Study of Adiabatic Capillary Tube in Carbon Dioxide Refrigeration System

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Abstract- A review of the literature on the flow of various refrigerants like R134a, R22, R410a, and CO_2 through the straight adiabatic capillary tubes has been discussed in this paper. Since CO_2 is natural and environment friendly study has concentrated on this refrigerant. The paper presents the correlation among thermodynamic properties of CO_2 refrigerant and geometric properties (length and diameter) of adiabatic Capillary tube. The paper provides information about the selection of capillary tube for optimum performance of CO_2 refrigerant

Keywords – Capillary tube; Transcritical CO_2; Adiabatic; Correlation

I. INTRODUCTION

Environmental control is one of the major requirements of a healthy and non-pollutant living condition. Hence the sagacious strategy would be to use advanced technologies that are eco-friendly. Refrigeration, heat pump and air conditioning systems play an important role in modern civilization. Over the last few decades, refrigeration, air conditioning and heat pump industries have seen major changes caused by restrictions on specific refrigerant use due to their detrimental effects on our climate. Two successive international agreements; Montreal Protocol and Kyoto Protocol were introduced to combat the twin menace of ozone layer depletion and global warming. The Montreal Protocol (MP) on substances that deplete the ozone layer was adopted in September 1987 to phase-out the use of Ozone Depleting Substances (ODSs) within a fixed time period[1-3]. Ozone depleting Potential (ODP), a comparative measuring index, is fraction of the ozone depleting potency of a substance compared to that of R11 or R12. The Kyoto Protocol (KP) was adopted at the third conference of the parties to the United Nations Framework Convention on Climate Change (UNFCCC) in December 1997, which has imposed restrictions on refrigerants on the basis of GWP. Global warming Potential (GWP) is an index that relates the potency of greenhouse gas to the CO_2emission over a 100-year period. The CFC refrigerants, although once considered to be the best refrigerants, were abandoned due to high ODP. The chlorine free synthetic refrigerants based on HFCs, which were taken as a permanent replacement of CFCs, are also in the list of regulated substances due to their considerably high GWP.In such context the carbon dioxide was revived as a natural refrigerant since it is the environmentally benign nature and largely beneficial heat transfer and safety characteristics compared to currently used refrigerants. Flow inside the capillary tube of a refrigeration system is complex in nature. Numerous combinations of bore and length can be provided to obtain the desired flow restriction. Tube geometry (diameter and length) at a given operating condition 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. In a transcritical CO_2 refrigeration cycle where pressure and temperature are two independent parameters unlike the conventional subcritical cycle, the flow factor of the expansion valve determines the gas cooler pressure, which is no longer related to the temperature of the heat transfer process[4]. Therefore, it is desirable to investigate the flow characteristics in the capillary tube for carbon dioxide refrigerant, where the flow is transcritical in nature.

A significant volume of work has been carried out by several researchers on flow Characterization of adiabatic capillary tube with halocarbon and hydrocarbon refrigerants.

Bansal and Rupasinghe(1998)[5]	Developed a homogeneous two -phase flow model to study the Performance of adiabatic capillary tubes for HFC- 134a[5]

Jung et al (1999)[6]	Modeled the pressure drop through a capillary tube to predict its size in residential air conditioners for HCFC22 and its alternatives, HFC134a, R407C and R410A.
Wong and Ooi (1996)[7]	Developed a homogeneous two-phase flow model to simulate the flow characteristics of R12 and R134a.
Bittle and Pate (1996)[8]	Presented a theoretical model for predicting adiabatic capillary tube performance for R-134a, R-22, R-152a, and R-410A under different flow rates and capillary tube length and diameter.
Sami and Maltais (2000)[9]	Proposed a numerical model to predict the capillary behaviour for HCFC-22 alternatives such as R-410A, R-410B and R-407C under different flow regimes
Kritsadathikarn et al.(2002) [10]	Presented a numerical study on the local pressure distribution of some common traditional and alternative refrigerants R12,R134a,R409A and R409A.
Gu et al. (2003)[11]	Analyzed and modelled an adiabatic capillary tube for the azeotropic-Mixed refrigerant R407C.
Bansal and Wang(2004)[12]	Presented a homogeneous simulation model for choked flow conditions for R134a and R600a in adiabatic capillary tubes.
K.Madsen et al.(2005)[13]	Formed and analysied Numerical Model for CO_2 refrigerants with capillary diameter 1 to 2 mm and Capillary length 0.5and 4m
N.Agrawal and S. Bhattacharyya.(2007)[14]	Anlaysed a Numerical Model for CO_2 refrigerants with capillary diameter 1 to 1.3 mm and Capillary length 1.5,1.6 and 2.0
N.Agrawal and S. Bhattacharyya.(2008)[15]	Numerical Model for CO_2 refrigerants with capillary diameter 1.4 to 1.6 mm and Capillary length 1.4,2.1 and 3.0 and surface roughness 0.001 to 0.003mm

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. The correlations are yet not formed. So the objective of the present work is to form correlations for various capillary tube geometry (diameter and length etc.)

II. MATHEMATICAL MODEL

The capillary tube can be divided into three distinct flow regions, namely, the supercritical flow region 1–2, transcritical flow region 2–3 and the subcritical flow region 3–4 as shown in Figure 1.Point '2' lies on the critical temperature line (Figure 1). Therefore, in the region 2–3, the fluid is considered as a subcooled liquid. In the supercritical and transcritical single-phase region, temperature does not remain constant unlike subcritical refrigeration cycle due to unique shape of temperature lines. As a result, density is not constant giving rise to compressible flow in the entire length of the capillary.

