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STUDY OF CAPILLARY TUBE FOR TRANSCRITICAL CO_2 SYSTEM

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ABSTRACT *: A review of the literature on the flow of Carbon dioxide refrigerants through the straight capillary tubes of different flow configurations especially adiabatic and non adiabatic, has been discussed in this paper. The paper presents the experimental and numerical analysis of different categories. The paper provides information about the range of input parameters especially tube diameter, tube length, surface roughness.Other information includes type of refrigerants used, correlations proposed and methodology adopted in the analysis of flow through the capillary tubes of different geometries operating under adiabatic and non adiabatic flow conditions.*

Keywords: CO_2, Transcritical cycle, Capillary tube, Adiabatic, Non adiabatic (diabatic)

1. INTRODUCTION

In recent years, the pursuit for environmentally friendly refrigerants has caused CFCs (chlorofluorocarbons) and HCFCs (hydro chlorofluorocarbons) refrigerants to gradually fade from use in the refrigeration industry. Research interests in this field turn to fluids with a low GWP (Global Warming Potential) and low Ozone Depleting potential(ODP), the global warming potential (GWP) is an index that relates the potency of a greenhouse gas to the CO_2 emission over a 100-year period. The Ozone Deflecting Potential (ODP) is an Deflecting Potency of substance compared to that of R-11 or R-12

Instead of continuing the search for new chemicals, there is an increasing interest in technology based on ecologically safe 'natural' refrigerants, i.e. fluids like water, air, noble gases, hydrocarbons, ammonia and carbon dioxide. Among these, carbon dioxide (CO_2, R-744) is the only non-flammable and non-toxic fluid that can also operate in a vapor compression cycle below 0 ^{0}C. In addition to its environmental advantages, the CO_2 has attractive thermal characteristics that make it a viable alternative refrigerant.

The commonly reported disadvantages of CO_2 were loss of capacity and low COP at high heat rejection temperature, and high expansion losses compared to other common refrigerants, CO_2 refrigerant has high operating pressure. Compared to conventional refrigerants, the most remarkable property of CO_2 is the low critical temperature of 31.1 ^{0}C. Vapor compression systems with CO_2 operating at normal refrigeration, heat pump and air-conditioning temperatures will therefore work close to and even partly above the critical pressure of 7.38 MPa. Heat rejection will in most cases take place at supercritical pressure, causing the pressure levels in the system to be high, and the cycle to be 'transcritical',[1,2] i.e. with subcritical low-side and supercritical high-side pressure as shown in figure 1.

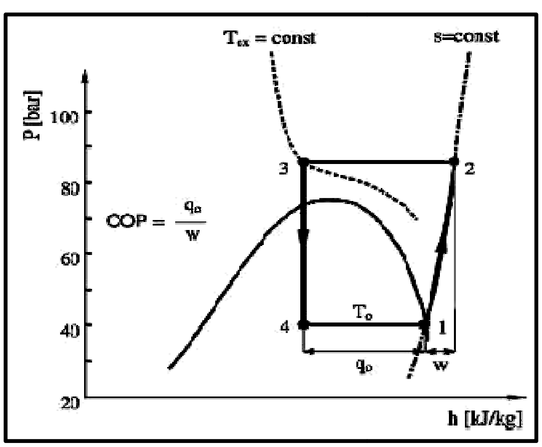

Figure 1 .Transcritical cycle in the CO_2 pressure–enthalpy diagram [1, 2]

The throttling loss in a refrigerating cycle is given by temperatures before and after the throttling device, and by refrigerant properties. Given the high liquid specific heat and low evaporation enthalpy of CO_2 near the critical point, the loss in refrigeration capacity (and the equal increase in compressor power) becomes large.The transcritical operation of the CO_2 is shown in Fig 1.

Owing to the higher average temperature of heat rejection, and the larger throttling loss, the theoretical cycle work for CO_2 increases compared to a conventional refrigerant as R-134a as indicated figure 2. This is showing additional thermodynamic losses for the CO_2 cycle when assuming equal evaporating temperature and equal minimum heat rejection temperature.

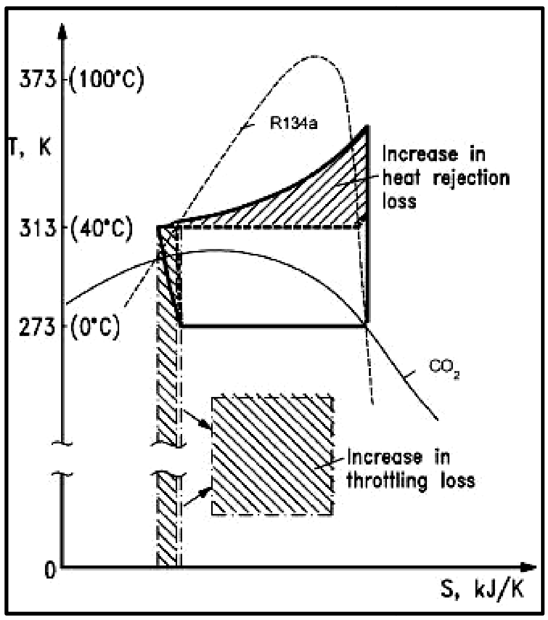

Figure 2 Comparison of thermodynamic cycles for R-134a and CO_2 in temperature–entropy diagrams [1]

