International Journal of Heat and Mass Transfer 128 (2019) 728–738

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental research on condensation of R134a and R404A refrigerants in mini-channels during impulsive instabilities. Part I

Waldemar Kuczynski

Technical University of Koszalin, Faculty of Mechanical Engineering, Department of Energy, ul. Racławicka 15-17, 75-620 Koszalin, Poland

ARTICLE INFO

Article history:
Received 15 July 2018
Received in revised form 9 September 2018
Accepted 10 September 2018

Keywords:
Condensation
Mini-channels
Impulsive instabilities

ABSTRACT

The following paper presents the results of experimental research on the condensation of R134a and R404A refrigerants in horizontal tubular mini-channels during impulsive hydrodynamic instabilities. Due to the complexity of the problem, it will be presented in two parts. The first part covers the results of experimental research on the influence of impulsive instabilities during the development of condensation of R134a and R404A refrigerants in mini-channels. The second part will cover the decay of condensation for similar conditions. The paper also provides a definition and conditions of the initiation and propagation of impulsive instabilities. Special attention was paid to the possible occurrence of characteristic instabilities during condensation in mini-channels, so-called *capillary blocking*.

The experimental investigation was based on the condensation of R134a and R404A refrigerants in horizontal tubular mini-channels with internal diameters of $D = 0.64$; 0.90; 1.40; 1.44; 1.92; 2.30 and 3.30 mm. Propagation of impulsive instabilities was a result of a sudden change in the refrigerant flow-rate inside mini-channels.

1. Introduction

Previous research by Bohdal [1–5], Teng et al. [6], Zhang et al. [7], Abdelghani-Idrissi et al. [8], Sikora [9] and Laskowski [10] shows that instabilities of boiling and condensation phase-change occurring in both mini-channels and conventional channels are of the same type. Their sources are hydrostatic and hydrodynamic forces. In mini-channels however, the influence of these instabilities on the phase-change process may have different results compared with conventional channels.

According to Teng et al. [6], instabilities during a condensation phase-change for both conventional and mini-channels are strictly connected with so-called capillary force. This phenomenon is a result of the interaction between the vapor phase and the internal surface of condensate film. A vapor flowing in the center of a channel has a different velocity than that of a liquid which causes hydrodynamic forces at the interface between these two. This results in an increase in surface tension at the interface phase and the formation of an instability in the form of a "waving" condensate film (Fig. 1).

In conventional channels, the influence of capillary forces is insignificant while instabilities in the form of the waving liquid phase layer has already been described by Zhang et al. [7] as so-called Kelvin-Helmholtz instabilities. In the case of channels with a small diameter (mini-channels), however, capillary forces have a significant impact on the phase-change process. To describe this phenomenon, the Rayleigh instability model is used [11].

According to Teng et al. [6], Chen et al. [12], Gauglitz et al. [13] and Ishii [14–16], the surface of a condensate layer is always unstable. It manifests itself as liquid layer surface waves. As a result of this waving, the thickness of the condensate film can reach up to a half of a channel's hydraulic diameter (r_o on Fig. 1). As a consequence, so-called liquid bridges will appear, that in conventional channels would be treated as a subcooled liquid zone.

The process of forming of liquid bridges in mini-channels is a source of instabilities described by Teng et al. [6] and Cao et al. [17] as capillary-collar-flow, capillary-bubble-flow (Fig. 2) and capillary blocking (Fig. 3). These phenomena are strictly connected with a vapor velocity in the center of a channel.

According to Henry et al. [18], Levy et al. [19], Wallis [20] and Wang et al. [21], a capillary-collar-flow occurs when a condensate layer is thin and a vapor flowing at a high velocity in the center of a channel induces a waving of the liquid phase surface. The periodic flow of the vapor phase makes the wavelength of disturbance on the condensate surface constant.

The growth of the liquid phase layer, resulting from an increase in the degree of condensation, causes a decrease in vapor phase velocity and leads to the sudden creation of liquid bridges in

E-mail address: waldemar.kuczynski@tu.koszalin.pl

https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.045
0017-9310/© 2018 Elsevier Ltd. All rights reserved.

Nomenclature

G	mass flux, kg/m^2 s
p	pressure, MPa
T	temperature, °C
t	time, s
v_p	velocity of *pressure wave propagation*, m/s
v_T	velocity of *condensation front*, m/s

Subscripts

c	closed
o	open
s	saturation
wall	wall of the canal

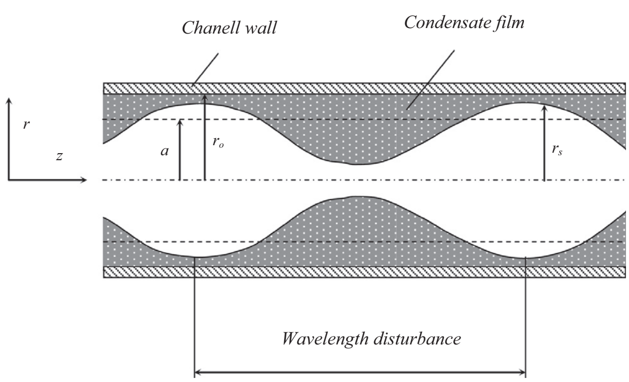

Fig. 1. Graphic interpretation of condensate film waving [6].

