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Condensation of R-134a on horizontal integral-fin titanium tubes

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ABSTRACT

Experimental research was conducted to evaluate the condensation of R-134a on horizontal smooth and integral-fin (32 fpi) titanium tubes of 19.05 mm outer diameter. Experiments were carried out at saturation temperatures of 30, 40 and 50 °C and wall subcoolings from 0.5 to 9 °C. The results show that the condensation heat transfer coefficients (HTCs) on the smooth tubes are well predicted by the Nusselt theory with an average error of +2.38% and within a deviation between +0.13% and +5.42%. The enhancement factors provided by the integral-fin tubes on the overall condensation HTCs range between 3.09–3.94, 3.27–4 and 3.54–4.1 for the condensation temperatures of 30, 40 and 50 °C, respectively. The enhancement factors increase by increasing the wall subcooling and with the rise of the condensing temperature. The condensate flooded fraction of the integral-fin tubes perimeter varies from 25% to 20% at saturation temperatures of 30 °C and 50 °C, respectively. The correlation reported by Kang et al. (2007) [1] predicted the experimental data with a mean deviation of −5.5%.

1. Introduction

The air conditioning and refrigeration industry is undergoing significant changes as it continues to replace the ozone depleting substances (ODSs) commonly used as refrigerants. Hydrofluorocarbons (HFCs) are synthetic fluids entirely harmless to the ozone layer since they do not contain chlorine. R-134a is the only pure HFC clearly established as a substitute for clorofluorocarbons (CFCs) and hydroclorofluorocarbons (HCFCs) in several types of applications at high and medium temperature levels despite of its high global warming potential (GWP = 1300, 100 years integrated time horizon).

In recent decades, enhanced tubes are widely used in manufacturing shell and tube condensers commonly used in refrigeration plants. The superior heat transfer performance of enhanced tubes allows a significant size reduction of the condensers. Externally low integral finned tubes are commonly used for the outer condensation of low surface tension fluids such as R-134a. Nowadays there are several types of enhanced tubes with two or three-dimensional fins commercially available from different manufacturers. Generally, these tubes are made of copper or copper–nickel alloys. The condensation heat transfer of HFC-134a on plain and different types of enhanced tubes is reported in several papers, Jung et al. [2], Honda et al. [3,4], Belghazi et al. [5], Kumar et al. [6–8], Gstoehl and Thome [9], Zhang et al. [10] or Kang et al. [1].

Titanium tubes are used in applications with corrosion problems, such as marine facilities on shore and onboard, desalination, chemical and power plants. Refrigerant condensers using sea water as cooling medium require the use of copper–nickel alloys, steel, stainless steel or titanium tubes to withstand corrosion. The use of titanium tubes allows the increase of the inside water velocity due to the higher titanium resistance to erosion than the other materials. It also allows the reduction of the heat exchangers weight by about 40% for the same heat transfer area due to the specific weight of titanium which is around 55% and 50% lower than the specific weight of stainless steel and copper alloys, respectively. If titanium tubes are used and high water velocities are considered, the water-side convection coefficient will become greater than the outer condensation coefficient. Then, the thermal resistance caused by the outer condensation becomes the controlling thermal resistance within the overall heat transfer process.

On the other hand, it is worth pointing out that the fins' efficiency and, consequently, the condensing enhancement factor provided by integral-fin tubes greatly depends on the thermal conductivity of the tube material. Zhang et al. [10] compared the condensation of R-12 and R-134a on different types of copper and cupronickel tubes. The authors demonstrated that the thermal conductivity of the tubes has a significant influence on the overall condensation HTCs over low-fin integral tubes. The thermal conductivity of titanium is low (22 W m^{-1} K^{-1}); therefore, the fins' efficiency could become a limiting factor and the enhancement provided by the finned tubes should be carefully evaluated. Consequently, the research on the R-134a condensation outside enhanced titanium tubes turns out to be interesting in order to evaluate the actual enhancement factors provided by these types of tubes.