In Transcritical CO_2 cycle, various expansion devices, like controllable throttle valve, work recovery turbine, vortex tube, ejectors, short tube orifice and capillary tube etc may be used. A capillary tube is a commonly used expansion device in the domestic refrigerators and window air conditioners. Usually, the capillary tubes have diameters ranging from 0.5 mm to 2.0 mm and lengths from 2 m to 6 m. The capillary tubes offer a number of advantages over the other expansion devices such as they are simple, inexpensive and cause the compressor to start at a low torque as the pressures across the capillary tube equalize during the off-cycle.

Adiabatic capillary tube, the refrigerant expands from high pressure side to low pressure side adiabatically. The inception of vaporization gives rise to two-phase flow in the capillary tube. This causes an increase in the vapour quality and fluid velocity resulting in an additional pressure drop called acceleration pressure drop. The increased pressure causes the temperature of the refrigerant to fall rapidly as in the two-phase region the temperature is a function of pressure. The adiabatic capillary tubes, occupy most of the literature available on capillary tubes. Most of the experimental research in the literature has been dedicated to the adiabatic capillary tubes neglecting the heat transfer from the capillary tube to the surroundings. In non adiabatic capillary tube has the unusual characteristic of flashing, while simultaneously being cooled by heat transfer to a wall where large frictional effects enhance flashing, while heat transfer retards flashing. These complexities of the non-adiabatic two phase flow make it challenging to analyse. Natural refrigerants have become the preferred choice to replace conventional refrigerants in view of their benign nature and CO_2 appears to be leading the pack.

2. LITERATURE REVIEW

Being an influential component of a refrigeration system, capillary tubes have been studied widely over many years. Numerous researchers have studied the design and flow behavior of adiabatic capillary tubes with halocarbon hydrocarbon and CO_2 refrigerants.

Madsen et al. [3] carried out the first theoretical and experimental studies to investigate the effects of using adiabatic capillary tube as an expansion device in a transcritical CO_2 refrigeration system. Various configurations of capillary tubes having length of 0.5 to 4m and diameter of 1 to 2 mm were tested and employing a static model.

Agrawal and Bhattacharyya [4] carried a comparative study of flow characteristics of an adiabatic capillary tube in a transcritical CO2 heat pump system have been investigated employing separated and homogeneous two phase flow models. Separated flow model is employed considering the annular flow pattern. The models are based on fundamental equations of mass, momentum and energy which are solved simultaneously. Two friction factor empirical correlations (Churchill, Lin et al.) and McAdams viscosity model are used. Chisholm correlation is used to calculate slip ratio while void fraction is calculated based on Premoli correlation. Sub-critical and super-critical thermodynamic and transport properties of CO2are calculated employing a precision in-house property code.

Agrawal and Bhattacharyya [5] carried out a theoretical study on adiabatic capillary tubes in a transcritical CO_2 heat pump cycle. A comprehensive experimental study on capillary tubes in a transcritical CO_2 heat pump for simultaneous heating and cooling applications is presented in the present investigation. They presented the flow characteristics of an adiabatic capillary tube flow in the CO_2 transcritical heat pump cycle. Occurrence of choking, cause and effects, were also discussed in their analysis. Comparatively, flow behavior in non-adiabatic tubes received much less attention in the literature.

D. Silva [6, 7] et al carried out an experimental and theoretical study of the adiabatic and non adiabatic flow of carbon dioxide through lateral capillary tube suction line heat exchangers is outlined. The influence of both operating conditions (capillary tube inlet and outlet pressures, capillary tube inlet temperature and suction line inlet temperature) and tube geometry (heat exchanger length and position, suction line diameter and capillary tube length) on the heat and mass flow rates was experimentally evaluated using a purpose-built testing facility.

C.Hermes [8] et.al carried an algebraic model for simulating the transcritical expansion of carbon dioxide through adiabatic capillary tubes. The model was put forward based on the analytical solution of the momentum conservation equation assuming an isenthalpic expansion process. The theoretical model predictions were compared with 66 experimental data points covering different operating conditions and tube geometries.

L. Cecchinato [9] et.al take flow rate through four capillary tubes of various lengths, diameters and materials was measured in a test rig. Each capillary tube was tested with

inlet pressure varying from 7.5 MPa to 11 MPa and inlet temperature from 20 ^{0}Cto40^{0}C. Outlet pressure varied from 1.5 MPa to 3 MPa. The experimental results were validated against different numerical and approximate analytical solutions of the capillary tube equations.

Chen and Gu [10] have developed a diabatic model for transcritical refrigeration cycle. In the analysis of the flow of CO_2 through diabatic capillary tube, the capillary tube has been divided into three distinct regions, viz., supercritical flow region, the transcritical flow region and subcritical two-phase flow. The model was based on the fundamental conservation equations of mass momentum and energy. These equations have been solved iteratively. A new transcritical refrigeration cycle was proposed, combining the characteristics of heat transfer and expansion into one capillary tube by assembling the capillary tube in an accumulator or suction line. Choking phenomenon of the flow through capillary tube was also investigated.