mini-channels. This is a direct result of the connection of a condensate film at the position where waving reaches its maximum amplitude (equal to half of a mini-channel hydraulic diameter). Liquid bridges split a flowing vapor phase into so-called gas pockets (bubbles). According to Wang et al. [21], this leads to capillary-bubble-flow. In conventional channels, the growth of a liquid bridge occurs in both co-current and counter-current directions. In a counter-current zone, the condensate film decays. In a co-current zone, vapor bubbles between liquid bridges are rapidly condensed.

If the driving force of the condensate flow is not sufficiently large to overcome the flow resistance, then the flow is blocked. This phenomenon, described by Tang et al. [6] and Mercredy et al. [22,23], is known as capillary blocking and occurs in mini-channels of any shape. This results from the significantly smaller flow velocities of condensate films in mini-channels than in conventional channels.

Unlike for conventional channels, which have been described by Martin et al. [24] and Starov et al. [25], vapor velocity in mini-channels is significantly smaller. Consequently, the decay of a condensate film due to hydrodynamic forces in the counter-current zone does not occur. Therefore, the occurrence of liquid bridges in mini-channels automatically leads to capillary blocking and the creation of a so-called "dead-zone" at the end of the condenser, especially in the case of multiport condensers. This is caused by the sudden condensation of vapor bubbles in a co-current direction that creates a so-called liquid plug. The occurrence of capillary blocking during condensation temporarily stops the flow. This phenomenon significantly affects the thermal performance of the condensation process in mini-channels as it reduces the effective length of a heat exchange zone. The length of the phase-change zone is also reduced. This phenomenon can occur only in channels with a diameter smaller than 5 mm and is strictly connected with the velocity of the vapor phase.

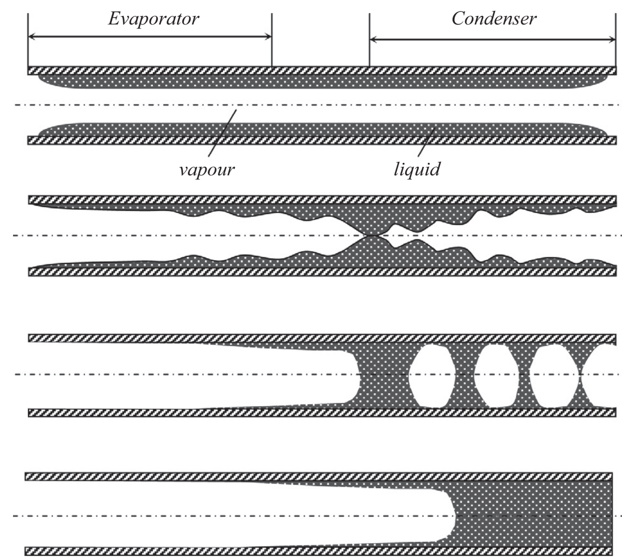

Fig. 3. Graphic interpretation of capillary blocking, Tang et al. [6].

2. Condensation of refrigerant in pipe-shaped tubular mini-channels during impulsive instabilities

Bohdal et al. [1], Boure et al. [26,27] and Breber et al. [28] have presented research results on the influence of impulsive instabilities on the condensation of R404A refrigerant in conventional channels. These instabilities were generated by the opening and closing a cut-off valve situated at an inlet to the condenser's coil.

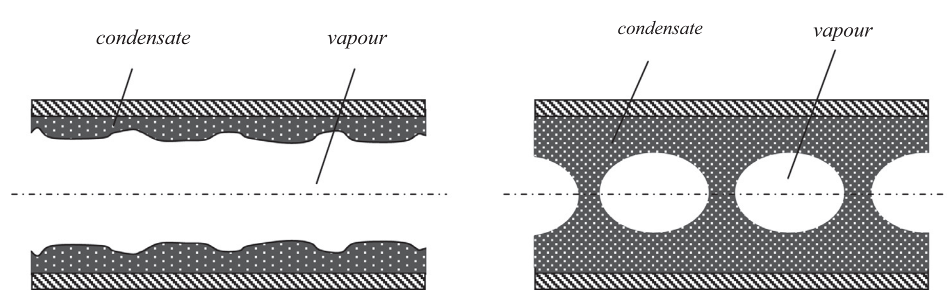

Fig. 2. Graphic interpretation of: (a) *capillary-collar-flow* and (b) *capillary-bubble-flow*, Tang et al. [6].