Hwang et al. [11] tested a bare and four enhanced titanium tubes of 1 m length, 16 mm outside diameter and 0.3 mm

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Nomenclature

A	area (m^2)
Cp	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
C_b	flooded fraction of tube perimeter
d	diameter (m)
EF	enhancement factor
f	friction factor
g	gravitational acceleration ($m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_f	fin height (m)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
m	mass flow ($kg\,s^{-1}$)
Nu	Nusselt number
Pr	Prandtl number
p	fin pitch (m)
q	heat flow (W)
R	thermal resistance ($K\,W^{-1}$)
Re	Reynolds number
s	fin spacing (m)
T	temperature (K)
t	fin thickness (m)
ΔT	temperature difference (K)

Greek symbols

β	condensate retention half-angle (rad)
λ	latent heat ($J\,kg^{-1}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	mass density ($kg\,m^{-3}$)
σ	surface tension ($N\,m^{-1}$)
φ	fin apex half-angle (rad)

Subscripts

c	condensate
cw	cooling water
cwi	cooling water inlet
cwo	cooling water outlet
ft	fin tip
fr	fin root
i	inner
$LMTD$	logarithmic mean temperature difference
l	liquid
o	outer
ov	overall
r	root
sat	saturation
sub	wall subcooling
t	tube
v	vapour

thickness. The enhanced tubes were a crushed type tube, a shrunken type tube, an expanded type tube and a spirally corrugated type tube. Experiments were carried out condensing steam on the outer surface of the tubes in a shell condenser and circulating water inside the tubes. In the paper, only the results of the steam condensation convection coefficients for the bare and the crushed type tube are given. The experimental condensation coefficients for the bare and enhanced tubes resulted slightly higher and 40% higher than predicted by the Nusselt [12] theory, respectively.

To the best of our knowledge, there is no available data on the condensation heat transfer of R-134a on integral low finned titanium tubes. Consequently, the main purpose of this investigation was to evaluate experimentally the condensation of R-134a on commercially available smooth and integral-fin titanium tubes. The experimental results are compared against the theoretical ones provided by several condensation models and empirical correlations found in the literature. In the paper, the experimental setup and procedure are described, the data reduction process is detailed, and the results are presented and discussed.

2. Experimental facility

The layout of the experimental facility is shown in Fig. 1. The facility is composed of a condensation test section (condenser), an electric-heated evaporator and a cooling water loop. The condenser and the evaporator consist of a 6 mm thick horizontal cylindrical body and blind flanges made of stainless steel (AISI-316L). The condenser has an external diameter of 168.3 mm and a total length of 1895 mm. The evaporator has an external diameter of 200 mm and a total length of 1530 mm. The refrigerant vapour is generated by heating the pool of the refrigerant liquid by means of three immersed electric resistances of 4 kW each, placed into stainless steel (AISI-316L) horizontal tubes. An electric power regulator allows the control of the heating power delivered by the electric resistances.

The generated vapour is conducted through a vapour line from the evaporator to the upper part of the condenser, where the tubes to be tested are placed. The vapour is split in four streams and goes into the condenser at four different points in order to guarantee an appropriate distribution at the condenser top (see Fig. 1). The vapour main line and the distributors are made of stainless steel (AISI-316L) with 40/43 and 30/33 mm inner/outer diameters, respectively. The vapour condenses on the tested tubes. The condensate returns to the lower part of the evaporator by gravity, through the condensate line of 10/12 mm inner/outer diameters. Both, the condenser and the evaporator, are equipped with six sight glasses for lighting up and visual observation of the condensation and boiling processes.

The tested tubes are internally cooled by circulating water through them. A centrifugal pump forces the cooling water from a reservoir tank through a plate heat exchanger and the tested tubes in a closed loop, as shown in Fig. 1. The cooling water is heated into the tested tubes and cooled in the plate heat exchanger by means of water from a cooling tower. A recirculation loop from the pump outlet to the reservoir tank is used to control the water flow rate through the tested tubes (see Fig. 1). A thermostatic control valve adjusts the water flow rate from the cooling tower through the plate heat exchanger and allows the control of the cooling water temperature at the test section.

The experimental setup was equipped with a data acquisition system based on a 16-bits data acquisition card and a PC. The vapour temperature in the condenser is measured by means of eight sensors (sensors T_{01}–T_{08} in Fig. 1). The vapour and liquid temperature in the evaporator are measured by using eight sensors, T_{09}–T_{12} for the vapour and T_{13}–T_{16} for the liquid, according to Fig. 1. These sensors are A Pt100 inserted in 100 mm long and 3 mm diameter stainless steel pockets. The pressure in the condenser is measured by using a pressure transducer with an accuracy of ±0.5% of the full scale (26 bar). The temperature, density and mass flow rate of the condensate returned to the evaporator are measured by means of a Coriolis flow-meter (FM_1 in Fig. 1) with an accuracy of ±0.25% of the measured value for the flow rate, ±1 °C for the temperature and ±2 $kg\,m^{-3}$ for the density. Two temperature sensors are used to measure the cooling water bulk temperature at the inlet and