International Journal of Heat and Mass Transfer 55 (2012) 1083–1094

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Influence of hydrodynamic instability on the heat transfer coefficient during condensation of R134a and R404A refrigerants in pipe mini-channels

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ARTICLE INFO

Article history:
Received 16 June 2011
Accepted 30 September 2011
Available online 14 November 2011

Keywords:
Mini-channels
Condensation
Hydrodynamic instability

ABSTRACT

This paper presents the results of an investigation of the influence of hydrodynamic instabilities on heat transfer intensity during the condensation of R134a and R404A refrigerants in pipe mini-channels. The heat transfer coefficient h is a measure of the effectiveness of the condensation process. It is particularly important to determine the value of the coefficient in the two-phase condensation area in a compact condenser. In other condenser areas (i.e., precooling of superheated vapor and subcooling of condensate), the heat efficiency is substantially smaller. Hydrodynamic instabilities of a periodic nature have an influence on size changes in these areas. A decrease in the heat transfer coefficient h in the two-phase area results in decreased intensity of the heat removal process in the whole condenser.

The experimental investigations were based on the condensation of R134a and R404A refrigerants in horizontal pipe mini-channels with internal diameters of $d = 0.64$; 0.90; 1.40; 1.44; 1.92; 2.30 and 3.30 mm. Disturbances of the condensation process were induced with a periodic stop and a repetition of the flow of the refrigerant.

In the range of frequencies, $f = 0.25–5$ Hz, of the periodically generated disturbances, an unfavorable influence on the intensity of the heat transfer during the condensation process in pipe mini-channels was identified. The reduction in the intensity of the heat transfer during the condensation process, which was induced with hydrodynamic instabilities, was presented in the form of the dependence of the heat transfer coefficient h on the vapor quality x and the frequencies f of the disturbances.

The influence of the refrigerant, the diameter of the mini-channels and the frequency f on the damping phenomenon of the periodical disturbances in the pipe mini-channels was identified.

1. Introduction

Highly efficient heat exchangers, which are used in refrigeration engineering, should be characterized by a compact structure, high energy efficiency and low environmental impact. Special challenges are related to compact heat exchangers. These challenges are associated with the transfer of large heat fluxes. For this reason, channels with small diameters (i.e., mini- and micro-channels) are used in the construction of compact heat exchangers. If there are phase changes in the flow of refrigerants in these channels, it is possible to meet the above-mentioned criteria for an efficient, yet compact, heat exchanger.

The present study covers the condensation process of environmentally friendly substitutes for the R12 and R22 freons in pipe mini-channels. There are many substitutes for freons, which are no longer used by the refrigeration industry; R134a and R404A refrigerants are most frequently used. When designing compact refrigerating condensers that are built using pipe mini-channels with internal diameter $d < 6$ mm, the same computational procedures are usually used as for conventional channels, as confirmed by Kandlikar in [1,38]. The scope of information available in the field of the energy transfer and momentum in mini-channels is limited, especially in regards to the condensation area in the flow. Regardless of the lack of information, heat and flow calculations concerning compact condensers are common, and several specific structural solutions have been proposed.

In design calculations, the heat exchanger (e.g., condenser) is usually assumed to work in a refrigerating system under stabilized conditions. Under this assumption, the heat efficiency of the condenser is determined by calculating the heat transfer coefficient h during the condensation of the refrigerant.

In the case of a compact condenser, which operates in a compressor vapor refrigerating unit, the characteristic heat transfer areas can also be determined during the design stage. These areas are presented as an example in Fig. 1.

A similar temperature distribution of the refrigerant in a condenser is obtained regardless of the method of cooling (i.e., with water or with air). In the case of cooling with water, heat removal

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0017-9310/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2011.10.002

Nomenclature

d	internal diameter of the mini-channel, mm
f	frequency, Hz
L	mini-channel length, m
m	mass flow rate, kg/h
p	pressure, MPa
T	temperature, °C
G	mass flux density, kg/(m^2 s)
Greek letters	
λ	thermal conductivity, W/m K
ρ	density, kg/m^3
τ	time, s
$\Delta\tau$	time interval, s
Subscripts	
c	closing of cut-off valve
g	gas
$in.$	inlet cross-section, moment measurement begins
l	liquid
o	opening of cut-off valve
$out.$	outlet cross-section
s	condensation (liquefaction)

is more effective. Heat removal intensity in the two-phase condensation area determines the energy efficiency of a condenser. The values of the heat transfer coefficient h in this area can be several times higher than in the remaining mono-phase areas [2].

