INTERNATIONAL JOURNAL OF REFRIGERATION 69 (2016) 175–185

Available online at www.sciencedirect.com

ScienceDirect

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

Heat transfer enhancement of ammonia pool boiling with an integral-fin tube

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ARTICLE INFO

Article history:
Received 29 March 2016
Received in revised form 16 May 2016
Accepted 17 May 2016
Available online 20 May 2016

Keywords:
Pool boiling
Ammonia
Heat transfer enhancement
Integral-fin tube

ABSTRACT

Ammonia has been and is used as refrigerant in many industrial refrigeration systems. Flooded shell-and-tube evaporators are normally employed in such systems. However, it is crucial to reduce the size and refrigerant charge of these evaporators, which can be achieved by improving their heat transfer performance using tubes with enhanced surfaces.

Tests were performed to analyse the enhancement achieved with a commercial integral-fin (32 f.p.i., 1260 f.p.m.) titanium tube, if compared to a plain tube of the same nominal external diameter, under pool boiling and using ammonia. The test conditions were those than can be found in water chillers and heat transfer coefficients were determined both in increasing and decreasing heat flux order to analyse nucleation hysteresis.

The average enhancement factor achieved with this tube was of 1.2 (maximum 1.3). Hysteresis on nucleation occurred and should not be neglected, particularly with the integral-fin tube. An experimental correlation is proposed for both the plain and the enhanced tubes and it predicts the experimental results within 5.5%.

Amélioration du transfert de chaleur d’ammoniac en ébullition libre avec un tube à ailettes intégrales

Mots clés : Ébullition libre ; Ammoniac ; Amélioration du transfert de chaleur ; Tube à ailettes intégrales

1. Introduction

The global situation concerning ozone depletion and global warming has been of main interest since the last decades of the 20th century. The topic has gained further relevance due to the 2015 United Nations Climate Change Conference, held in Paris, where a universal agreement was achieved with the aim of reducing the effects of global warming. The refrigeration and air conditioning sectors are part of this issue, mainly due to the environmental implications of some refrigerants used, such as HFCs. The solution in industrial refrigeration should lie in ammonia, due to its extraordinary thermodynamic and transport properties that lead to more efficient refrigeration plants. Even though ammonia is a toxic refrigerant, its deep and characteristic odour is an important safety factor and flammability issues are slight if compared with other refrigerants (Lorentzen, 1995).

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http://dx.doi.org/10.1016/j.ijrefrig.2016.05.012
0140-7007/

Nomenclature

Roman symbols

A	area [m^2]
C	tube geometry fitting constant
c_p	specific heat capacity of the liquid [J kg^{-1} K^{-1}]
d	diameter [m]
EF	enhancement factor [dimensionless]
f	Darcy–Weisbach friction factor [dimensionless]
f.p.i.	fins per inch
f.p.m.	fins per meter
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	tube length [m]
LMTD	logarithmic mean temperature difference [K]
$\dot{m}$	mass flow rate [kg s^{-1}]
p	pressure [Pa]
Pr	Prandtl number [dimensionless]
q	heat flow [W]
R	thermal resistance [K W^{-1}]
Re	Reynolds number [dimensionless]
T	temperature [K]

Greek symbols

Δ	difference

Subscripts and superscripts

boiler	boiler
corr	correlation
crit	critical
en	enhanced
evap	evaporator
exp	experimental
hw	heating water
i	inner
in	inlet
l	liquid
o	outer
out	outlet
ov	overall
pl	plain
red	reduced
sat	saturation
sf	surface
SH	wall superheat
w	wall

Flooded shell-and-tube evaporators are widely used to cool secondary fluids, for instance water, in refrigeration systems with high cooling loads. Liquid refrigerant fills the shell side, wetting the outer surface of the tubes, and the fluid to be cooled circulates through them. The main drawback of these evaporators lies in the high refrigerant charge needed and it is crucial to minimise it to reduce risk, cost and environmental impact. The use of enhanced surfaces normally improves the heat transfer performance of flooded evaporators, leading to smaller, affordable and efficient systems (Webb and Kim, 2005). Enhanced surfaces enter into the group of passive enhancement techniques, following the classification developed by Bergles (1997). The aim of these surfaces is to achieve thin-film vaporization and vapour–liquid exchange, a main issue to assure a continuous process.

Spindler (2010) carried out a comprehensive review on boiling heat transfer of ammonia, including experimental data and correlations of pool boiling on plain and enhanced tubes. Of special interest for this paper are the results from the works of Danilova et al. (1990) and Djundin et al. (1984). The first analysed ammonia pool boiling on different horizontal steel tubes with aluminium coatings. According to Danilova and co-workers, these coatings improve heat transfer between 100% and 400%, if compared to the plain tube used as reference. Concerning the second work, the tubes tested included a plain steel tube and several enhanced tubes. A porous aluminium layer on the tube led to an enhancement of 40%. Mechanical grooves improved pool boiling heat transfer between 30% and 60%. Finally, a fluorocarbon layer with spots on the surface enhanced heat transfer in percentages that ranged between 300% and 400% of the value obtained with the plain tube.

Pool boiling processes are classified depending on the heat flux transferred and the wall superheat (difference between the temperature of the wall and the saturation temperature of the refrigerant) in one of the boiling following regions of the boiling curve: natural convection, nucleate boiling, transition boiling and film boiling (Collier and Thome, 1994). Flooded evaporators are expected to operate in natural convection or nucleate boiling, being the last one more convenient from a heat transfer performance point of view. The transition between natural convection and nucleate boiling occurs at a specific point, called Onset of Nucleate Boiling, for which the wall superheat is enough to cause vapour nucleation at the surface. According to Poniewski and Thome (2008), there is a hysteresis in this transition, denoted as nucleation hysteresis, since it depends on whether the process comes from natural convection (increasing heat flux) or from nucleate boiling (decreasing heat flux). Kuprianova (1970) observed this effect in the pool boiling of ammonia on horizontal tubes. In addition, Poniewski and Thome stated that nucleation hysteresis is greater on enhanced boiling surfaces than on smooth surfaces.

The use of tubes of titanium with ammonia in shell-and-tube heat exchangers is becoming an interesting option, particularly in applications under very severe corrosion conditions (marine) or if the velocity of the fluid wants to be increased in order to reduce the inner thermal resistance (Ayub, 2004). In addition, titanium is a very light material, with half the density of steel, which reduces the weight of the heat exchangers manufactured with it. However, the cost of titanium is its most important disadvantage.

In the present work, the enhancement achieved under pool boiling of ammonia with a commercial integral-fin (32 f.p.i., 1260 f.p.m.) titanium tube, compared to a plain tube of the same nominal external diameter, is analysed experimentally. The effect of nucleation hysteresis on the pool boiling heat transfer coefficients obtained is also detailed. The paper describes the experimental facility, the experimental procedure and the