International Journal of Heat and Mass Transfer 92 (2016) 252–267

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Flow regimes and void fractions during condensation of hydrocarbons in horizontal smooth tubes

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ARTICLE INFO

Article history:
Received 4 July 2015
Accepted 5 August 2015
Available online 12 September 2015

Keywords:
Flow regimes
High-speed flow visualization
Void fraction
Condensation
Hydrocarbons

ABSTRACT

Phase change in hydrocarbons is of interest to the petroleum, refining, and chemical processing industry, as well as in HVAC and in organic Rankine power cycles. An experimental investigation of flow regimes and void fractions during condensation of propane flowing through smooth horizontal tubes with internal diameters of 7.0 mm and 15.0 mm was conducted. Measurements were made over mass fluxes ranging from 75 to 450 kg m^{-2} s^{-1}, operating pressures ranging from 952 to 1218 kPa, and nominal vapor qualities ranging from 0.05 to 0.95. Results from this experimental study are compared with predictions from correlations in the literature, and agreement and differences are interpreted and discussed. Appropriate flow regime transition criteria between the wavy and annular flow regimes are highlighted. Detailed analyses of the video frames are also used to develop a new multi-regime void fraction model that uses the drift flux model framework. The model provides improved agreement with the experimental results when compared to correlations from the literature, and predicts the trends with mass flux, tube diameter and pressure well.

1. Introduction

Over the past decade, renewed emphasis has been placed on increasing the energy efficiencies of HVAC&R, power generation, and industrial processes. To address this challenge, natural fluids such as propane have been proposed as alternatives to working fluids such as R-134a for use in HVAC&R systems and organic Rankine cycles. Accurate flow regime characterization and void fraction models are vital for the modeling of pressure drop and heat transfer in two-phase flow. Such understanding also benefits applications in the process industry, where propane is commonly used as a working fluid.

1.1. Flow regime studies

Several studies in the literature have documented flow regimes for adiabatic flows of air–water mixtures [1–5], condensing flows [6–16] of steam, refrigerants, and select low-pressure hydrocarbons such as *n*-pentane. There have also been some studies that deduce flow regime transitions from heat transfer data [17,18]. However, flow phenomena during condensation of high pressure hydrocarbons in large diameter tubes have not received adequate attention.

Flow regimes have long been understood to affect heat transfer and pressure drop in two-phase flows. As such, flow regime maps and transition criteria [1,4,7–11,16,18–21] have been developed to facilitate the development of regime-specific heat transfer and pressure drop models. Broadly, such flows can be divided into four primary categories: dispersed, intermittent, wavy, and annular as done by Coleman and Garimella [16,22,23]. Taitel and Dukler [24] derived theoretical dimensionless flow regime boundaries as functions of phase mass fluxes, fluid properties, and tube diameter. They divided the flows into five regimes: intermittent (slug and plug), stratified-smooth, stratified-wavy, dispersed bubble, and annular–annular dispersed. Breber et al. [9,20] proposed simple vertical and horizontal transition regions for the condensation of R-11, R-12, R-113, and *n*-pentane in 4.8–50.8 mm diameter tubes. *N*-pentane experiments were conducted with larger diameter tubes of 22 mm internal diameter. Using a database of experimental results for R-22, R-134a, R-236ea, R-125, R-32, and R-410A in 8 mm diameter horizontal tubes for saturation temperatures ranging from 30 to 60 °C and mass fluxes ranging from 65 to 750 kg m^{-2} s^{-1}, Cavallini et al. [17] and El Hajal et al. [18] proposed different flow regime maps. Sardesai et al. [10] used a local heat transfer coefficient ratio between the top and bottom of the tube for R-113, steam, propanol, methanol, and *n*-pentane data in a

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.08.017
0017-9310/

Table 1
Test matrix.

Property	Range
Mass flux, G	75–450 kg m^{-2} s^{-1}
Internal diameter, D	7.0, 15.0 mm
Saturation Temperature, T_{Sat}	25, 35 °C
Reduced pressure, P_{r}	0.22–0.29
Saturation pressure, P_{Sat}	952, 1218 kPa

24.4 mm tube to identify the transition between shear and gravity controlled flows.

Dobson et al. [25] conducted flow visualization and heat transfer experiments and found the Froude number-based annular to wavy-annular transition proposed by Soliman [26] to represent their data well; they proposed a constant transitional Froude number of 18 to define the boundary between annular and wavy-annular flows. They also found the annular-to-mist transition (WeSo > 30) of Soliman [27] to provide reasonable agreement with their experiments. Dobson and Chato [14] proposed that annular flow exists for all conditions above a mass flux of 500 kg m^{-2} s^{-1}. For mass fluxes below 500 kg m^{-2} s^{-1}, a transitional Froude number of 20 represented the transition to annular flow.

Cavallini et al. [21] developed a shear-to-gravity controlled flow transition criterion based on an experimental database of heat transfer coefficients for HFC and HCFC refrigerants, hydrocarbons (including propane), and other natural fluids in 3.1–17 mm diameter horizontal tubes for reduced pressures less than 0.8 over a mass flux range of 24–2,240 kg m^{-2} s^{-1}, and saturation temperatures ranging from −15 to 302 °C. Their transition criteria require different coefficients for refrigerant and hydrocarbon fluids.

1.2. Void fraction studies

Void fraction models can be classified into four categories, the homogeneous model, Martinelli parameter based models, slip-ratio based models, and mass flux based models. However, early development and validation of these modeling methods was limited to very few fluids, including liquid metals [28], steam–water [29–34] and air–liquid mixtures of air–benzene, air–kerosene, air–water, and air–oil [33,35].

Void fractions and film thicknesses have been measured using several different techniques, including quick-closing valves [36], electrical conductance [37], gamma radiation attenuation [38], and neutron radiography [39], index of refraction [40], and various forms of photography [41–43]. However, these studies focus primarily on steam and air–liquid mixtures with the more recent studies investigating two-phase refrigerants.

Koyama et al. [36] used quick closing valves to measure void fractions of R-134a condensing in 7.52 mm smooth tubes and 8.86 mm internal diameter microfinned tubes at pressures ranging from 800 to 1,200 kPa and mass fluxes ranging from 90 to 250 kg m^{-2} s^{-1}. They found that the Smith [33] and Baroczy [28] correlations represent their data well. Jassim et al. [44] found that using correlations from the literature [45,46] within their proposed flow regime map represents a database of void fraction measurements well, including data obtained using several methods for condensing, adiabatic, and evaporating flows.

The above methods for obtaining void fraction each present their own challenges, particularly for measuring void fractions of hydrocarbon flows at elevated pressures. The need for a radiation source for the attenuation based measurements, and the potential hazards of using electrical conductance methods for hydrocarbons limit this study to using high-speed video imaging. Various photo and video recording techniques have been used to obtain void fractions.

Hewitt et al. [42] used high speed video to obtain void fractions for air–water mixtures in a 32-mm internal diameter horizontal tube at near-ambient pressures and 20 °C. A photochromatic dye was used to differentiate the phases by illuminating the water. They observed a significant amount of air entrained in the liquid phase.

Triplett et al. [47] measured air–water void fractions in 1.1–1.45 mm internal diameter round tubes and 1.09 and 1.49 mm hydraulic diameter triangular tubes by analyzing photographs. Analyzing multiple images, they made several assumptions to create three-dimensional views required to calculate the void fraction from a two-dimensional photograph. Slug flows were assumed to be cylindrical with slug ends modeled as partial spheres. Churn flows were assumed to have a void fraction of 0.5 due to the difficulty in analyzing the photographs.

Winkler et al. [48,49] measured flow-regime-specific void fractions in round, square, and rectangular channels with hydraulic diameters ranging from 2 to 4.91 mm for R-134a at 1,400 kPa using analysis of video images. They recommend new drift-flux void fraction models for the wavy and intermittent regimes, and did

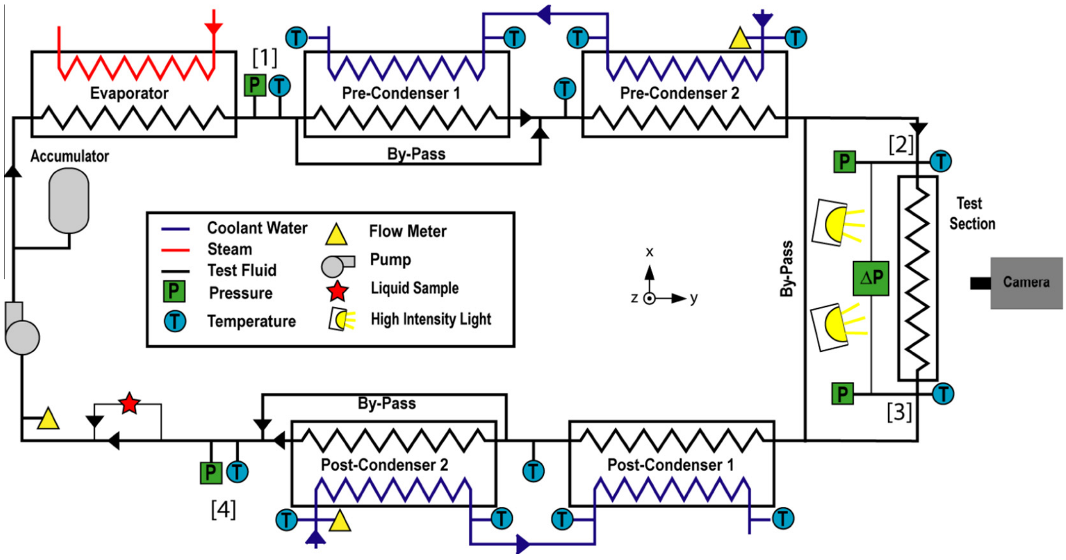

Fig. 1. Facility schematic.