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Review

Intensive literature review of condensation inside smooth and enhanced tubes

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ABSTRACT

This paper presents a detailed review of research work on in-tube condensation in the literature due to its significance in refrigeration, air conditioning and heat pump applications. The heat transfer performance of heat exchangers can be improved by heat transfer enhancement techniques, such as active and passive techniques. Passive techniques requiring fluid additives or special surface geometries are mentioned in depth, by comparison with active techniques requiring external forces, e.g. electrical field, acoustic or surface vibration, etc., in the paper due to their common usage in condensation applications. In addition, the importance of usage of hydrocarbons instead of fluorocarbons is emphasised. This paper can not only be used as the starting point for the researcher interested in in-tube condensation process, but it also includes new investigations on condensation inside tubes.

Contents

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Nomenclature

A	area, m^2
B	fin root distance, m
d	inner diameter, or average inner diameter of tube, m
EHD	Electrohydrodynamic
G	mass flux, kg m^{-2} s^{-1}
g	gravitational acceleration, m s^{-2}
h	heat transfer coefficient, W m^{-2} K^{-1}
L	length of test tube, m
l	fin height, m
n	number of fins
R	radius, m
P	pressure, N m^{-2}
p	fin pitch, m
Re	Reynolds number
S	slip ratio
t	fin tip thickness, m
u	axial velocity, m s^{-1}
v	radial velocity, m s^{-1}
w	tube wall thickness, m
We	Weber number
x	average vapor quality
X	Lockhart Martinelli parameter
y	wall coordinate, m
z	axial coordinate, m
ΔP	pressure drop, Pa

Greek symbols

γ	apex angle, °
α	void fraction
τ_i	interfacial shear stress, N m^{-2}
δ	film thickness, m
β	helix angle, °
σ	surface tension, N m^{-1}
ρ	density, kg m^{-3}
μ	dynamic viscosity, Pa s
η	kinematic viscosity, m^2 s^{-1}
Θ	angle of the condensate film layer, °

Subscripts

f	frictional term
g	gas/vapor
l	liquid
mf	micro-fin
o	outer
s	smooth

1. Introduction

Heat exchangers are devices that are commonly used to transfer heat between two or more fluids at different temperatures. They are used in a wide variety of applications, e.g. refrigeration and air conditioning systems, power engineering and other thermal processing plants.

One of the major contributors to the depletion of the ozone layer is hydro chlorofluorocarbon refrigerants used in the refrigeration and air conditioning industry. More compact equipment with higher system operating efficiency for air conditioning equipment has been investigated following the changes in efficiency standards. Refrigerant mixtures with enhanced surfaces have been developed as an alternative solution to replace hydro chlorofluorocarbon refrigerants. Accurate methods for the determination of the thermal and fluid-dynamic behaviour of new refrigerants need to be researched in order to improve the efficiency of heat exchangers. To the design and develop of new equipment, the usage of a numerical simulation can be an alternative technique besides experimental investigation. Because of the multidimensionality of the two-phase flow, analytical and numerical methods present rather limited solutions, while on the other hand, two-phase flow through tubes can be treated assuming a one-dimensional flow. One-dimensional analysis involves empirical knowledge of the shear stress, heat flux, and two-phase flow structure. Determination of the heat transfer coefficient is a significant value to obtain for accurate solutions.

In this paper, studies on in-tube condensation using smooth and enhanced tubes are intensively reviewed since two-phase flow in tubes is the most challenging phenomenon in the heat exchanger systems. All effective possible research subjects of in-tube condensation were classified generally according to the tube orientation (horizontal, vertical, and inclined tubes) and tube geometry (smooth and enhanced tubes). Detailed information on the in-tube condensation studies of heat transfer, pressure drop, flow pattern, void fraction, and refrigerants in the literature were given. This paper mentions not only the new enhancement techniques of heat transfer, but also includes some information on the new refrigerants. Finally, it is expected to be the pioneer source as an intensive literature review for in-tube condensation processes.

2. Condensation heat transfer inside tubes

Heat exchangers using in-tube condensation have great significance in the refrigeration, automotive and process industries. Effective heat exchangers have been rapidly developed due to the demand for more compact systems, higher energy efficiency, lower material costs and other economic incentives.

Enhanced surfaces, displaced enhancement devices, swirl-flow devices and surface tension devices improve the heat transfer coefficients in these heat exchangers.

2.1. Tube orientation

2.1.1. Horizontal tubes

Condensation inside horizontal tubes is important in the chemical process and power industries. Shell side condensation is rarely preferred to tube side condensation when the coolant is air or a process gas, or when the condensing refrigerant is at high pressure, dirty or corrosive. For tube side condensers, the horizontal orientation is most commonly applied.

Dobson and Chato [1] investigated condensation of zeotropic refrigerants over the wide range of mass flux in horizontal tubes. They stated that heat transfer coefficient increases with increasing the mass flux and quality in annular flow due to increased shear stress and thinner liquid film than in other flow regimes. They used a two-phase multiplier approach for annular flow. Sweeney and Chato [2] extended their model for R407C, using mass flux based modification.

Cavallini et al. [3] presented a theoretical analysis of the condensation process and a critical review of a number of correlations for predicting the heat transfer coefficients and pressure drops for refrigerants condensing inside various commercially manufactured tubes with enhanced surfaces. Recently, Cavallini et al. [4] reviewed the most recent work in open literature on the condensation inside and outside smooth and enhanced tubes.