International Journal of Heat and Mass Transfer 98 (2016) 350–358

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Free convection condensation heat transfer of steam on horizontal square wire wrapped tubes

Hafiz Muhammad Ali *, Muhammad Zeshan Qasim, Muzaffar Ali

Department of Mechanical Engineering, University of Engineering and Technology, Taxila 47050, Pakistan

ARTICLE INFO

Article history:
Received 5 July 2015
Received in revised form 10 March 2016
Accepted 11 March 2016
Available online 25 March 2016

Keywords:
Condensation
Heat transfer
Square wire wrapped tube
Thermal conductivity
Phase change
Steam

ABSTRACT

New experimental data are reported for the condensation of steam on square wire wrapped on horizontal instrumented copper tube. 0.8 mm square cross-section wires made of copper and brass and 1.0 mm square cross-section wire made of copper with pitches of 2.0 mm, 4.0 mm and 6.0 mm are used. For both 0.8 mm and 1.0 mm square cross-section wire wrapped tubes, best performing pitch was found to be 4.0 mm i.e. 1.53 and 1.5 for 0.8 mm and 1.0 mm square wire wrapped tubes respectively. The effect of thermal conductivity was evident in case of 0.8 mm (copper and brass) square wire wrapped tube at all pitches tested with significance at 2.0 mm pitch. Compared to equivalent round cross-section wire wrapped tubes, 0.8 mm square wire wrapped tubes showed lower heat transfer enhancement than 0.8 mm diameter round wire wrapped tubes while heat transfer enhancement was higher for 1.0 mm square wire wrapped tubes than 1.0 mm diameter round wire wrapped tubes i.e. 13.4%, 7.1% and 3.7% higher enhancement than the round wire wrapped tubes at 2 mm, 4 mm and 6 mm respectively.

1. Introduction

It has been now understood that one of the major factors effecting the condensation heat transfer is condensate retention. Heat transfer may be enhanced by lowering the condensate retention or by increasing the active surface area of tube. For the enhanced condensation heat transfer different types of enhanced geometries have been used for many years. Commonly used enhanced geometries are simple two dimensional rectangular "integral-fin tubes", three dimensional "pin-fin tubes" or simply "wire wrapped tubes".

For last few decades two dimensional integral-fin tubes have been used to enhance heat transfer rate. Different investigators have reported the higher heat transfer rate using integral-fin tubes compared to the simple plain tube. Important parameters effecting condensation heat transfer rate were fin spacing, thickness and the ratio of surface tension to density of condensate. Kumar et al. [1] performed the experimental study for the condensation of steam and refrigerant R-134a on two different types of finned tubes as circular integral-fin tubes (CIFTs) and spine integral-fin tubes (SIFTs). Spine integral-fin tubes (SIFTs) gave higher heat transfer enhancement than circular integral-fin tubes (CIFTs) for both fluids (steam and refrigerant R-134a) tested. Marto et al. [2] investigated twenty four different machined rectangular finned and commercial horizontal integral-fin tubes for the condensation of refrigerant R-113. It was reported that optimum fin spacing should be between 0.2 mm and 0.5 mm depending upon its fin height and fin thickness. The highest heat transfer enhancement was found to be 7 for the integral-fin tube having fin height, fin thickness and fin spacing about 1.0 mm, 0.5 mm and 0.25 mm respectively. Jung et al. [3] investigated the condensation heat transfer coefficients of plain tube, low fin tube and turbo-C tube. The fluids used were low pressure refrigerant CFC11 and its alternative HCFC123 and medium pressure refrigerant CFC12 and its alternative HFC134a. Highest enhancement of almost 8 times greater than plain tube was found to be in the case of turbo-C tube for all the refrigerants tested. They reported that heat transfer enhancement of HFC123 was lower than its alternative CFC11. While heat transfer enhancement of HFC134a was higher than its alternative CFC12. Briggs et al. [4] reported the experimental study on integral-fin tubes made of copper, brass, and bronze varying fin height and fin spacing for the condensation of steam and R-113. For refrigerant R-113, heat transfer was found to be weakly dependent on thermal conductivity, however, strongly dependent for the case of steam. While heat transfer enhancement was found to be strongly dependent on fin height and fin spacing for R-113 but it was relatively weakly dependent for the case of steam. Honda and Nozu [5] presented the theoretical model for the integral-fin tubes which also included the effect of condensate retention on integral-fin tubes. Rose [6] presented the modal for heat transfer on horizontal

* Corresponding author.
E-mail address: h.m.ali@uettaxila.edu.pk (H.M. Ali).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.053
0017-9310/

Nomenclature

B	constant used in $q = B\Delta T^{3/4}$
d_w	diameter of wire, mm
q	heat flux, kW/m^2
ΔT	vapour-side temperature difference, K
$\varepsilon_{\Delta T}$	enhancement ratio, heat flux or heat-transfer coefficient for wire-wrapped tube divided by the corresponding value for a plain tube

integral-fin tube suggesting that 'fin efficiency' may have the vital effect on condensation heat transfer which was later incorporated in the model of Briggs and Rose [7].

