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Research Paper

Adiabatic flow characteristics of R-600a inside a helically coiled capillary tube

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HIGHLIGHTS

- Effect of sub-cooling on mass flow rate of R-600a inside coiled capillary tube.
- Coiling reduces mass flow rate by 1.5–16% as compared to straight capillary tube.
- Correlation predicts mass flow rate of R-600a is proposed with an agreement of ±20%.

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ABSTRACT

This paper presents an experimental investigation of a helically coiled capillary tube with an adiabatic flow of R-600a. The details of experimental facility for testing a capillary tube with different inlet sub-cooling degree and varying pressure are discussed. The effect of coil diameter, capillary length, capillary tube diameter, sub-cooling degree and inlet pressure on mass flow rate are described. The degree of sub-cooling at the inlet of both straight and helical capillary tube is varied from 3 to 15 °C. The experimental results confirm that, the mass flow rate in the straight capillary tube is 1.5–16 percent higher than the coiled capillary tube. A non-dimensional correlation to predict the mass flow rate through a straight and helical coiled capillary tube has been developed with a good agreement of ±20 percent of measured mass flow rate.

1. Introduction

The capillary tube with 0.5–2.0 mm in diameter and 1.0–6.0 m length is normally used as expansion device in low capacity refrigerating systems [1]. The feasibility, low cost, zero maintenance and low initial torque requirement to the compressor, lead the capillary tube towards research. Normally a capillary tube regulates the refrigerant flow from condenser to evaporator while reducing the pressure. The installation of capillary tube needs a keen attention in the application and its operating conditions as well. Certainly it is possible to know the applicability based on system's capacity in the order of 10 kW. Once the capillary tube is installed in a refrigeration system, it cannot be altered or controlled. Therefore, the sizing of a capillary tube is necessary before installation.

The scientist have started working on the capillary tubes with refrigerants and refrigerant mixtures of HCFC, CFC and HFC groups to reveal their flow characteristics [2,3]. Certainly in the recent past years the natural refrigerants also gained importance towards research due their low global warming potential and low ozone depletion potential [4]. Even after several attempts of the researchers, the scarcity of measured data of natural refrigerants as compared to the HCFC, CFC and HFC groups is noticed. However, there are algebraic and numerical models to predict the mass flow rate of familiar refrigerants viz., R-600a, R-290, R-744, etc. Hermes et al. [5] have explicitly solved a set of thermodynamic relations governing an adiabatic flow through a capillary tube to formulate a semi-empirical algebraic model for mass flow rate. Schenk and Oellrich [6] built a test rig to measure the mass flow rate of R-600a through different capillary tubes in a controlled boundary conditions.

The inlet pressure fluctuation amplitudes of coiled capillary tubes are ~4 times higher as compared to straight capillary tube [7]. In addition, the coiled capillary tube need 4—10 times longer duration to stabilize down. The coiled capillary tube of small coil diameter and core diameter, the magnitude of pressure fluctuation amplitude is less. The pressure fluctuation amplitudes at the inlet of parallel coiled capillary tubes are 1/6—1/2 of the single capillary tube. The stabilization time significantly low with the parallel capillary tube arrangement. Hence, the higher mass flow rates in

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Nomenclature

d	capillary tube internal diameter, mm
L	length of the capillary tube, mm
D	coil diameter, mm
T	temperature, °C
ΔT_{sub}	sub-cooling degree, °C
$\dot{m}$	mass flow rate, kg h^{-1}
P	pressure, Pa
ΔT	temperature difference, °C
C_p	specific heat capacity, J kg^{-1} K^{-1}
h	enthalpy, J kg^{-1}

Greek letters

μ	dynamic viscosity, Pa-s
ρ	density, kg m^{-3}
ϵ	surface roughness, μm

Subscripts

in	inlet
e	evaporator
out	outlet
c	condenser
cap	capillary tube

parallel capillary tubes results more stability than single capillary tube. Dubba and Kumar [8] proposed the semi-empirical models to predict the mass flow rate of refrigerant inside diabatic helically capillary tube. The possibility of partial condensation at the entrance of the capillary tube is true and investigated an adiabatic flow of R-134a inside a straight capillary tube for different inlet refrigerant qualities [9].

