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Pressure wave propagation during the condensation process of the R404A refrigerant in mini-condenser under periodic hydrodynamic disturbances

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ABSTRACT

Hydrodynamic disturbances often occur during the condensation process of the refrigerant in the mini-channels of a compact refrigeration condenser. These disturbances are periodic, accompanied by the propagation of the pressure wave. The present study is dedicated to modeling the propagation velocity of this wave in the two-phase medium during the condensation of the R404A refrigerant and the pressure wave attenuation. The pressure wave propagation model was presented and the model calculations were compared with the results of the experiments; a satisfactory compliance was obtained.

1. Introduction

In recent years, numerous studies have addressed the determination of the propagation velocity of the pressure acoustic wave in two-phase media, including those by Helmholtz [1], Kirchhoff [2] and Rayleigh [3], who provided the first solutions for the propagation of acoustic waves in a gas flowing through a channel with a circular cross section. The development and application of the theory of wave phenomena, which occur in one- and two-phase media, occurred during the second half of the previous century. Later, Carstensen and Foldy [4] conducted experiments concerning the determination of the propagation velocity of sound in the form of a one-dimensional flat wave. Karplus [5], Henry et al. [6] and Legius et al. [7] conducted research on the propagation of sound speed in the form of an acoustic pressure wave in a two-phase air–water flow. Ruggles et al. [8] first demonstrated the dispersive dependence of the propagation velocity of a pressure wave through experiments from the frequency of its generation. Investigations were also conducted in the bubble flow of an air and water mixture.

Studies focused on theoretically determining the moment at which pressure instabilities occur were conducted concurrently with experiments, including the study by Ishii [9]. Previous studies, such as the study by Boure et al. [10], also focused on the influence of the "*choking*" of the flow on the propagation velocity of acoustic pressure waves. Two methods concerning the calculation of the propagation velocity of the pressure wave have been presented in the literature. The first method was presented by Morse and Feshbacha [11] and Tremmella [12]. In this model, the occurrence is considered to be a mutual influence of the waves produced by the individual vapor bubbles. This influence was described with the use of the statistical theory of the physical model for the total dispersion of sound and the attenuation of the wave front.

In the second method, referred to as continuous models, the two-phase mixture is treated as a compressible medium with adequately averaged parameters. These models, which were established by Mercredy and Hamilton [13] and Hsiech and Plesset [14], are used to determine the propagation velocity of the acoustic pressure wave. In this method, the dispersive dependence can also be determined for the individual flow structures by taking the velocity slip into consideration. The method is based on solving the mass, momentum and energy conservation equations for each of the phases under consideration. Based on these assumptions, Mercredy et al. [13,15] proposed the so-called two-fluid model, which considers a non-equilibrium exchange of the mass, momentum and energy between phases in the two-phase flow of a vapor–liquid mixture. Using this model for the propagation velocity of the pressure wave in two-phase media (with various compositions), investigations were conducted by Karplus [5], Boure et al. [10], Feldman et al. [16], Ardron and Duffey [17], Cheng et al. [18], Chung [19], Xu and Chen [20,21], and Li et al. [22], among others.

As demonstrated by Ishii [23], Ramshaw and Trapp [24], Stewart [25], and Delhaye et al. [26], when solving this issue for wave phenomena occurring in single- or multi-phase flows, the same set of mass, momentum and energy conservation equations cannot be used. This results from the non-homogeneity of the

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Nomenclature

a_i	interfacial area per unit mixture volume, m^2/m^3
c	sound speed, m/s
c_L	sound speed of saturated liquid, m/s
c_G	sound speed of saturated vapor, m/s
c_{TPF}	the two-phase sound speed, m/s
D_H	internal diameter of minichannel, m
D_L	thermal diffusivity of liquid phase,
f	frequency, s^{-1}
f_{Lw}	wall shear stress coefficient (liquid phase)
f_{Gw}	wall shear stress coefficient (vapor phase)
G	mass flux, kg/m^2 s
i	imaginary number $\sqrt{-1}$
j	apparent velocity of the phase
k	wave number
p	pressure, Bar
T	temperature, K
u	velocity, m/s
u_r	slip velocity, m/s
q	heat flux density, W/m^2
x	thickness the condensate film