Honda et al. [8] also measured the condensation heat transfer for R-113 and methanol on more complex "Thermoexcel" tube having "three-dimensional" fins. They reported a little enhancement compared to the likely integral-fin tubes. Belghazi et al. [9] condensed R-134a on "Gewa-C" tube and found that the enhancement ratio was significantly improved compared to many of the integral-fin tubes. Ali and Briggs [10] reported the condensation of ethylene glycol on eleven different three-dimensional pin-fin tubes varying pin geometry systematically. The highest enhancement ratio of 5.5 was found for the pin-fin tube having longitudinal pin thickness, circumferential pin spacing and longitudinal pin height of 0.5 mm, 0.5 mm and 1.6 mm respectively. This enhancement was about 24% higher than the "equivalent" (i.e. having same longitudinal and radial dimensions) two-dimensional integral-fin tube. It was reported that enhancement ratio would be higher for larger pin height and smaller circumferential pin spacing. Ali and Briggs [11] condensed R-113 on five three-dimensional pin-fin tubes with parameters varied were only circumferential pin thickness and spacing. These parameters showed effect on condensate retention. The highest heat transfer enhancement ratio was found to be about 6 for the pin-fin tube having pin thickness and circumferential pin spacing of 0.5 mm and pin height of 1.6 mm respectively. This enhancement was about 13% higher than the "equivalent" two-dimensional integral-fin tube. Based on the reported experimental data on pin-fin tubes, recently, Ali and Briggs [12] reported a semi-empirical model for condensation heat transfer on pin-fin tubes. Model showed agreement to data within ±20%. Briggs [13] reported the experimental study on the phenomenon of condensate retention for water, ethylene glycol and R-113 on twelve different pin-fin tubes and three integral-fin tubes. He found that retention angle was found to be somewhat larger for the case of pin-fin tubes than equivalent integral-fin tubes. It was also found that condensate retention was lower for the case of R-113 than steam and ethylene glycol due to the lower surface tension to density ratio. Ali and Briggs [14] further reported a semi-empirical model to predict condensate retention on pin-fin tubes. Ali and Briggs [15] reported systematic experimental data to study the effect of thermal conductivity for the condensation of ethylene glycol and R-113 on six three-dimensional pin-fin tubes made of copper, brass and bronze. The only parameter varied was pin height. Heat transfer enhancement ratio was found to be higher for copper than brass and bronze due to higher thermal conductivity. It was revealed that heat transfer enhancement ratio was increased by increasing pin height. The effect of thermal conductivity was less evident for R-113, however, more evident for the case of ethylene glycol.

Another common method used to enhance heat transfer is wrapping the tube with wires. Though this method does not give as high heat transfer enhancement as found in the case of integral-fin and pin-fin tubes. However, this is cost effective method of enhancement as it does not need any machining. Many researchers have reported investigations in this area. Marto et al. [16] investigated condensation heat transfer of steam by wrapping steel wires on tube having diameters of 0.5 mm, 1.0 mm and 1.6 mm and varying their spacing by 1.0 mm, 2.0 mm and 3.0 mm at atmospheric and vacuum conditions with vapour velocity of 1 and 2 m/s. He found maximum heat transfer enhancement of 1.8 for 0.5 mm wire with pitch about 3.6 mm. Sethumadhavan and Raja [17] condensed steam on horizontal tube by wrapping copper wires having diameters about 0.71 mm, 1.5 mm and 3.0 mm and varying their pitch from 7.5 mm to 30 mm. They reported the highest heat transfer enhancement of 1.45 by using 1.5 mm and 7.5 mm diameter of wire and pitch respectively. They also suggested that the optimum pitch for highest enhancement should be less than 7.5 mm. Fujii et al. [18] reported data for condensation of R-11 and ethanol on a horizontal wire-wrapped tube. Wire having a diameter of 0.3 mm with varying pitch of 0.5 mm, 1.0 mm and 2.0 mm was used for R-11. Highest heat transfer enhancement was found to be 3.4 in the case of smallest pitch of 0.5 mm. For ethanol three wires having diameters of 0.1 mm, 0.2 mm and 0.3 mm with fixed pitch of 1.0 mm were used. Highest heat transfer enhancement found in the case of largest diameter of 0.3 mm was about 2.8. They suggested that highest enhancement could be found using large diameter and small pitch. The first theoretical model on horizontal wire-wrapped tubes for film-wise condensation was reported by Fujii et al. [18]. Rose [19] modified the model to incorporate the effect of film thickness. He suggested that film thickness would not always remain uniform as it varies by varying pitch. Golubnichniy et al. [20] reported heat transfer enhancement for the condensation of nitrogen dioxide on single horizontal wire-wrapped tube at different pressures of 0.15 MPa and 0.35 MPa. Steel wires were wrapped having 0.5 mm and 1.0 mm diameter and pitches about 1.0 mm, 1.5 mm, 5.0 mm and 9.0 mm. Murase et al. [21] conducted experiments for the condensation of steam, ethylene glycol and R-113 on single horizontal wire-wrapped tube. They wrapped steel wires having different diameters of 0.2, 0.35, 0.4, 0.75 and 1.0 mm on horizontal plane tubes. The pitches varied were in the range of 0.5 mm to 6.0 mm. The optimum pitches were found to be different for different diameters. Maximum enhancement was found in the case of R-113 which was almost 3. In case of steam and ethylene glycol, a maximum enhancement ratio was found around 2. Recently, the effect of wire thermal conductivity on wire wrapped tubes for the condensation of steam has been reported by Ali and Qasim [22]. For 0.8 mm diameter, wires made of copper and brass were used and for 1.0 mm diameter, wires made of copper, aluminium and brass were wrapped on horizontal tubes. For 0.8 mm and 1.0 mm diameter wires, the pitch of windings were kept 2 mm, 4 mm and 6 mm respectively. For both cases (0.8 mm and 1.0 mm), copper wire wrapped tubes showed higher heat transfer enhancement than brass wire wrapped tubes at all the pitches tested. The subject of condensation heat transfer enhancement on horizontal tubes by using enhanced surfaces has been well researched, models are now readily available [see Refs. 6,7,12]. These models can be used to optimize such geometries for different applications; however, such an optimization exercise would be complex, given that the model includes several independent geometric variables. Recent