In the real operating conditions of a refrigerating condenser, there are usually transient states. There are several unfavorable influences on the condensation process of the refrigerant in a pipe mini-channel; these influences may be of an internal or external nature. Disturbances may occur inside the installation, or they may be the result of external influences. These disturbances cause instabilities in the realization of the two-phase condensation transformation and always result in a reduced heat transfer efficiency. The disturbances may be of a static or dynamic nature.

1.1. Static flow instability

The flow is statically instable when the source of the disturbance is inherently connected with a change of the system state. Roache [32] discussed this type of instability. The beginning of a static instability process can be predicted based on a change of the stationary state; therefore, the system is deterministic. Most frequently, this leads to another new stationary state or to a periodic oscillation of the parameters around this state (i.e., Ledinegg instability, which is an example of a static instability). Papers concerning this issue have been published by Kakač and Bon [3] and Zhang et al. [4]. The instability can be manifested in the form of a pressure drop as a response of the system to an increase in flow resistance connected with the two-phase flow.

There are certain instabilities that are characteristic only of mini-channels. For example, as Kennedy et al. [5] reports, when the hydraulic diameter of a mini-channel meets the criterion of $D < 0.3\sqrt{\sigma/(\rho_f - \rho_g)}$, instabilities of a static nature constitute the influence of surface tension (σ is surface tension, while ρ_f and ρ_g are the densities of the liquid and gaseous phases, respectively).

1.2. Dynamic flow instability

When the main factors affecting the disturbances to the system are heat or hydrodynamic influences, which cause evident inertial effects, the flow instabilities are dynamic. Dynamic instabilities

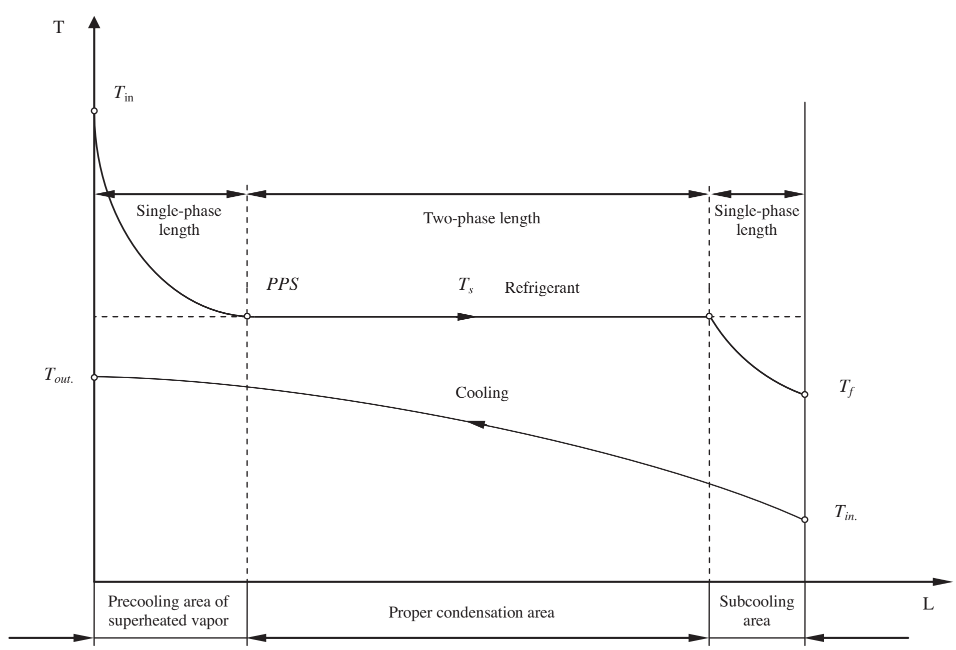

Fig. 1. A diagram of the distribution of the temperature of the refrigerant and the cooling medium during condensation inside a horizontal condenser pipe. The following abbreviations are used: T_p – superheated vapor temperature, T_s – temperature of condensation (saturation), T_f – final temperature of the process, $T_{in.}$, $T_{out.}$ – temperature of the cooling medium, at the beginning and end of the process, respectively, and *PPS* – starting point of condensation [2].