Heimel et al. [10] developed a 1-D homogenous Artificial Neural Network (ANN) model to understand the flow characteristics of R-600a inside a diabatic capillary tube. The model is valid for choked, non-choked and two-phase inlet conditions. A computational model to simulate the diabatic flow under concentric and lateral configurations was developed by Hermes et al. [11] based on the mass, energy and momentum conservation equations. In addition, Hermes et al. [12] also developed an algebraic model to predict the mass flow rate of refrigerant and the heat exchanger effectiveness. Where the mass flow rate and heat transfer were treated as two independent phenomena.

The experimental facility to investigate the capillary tube under adiabatic flow conditions is described in the present paper. Furthermore, all the capillary tubes were tested under sub-cooled inlet conditions. The straight and coiled capillary tubes of different combinations of length and core diameter were chosen to perform the experiments. The helical coiled capillary tubes with coil diameters of 40 mm, 60 mm and 80 mm were investigated. A semi-empirical correlation to predict the mass flow rate of R-600a through an adiabatic straight and helical coiled capillary tube has also been developed. The experiments were conducted at three different pressures.

2. Experimental set-up and procedure

The experimental set-up is a simple vapour compression system with capillary tube as an expansion device (test-section). The function of a capillary tube is to reduce the pressure of refrigerant to evaporator conditions and to regulate the flow of refrigerant to the evaporator. A schematic view of an experimental set-up is shown in Fig. 1. The low pressure refrigerant coming from the capillary tube enters the evaporator to absorb the heat. The evaporator equipped with an electric heater through the variac (facilitates the regulation of power input). The refrigerant vapour coming from the evaporator directed to an open type compressor run by a three phase motor. The low pressure saturated/two-phase/superheated refrigerant is compressed to high pressure by compressor. This high pressure refrigerant directed to water cooled condenser through an oil separator. The oil separator ensures no oil particles are present in the refrigerant lines. The high pressure superheated vapour condensed in the condenser. The condensed refrigerant at the outlet of the condenser collected in a liquid receiver to ensure the continuous supply of refrigerant to the capillary tube. The drier-cum-filter provided after liquid receiver to ensure the refrigerant doesn't contain any moisture or foreign particle. A hand operated expansion valve was also fitted between the condenser and the evaporator to bypass the excess refrigerant into the evaporator and thereby no accumulation at the inlet of the capillary tube. The hand operated expansion valve also used to regulate the evaporator pressure. A Coriolis mass flow meter was fitted after the drier-filter to measure the mass flow rate of high pressure liquid refrigerant.

A sub-cooler was provided to attain the sub-cooled conditions of the refrigerant by circulating chilled water in the shell side. This chilled water supplied by means of a chiller unit working on simple vapour compression cycle (R-22). The chilled water was circulated in the sub-cooler by using a centrifugal pump. A preheater was fixed after sub-cooler to control the sub-cooling degree of the refrigerant before entering the capillary tube. The power input to the preheater was supplied through a variac.

A sight glass to visualize the state of refrigerant entering the capillary tube was provided at the inlet of the capillary tube. The refrigerant lines were well insulated with asbestos material on high pressure side and low pressure side. The pressure taps were provided at critical locations viz., condenser line, capillary inlet, suction line and capillary exit as shown in Fig. 2(a). The pressure transducers having an accuracy of ±0.25% FS (2 MPa) were used to measure the refrigerant pressure. The pressure gauges were also fitted to refrigerant line to cross verify the transducers and to monitor the running conditions.

A total of eight T-type thermocouples with an accuracy of ±2% are fitted along the length and two of the same were fitted at the entry and exit of a straight and helical coiled capillary tubes. These thermocouples attached directly on to the tube surface as shown in Fig. 2(b). The hand shut-off valves were fitted at the entrance and exit of major components for ease of repairs, if any. The helical capillary tube produced by using a wooden pattern with helical groves of three different coil diameters as shown in Fig. 3.

The experimental data were collected under the steady state conditions. The whole system is assumed to be running in a steady state condition, if the temperature and pressure remains steady within the bands of ±0.4 °C and ±10 kPa respectively. The sub-cooling degree was set by regulating the chilled water temperature in sub-cooler and preheater. The chiller unit is to supply the water at a specified temperature controlled by means of thermostat. The range of inlet operating conditions and specifications of a tested capillary tube are shown in Table 1.

The reliability of the experimental results is presented by using the uncertainty analysis. The uncertainty of π-Terms in proposed correlation is obtained through the uncertainty associated with the individual measurements by using following equation proposed by [13]: