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An empirical study on evaporation heat transfer characteristics and flow pattern visualization in tubes with coiled wire inserts☆

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ABSTRACT

In the present work, heat transfer and flow pattern visualization during forced convection evaporation of hydrocarbon R-600a (Isobutane) inside a horizontal tube with coiled wire inserts has been experimentally studied. The system consists of a pump, two preheaters, the test section, two condensers, flow meter and bypass. The test evaporator was an electrically heated copper tube of 1000 mm length, 8.1 mm inside diameter and a wall thickness of 0.71 mm. Coiled wires with three different wire diameters of 0.5, 1.0 and 1.5 mm and three different coil pitches of 10, 20 and 30 mm were made and used in full length of test evaporator. The test runs were carried out at refrigerant mass fluxes from 109.2 to 505 kg/m^2 s and heat fluxes between 18.6 and 26.1 kW/m^2. The use of coiled wires was found to increase the flow boiling heat transfer coefficients up to maximum value of 124% above the plain tube values with wire coiled having a twist ratio ($^P/_{D_{in}}$) of 1.243 and a thickness ratio ($^e/_{D_{in}}$) of 0.183. Four different flow patterns were observed and classified as bubbly, stratified, intermittent and annular flow. This study reveals the developments of the flow patterns. Also it was observed that the presence of coiled wire inserts induces disturbance into gas and liquid flows and so that the shape and motion of bubbles and slug are different from those observed in a plain tube. The correlation suggested by Shah [20] gave the best prediction to the flow boiling heat transfer coefficient in the plain tube within the studied ranges.

1. Introduction

Evaporator is an important and widely used equipment of refrigeration and air-conditioning industry and it also forms an integral part of many other engineering systems such as steam power plants and chemical apparatus. The design of efficient heat exchange equipment is conducive to the current drive towards energy conservation. The desire to improve the performance of evaporators has resulted in the development of method such as the use of heat transfer augmentation devices in the boiling equipment. The use of augmentative techniques, either active or passive, to increase the convective heat transfer rates on tube side has been studied for quite some time.

A review of the existing research showed that a lot of investigations have been carried out to study the effect of various passive techniques such as twisted tape, wire coil on augmentation of heat transfer coefficient inside tubes, both in single-phase and in two-phase flow [1–5]. In addition, the inserts are low in cost, easy to manufacture and assemble, and easy to remove from the tube for cleaning purposes. Thus, wire inserts represent an important technology, and require more intensive studies.

Yun et al. [6] experimentally investigated the effects of wire coil inserts on the boiling heat transfer characteristics of nitrogen in a stainless steel plain tube with inner diameter of 10.6 mm and length of 1.65 m. Their test was conducted at the saturation temperature of −191 °C, mass fluxes ranging from 58 to 105 kg/m^2 s and heat fluxes from 22.5 to 32.7 kw/m^2. Test section heated by direct heating method using the DC power supply at constant heat flux condition. They found that the heat transfer coefficient increased with the increase of mass flux, while it decreased with the increase of heat flux because the dry-out vapor quality reduced with the increase of heat flux. They showed that the maximum heat transfer enhancement of the wire coil inserted tubes was 174% with a twist ratio (P/D_w) of 1.84 and a thickness ratio (e/D_w) of 0.25. Agrawal et al. [7] studied the condensation of R22 in a tube-in-tube heat exchanger with an inner hard-drawn copper tube of 12.7 mm inside diameter. The tested mass fluxes of refrigerant R22 were from 200 to 372 kg/m^2 s. A 100% condensing heat transfer coefficient increase was found by using the helically coiled wire inserts compared to the plain smooth tube values. The heat transfer coefficients were observed to increase as the vapor quality or mass flux increased respectively, when other parameters remained unchanged. They also found that with the same mass flux and same pitch, at high vapor qualities,

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Nomenclature

D	tube diameter, m
e	wire diameter, m
G	mass flux, kg/m^2 s
h	heat transfer coefficient, kw/m$^2\cdot$k
L	tube length, m
P	pressure, kPa
P	coil pitch, m
q	heat flux, kw/m^2
T	temperature, K
K	thermal conductivity, W/m$\cdot$K
x	vapor quality

Greek symbols

β	helix angle of coiled wire, degree
η	insulation efficiency

Subscripts

ev	evaporator
h	hydraulic
in	inside tube
out	outside tube
s	saturated
w	tube wall
wi	inside wall
wo	outside wall

the highest coil insert achieved maximum heat transfer enhancement, but, with low vapor qualities there is a reverse trend.

Regarding the single phase flow, San et al. [8] investigated heat transfer and fluid friction correlations for airflow and water flow in circular smooth tubes with coiled-wire inserts. They found that the Nusselt number increased with the increasing of wire diameter, whereas it increases with a decreasing of coil pitch. They also proposed two empirical heat transfer equations, one for air and another one for water. More recently, Shahin et al. [9] experimentally and numerically investigated the heat transfer and friction characteristics of a concentric tube heat exchanger with different pitches of coiled wire turbulators. They used air as the working fluid in a horizontal plain tube with the inner diameter of 40 mm. Their results showed that the heat transfer augmentations using turbulators were 2.28, 2.07 and 1.95 times better than the smooth tube for pitch distances of $p = 15$, 30 and 45 mm, respectively.

On the other hand, the refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. As the ODS (ozone depleting substances) phase-out is taking effect, most equipment is being or will eventually be retrofitted or replaced to use HFC-based substitutes [10]. However the use of HFCs has also come under scrutiny as they have high global warming potential (GWP) and inferior thermodynamic and lubricating properties and have been replaced by hydrocarbon (HC) refrigerants. Refrigerant HC-600a, is a possible replacement for other refrigerants due to its low environmental impact and excellent thermodynamic performance. It is non-toxic with zero ODP (Ozone Depletion Potential) and very low GWP. The refrigerant R-600a has been in use in the past, in refrigerators up to the 40s, and has now again found a wide use in domestic and small commercial refrigerators and freezers in Europe. Because of the availability of isobutane (R-600a) all over the world, it has been discussed widely for CFC replacement. Isobutane is a possible refrigerant for this application, with good energy efficiency, but with a very different characteristic in several points, which implies the design to be made or adopted for this refrigerant. Special care has to be taken to the flammability of isobutane. The use of R-600a is increasing due to its low environmental impact and excellent thermodynamic performance.

In this regard, Nasr et al. [11] presented an experimental investigation of heat transfer characteristics and flow visualization of the hydrocarbon refrigerant R-600a during flow boiling inside horizontal smooth tube in a range of mass fluxes 130–380 kg/m^2 s and vapor qualities up to 0.70. They observed that the dominant flow patterns are intermittent and annular flow patterns. They concluded that the heat transfer coefficient increased as the mass velocity increased in the fixed vapor quality, in addition, as the vapor quality increased in the fixed mass velocity. Copetti et al. [12] experimentally studied the boiling of R-600a inside a 2.6 mm horizontal smooth tube. Their experimental conditions included heat fluxes in the range of 44–95 kW/m^2, mass velocities of 240 and 440 kg/m^2 s. They presented that the effect of heat flux on the heat transfer coefficient was significant at low vapor qualities for lower mass velocity. According to their study, in comparison with R-134a, R-600a provides higher heat transfer coefficient and pressure drop for similar operation conditions.

Considering all the above mentioned facts, in the present paper an experimental investigation was carried out to study the effects of wire coil inserts on the flow patterns and heat transfer characteristics of R-600a in a horizontal tube. Considering all the above mentioned facts, the effect of coiled wire inserted with different wire diameters and coil pitches on the flow boiling heat transfer of R-600a and simultaneous visualization of the boiling process were investigated.

2. Experimental facility and procedure

The experimental set-up is shown schematically in Fig. 1. The general features of the experimental facility, which is designed for the flow boiling are described below. The refrigerant used in the closed-loop system was HC-R600a (ISOBUTANE), which covered the mass flux range from 109.2 kg/m^2 s to 505 kg/m^2 s and the vapor quality ranges from 0.08 to 0.7. Also, the working fluid is typically at least 99.5% pure with minimal levels of critical impurities including moisture and unsaturated hydrocarbons that makes it ideal for use in all types of refrigeration systems. A variable frequency gear pump with 0.5 HP power is used to circulate the working fluid through the test loop. One Coriolis-effect mass flow meter is arranged to measure flow rates in different ranges during the tests. The pre-heaters were installed upstream of the test evaporator to obtain desired vapor quality at the inlet of a test evaporator to cover the entire ranges of vapor qualities. The test evaporator was a smooth horizontal copper tube with outside diameter of 9.52 mm and thickness and length of 0.71 mm and 100 cm, respectively. A sight glass is located in the terminal of test section for visualization of the flow patterns. The sight glass, has the same inner diameter as the test section i.e. 8.1 mm which is made of Pyrex glass, and has lengths of 200 mm and was specially designed for flow pattern observation under high working pressure. A digital camera based flow visualization technique utilizing an illuminated diffuse white film pigmented with evenly spaced black stripped background (behind the glass tube) was utilized to enhance images, detect fine films, and aid to the image recognition process. This method has been originally developed by Jassim et al. [13].

The test section is heated using an electrical resistance circuit. Coils were wound around the test section and ensure a homogeneous or uniform heat flux over it. The heating power was provided by a 2 kW dimmer. To reduce ambient heat losses, the test section was covered with glass wool pad and armoflex foam rubber. All temperature measurements in the test facility are performed using high quality K-type thermocouples with a calibrated accuracy of 0.1 °C and were directly welded at the top, bottom and sides of the tube at five axial positions. K-type thermocouples have a positive Chromel wire and a negative Alumel wire. The preheaters were used to set desired vapor quality prior to the inlet of the test evaporator. Similar to the test section,