed that the thermal resistance of the water layer is appreciably large in the thick water layer. Park et al. [6] investigated an interfacial heat transfer for both co- and counter-current steam–water stratified flows in a horizontal circular pipe. They investigate the effects of the flow direction and channel geometry on the condensation heat transfer.

Some other attempts have been made to derive the analytical correlation of the heat transfer coefficients in terms of the turbulent properties for its implementation in computational fluid dynamics simulations. Hughes and Duffey [7] developed a description of the mass, heat, and momentum transfer based on the so-called surface renewal concepts for DCC in turbulent separated shear flows, which points out an important role of the turbulence characteristics of the liquid layer. Coste et al. [8] introduced a condensation model using a turbulent Reynolds number and Prandtl number of the liquid phase based on the surface renewal theory. Banerjee et al. [9] introduced a surface divergence model using the divergence of the 2D velocity vector tangential to the interface due to its fluctuation motions. Lakehal et al. [10] modified a surface divergence model from Banerjee et al. [9] and applied it in their direct numerical simulations.

Experimental data have been used to validate the analytical model and computational fluid dynamics analysis. However, most of the previous experimental studies adopted point-wise thermocouples and pitot tubes for measuring the temperature and velocity profiles in the flow. Even though local measurements provide information about the interfacial heat transfer characteristics, their usefulness is rather limited compared to the field-wise measurement method. Experimental data for visualizing the flow motion and turbulence structure caused by a DCC in a stratified flow are still lacking despite a lot of experiments having been performed.

The main objective of this study is to experimentally investigate the flow characteristics of a co-current air–water and steam–water stratified flow in a horizontal rectangular channel by visualizing the liquid motion, which causes a mixing and stratification of hot and cold water by exchanging the mass, momentum, and energy at the gas–liquid interface. This work presents experimental measurements of the local interfacial characteristics, temperature, and velocity distributions of the water layer in a co-current stratified two-phase flow for both condensing steam–water and noncondensing air–water cases.

2. Materials and methods

2.1. Experimental apparatus

The test facility, called the HOCO (horizontal condensing two-phase flow test loop), was designed and constructed in such a way that the DCC of steam in a stratified flow and the behavior of the water layer along a horizontal channel can be easily measured in a steam–water or air–water flow with either a co-current or counter-current flow configuration. Fig. 1 shows a schematic of the HOCO test facility. The test loop consists of a test section; supply systems of air, steam, and water; a

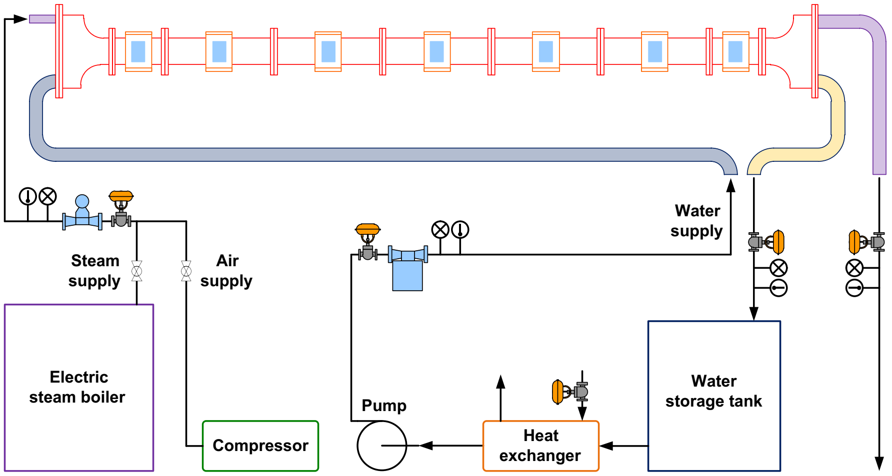

Fig. 1 – Schematic of the HOCO test loop. HOCO, horizontal condensing two-phase flow.