Agrawal and Bhattacharyya [11] presents a Performance evaluation of a non-adiabatic capillary tube in a transcriticalCO2 heat pump cycle A numerical model based on conservative laws of mass ,momentum and energy of refrigerant flow form. The characteristics were investigated by varying thermodynamics and geometric parameters. the model was validated with Y. Chen, J. Gu [10] results.

Neeraj Agrawal, Souvik Bhattacharyya [12] a steady state simulation model has been developed to evaluate the performance of a capillary tube based transcritical CO2 heat pump system for simultaneous heating and cooling at 73^{0}C and 4^{0}C, respectively against optimized expansion valve systems. Capillary tubes of various configurations having diameters of 1.4, 1.5 and 1.6 mm along with internal surface roughness of 0.001– 0.003 mm have been tested to obtain the optimum design and operating conditions.

Neeraj Agrawal, Souvik Bhattacharyya [13] Tests were conducted with two stainless steel capillary tubes having specifications of ID=1.71mm, L=2.95m, surface roughness=3.92mm and ID=1.42mm, L=1.0 m, surface roughness=5.76mm. System performance is significantly influenced by gas cooler water inlet temperature, whereas the effect of water flow rate on system performance is modest. An optimum charge is also recorded at which the system yields the best COP with a capillary tube. Performance deterioration is more severe at undercharged condition than at overcharged condition

B. Xu, P.K. Bansal [14] developed a homogeneous model to simulate the refrigerant flow behavior in a non-adiabatic capillary tube. It is concluded that the flow behaviour depends on relative influence of heat transfer and frictional effects.

P.K. Bansal, B. Xu [15] presented a parametric study of refrigerant flow behaviour in a non-adiabatic capillary tube. Effects of various geometric and thermodynamic parameters on the refrigerant flow characteristics were reported. Very few studies were carried out on flow behavior in non-adiabatic tubes carbon dioxide cycles in the open literature.

Melo et al. [16] have conducted the experiments on the concentric diabatic capillary tubes by using R-600a refrigerant. Based on their experimental results, they have proposed separate empirical correlations for the determination of refrigerant mass flow through the capillary tube and the suction line outlet temperature. Unlike earlier experimental research works on diabatic capillary tubes, the two heat exchange lengths, 1.0 m and 2.2 m and two suction line diameters, 6.3 mm and 7.86 mm have been used in the investigation.

Xu and Bansal [17] have developed a numerical model by dividing the flow domain into numerous control volumes along the capillary tubes. They observed that when the effect of heat transfer is stronger than that of the pressure drop the refrigerant tends to condense within the heat exchanger region whereas if the pressure drop effect is stronger the refrigerant flashes within the heat exchanger. Bansal and Xu [18] have conducted parametric study on the flow of R-134a in diabatic capillary tube. It has been found that the diabatic capillary flow characteristic is discontinuous in some situations and the discontinuity is caused by the re-condensation of the refrigerant within the heat exchange region.

Yang and Bansal [19] have proposed a model for the flow of refrigerant through a diabatic capillary tube. They have found that the rate of heat transfer from the capillary tube to suction decreases by 8–10% if the inlet diabatic arrangement is considered, compared to adiabatic inlet conditions. Bansal and Yang [20] have presented a numerical simulation model to investigate the reverse heat transfer phenomena. They have concluded that with the choked flow condition occurring at the capillary outlet, a longer heat exchanger length is responsible for the heat transfer. Bansal and Yang [21, 22] presented performance of a CL-SLHX with HFC-134a and HC-600a refrigerants with respect to various thermodynamic and geometric parameters Although bulk of the capillary tube studies were engaged to subcritical refrigeration cycles with HFCs and hydrocarbon refrigerants, very little effort has been spared to understand the flow characteristics of adiabatic and non-adiabatic capillary tube in a transcritical CO_2 heat pump cycle.

It is observed that the majority of such studies has concentrated on the HFCs, hydrocarbon refrigerants and their mixtures. Relatively, much less information is currently available in the open literature on flow characteristics of capillary tube with CO_2 as a refrigerant. Tube geometry (diameter and length) at a given operating ondition is the main concern in the design of a capillary tube. In redesigning the system using alternative refrigerants, therefore, it is vital and critical to select a capillary tube which is compatible with the system Components. it is observed that previous researcher take various combinations of length, diameter of capillary tube for CO_2 refrigerant. So the objective of the present work is used to To optimise the performance of a CO_2 transcritical heat pump cycle by analyzing the flow behaviour in capillary tube under different geometric and thermodynamic boundary conditions.

3. CONCLUSION

It is understood from the literature survey that most of the researchers made research on CO2 transcritical system and very few research had done on the flow behaviour of capillary tube. It is challenging to analyse two phase flow in capillary tube and study the flow behaviour in capillary tube in a CO_2 transcritical heat pump cycle under different geometric and thermodynamic boundary conditions to optimise the system.

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