Greek letters

α	void fraction
δ	change the parameter
ρ	density, kg/m^3
ξ	disturbance parameter
λ	heat conductivity
η	wave attenuation coefficient, m^{-1}
σ	surface tension coefficient, N/m
τ	shear stress, time
Γ	condensation rate,
ω	angular frequency ($\omega = 2\pi f$)

Subscripts

DG	velocity different between the vapor phase and the drop
G	vapor
L	liquid
i	interfacial area
m	mixture
o	steady state
TPF	two-phase flow
Re	Reynolds number
T	transposed matrix

media and the two characteristic phenomena that accompany the propagation of the acoustic pressure wave in the phase change. The former factor was described by Feldman et al. [16], Ardron and Duffey [17], Mori et al. [27], Weisman et al. [28], and Kuczyński and Charun [29], among others. The authors of these papers demonstrated that as the void fraction increases, the propagation velocity of the acoustic pressure wave abruptly decreases. This velocity is minimized in the area of the two-phase change. This phenomenon is closely connected to and dependent on the flow structures that occur during the phase change because the pressure wave moves through these structures. Furthermore, the propagation velocity of the pressure wave increases with increases in the void fraction. Wallis [30] presented the types of flow structures that occur in multi-phase media, while Trusler [31] described the dependence of the sound speed on the regime type.

Acoustic pressure wave attenuation is another important phenomenon occurring in the generation and propagation of the acoustic pressure wave. The phenomenon of attenuation in multi-phase flows was described by Martin and Padmanabhan [32], Nigmatulin [33], Atkinson and Kytömaa [34], and Chung et al. [35], among others. In multi-phase media, pressure wave attenuation is the result of interfacial tension and thermal interactions, including viscous tension, the interfacial drag force, the inertial effect connected to the so-called "virtual mass", Basset's coefficient (the influence of the by-wall layer on the surface of a drop or solid molecule), the interfacial heat exchange, the compressibility of the vapor and liquid phases, the gradient of the concentration effect of the particles of drops, bubbles or solid particles on the boundary of the interfacial area, the phase change, the deformation or fragmentation of bubbles or drops and the interfacial reflection. The acoustic pressure wave attenuation is dependent on the circular frequency ω in the same manner as the propagation velocity of the wave. For example, for dispersive flow, Cheng et al. [18] graphically presented the dependence of the pressure wave attenuation coefficient η on the circular frequency ω. Nigmatulin [33] and Chung et al. [19] described the influence of thermal dispersion on the generation of the pressure wave attenuation in a bubble flow with a low circular frequency ω.

Previous studies concerning the determination of the propagation velocity of the pressure wave and its attenuation using a transient two-fluid model all consider vapor–water, water–air, or water–oil systems. In the studies by Ardron and Duffey [17], Cheng et al. [18], and Chung et al. [35], the authors obtained a satisfactory conformity of the proposed model results with the results of the experiments.

This study attempts to determine the propagation of the pressure wave based on the transient two-fluid model proposed by Xu and Chen [20,21], among others. This model allows the sound speed in a two-phase mixture to be determined under a wide range of pressures (1–25 MPa) and under the entire range of void fractions α. The calculations were performed for an annular and dispersive regime. In the proposal put forward by the authors, the computational code that they developed in the MATLAB2008 program was used. In accordance with the direction of the flow, the average values of the parameters, including the local temperature, the velocities of the liquid and gas and the void fraction, were accepted. The closing equations, which define the condensation phase change provided by Ardron and Duffey [17], and the dispersive equation were taken into account. The correlations allowing the interfacial area and drag forces between the phases that are adequate for a given flow structure to be determined were used. The theoretical calculations and experiments were performed using the R404A refrigerant, which is a proposed pro-ecological substitute for the withdrawn R22 Freon. The R404A refrigerant is a near-azeotropic mixture consisting of the R125, R143a, and R134a ingredients with mass shares of 44%, 52%, and 4%, respectively. The experiments concerning the condensation of this refrigerant in pipe mini-channels conducted by Kuczyński and Charun [29] demonstrated that the annular and dispersive structure was the most frequently occurring structure during condensation in the flow of this mixture. The calculation results were compared with those of the experiments concerning the propagation of pressure instabilities periodically generated during the condensation of the R404A refrigerant in mini-condenser (multiport) pipe