Total tube length is expressed as: $L=L_{\mathbf{sup}}+L_{\mathbf{subliq}}+L_{\mathbf{tp}}$ The expansion process from point 1 to 4 is shown in Figure 1 on the pressure–enthalpy plane cycle plot. The capillary tube flow model is developed employing the The model is set around fundamental equations of conservation of mass, energy and momentum and it incorporates variation in property values.

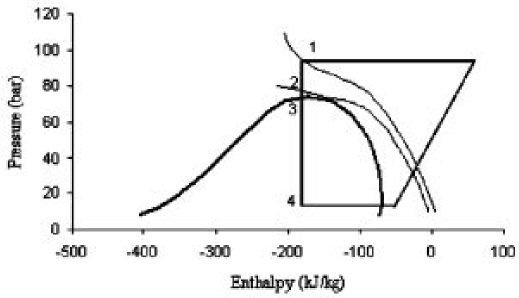


Figure No. 1Adiabatic capillary tube showing different flow regions and corresponding cycle on the P–h plane

Following assumptions:

- Straight tube with constant inner diameter and roughness.
- Homogeneous and one-dimensional flow through the tube.
- Flow is adiabatic with no work done.
- Thermodynamic equilibrium prevails in the system.
- Refrigerant is free of oil.
- Flow through the tube is fully developed turbulent flow.
- Entrance losses are negligible.

The model is set around fundamental equations of conservation of mass, energy and momentum and it incorporates variation in property values. The subsequent parametric study includes the effect of various design parameters, namely, tube diameter, tube relative roughness and refrigerant flow rate. Single phase friction can be calculated from the Churchill correlation factor, while Lin and Churchill correlation are used to find two phase friction factor and viscosity find by four methods viz. Mcadams model, cichitti model, dukler model and Lin Model are used

Capillary tube with diameters 1and 2mm and lengths of 0.5 to 2m are employed. The entire system is modeled based on the energy balance of individual components

III. Result And Discussion

Capillary tube geometry(diameter and length)correlation are reported here. The capillary tube diameter ranging from 1 to 2mm, Length is 0.5 to 2 m and surface roughness is 1.0 to 0.0015mm.Mass flow varied from 0.01 to 0.018 kgs^{-1}

Figure1 and 2 shows the pressure and temperature variation along the capillary tube consider in Lin et al. and McAdams as the friction factor and viscosity model, respectively. As the capillary length increases, the pressure and temperature decrease fairly linearly up to saturation point (i.e. for the single-phase region). On inception of vapourization, the pressure drop rapidly in a nonlinear trend. It has correlation between Pressure(y) and Distance from capillary tube(x) is as $y=-34.01x+100.0$ with standard deviation value ranging from -1 to +1 and R-square value is 0.998The correlation between Temperature (y) and Distance from capillary tube(x) is as $y=-12.94x^3+11.10x^2-10.18+312.8$ with standard deviation value ranging from -2 to +1.5 and R-square value is 0.999

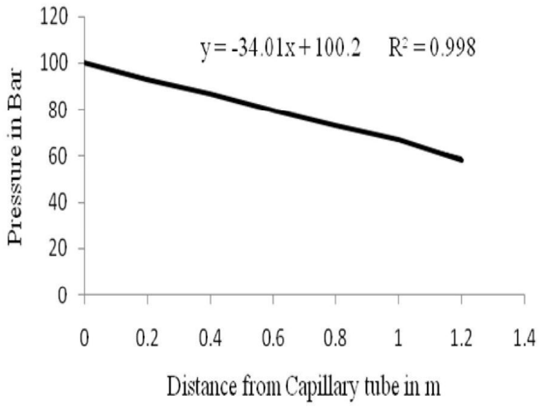


Fig. 1 Pressure variation along the capillary tube

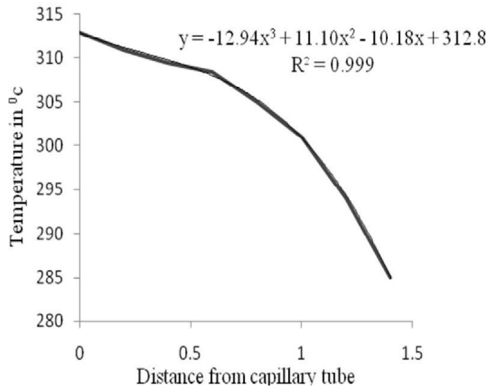


Fig. 2 Temperature variation along the capillary tube

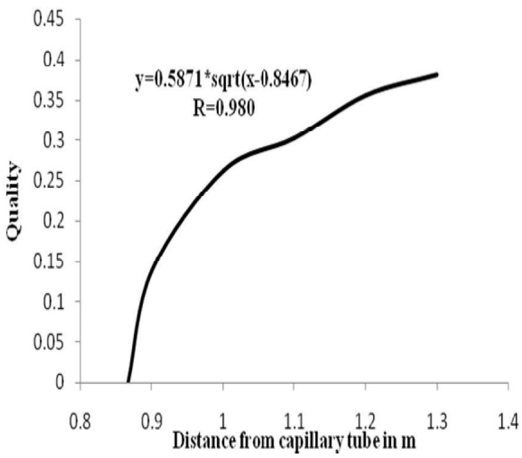


Fig.3 Variation of CO_2 quality along the capillary tube

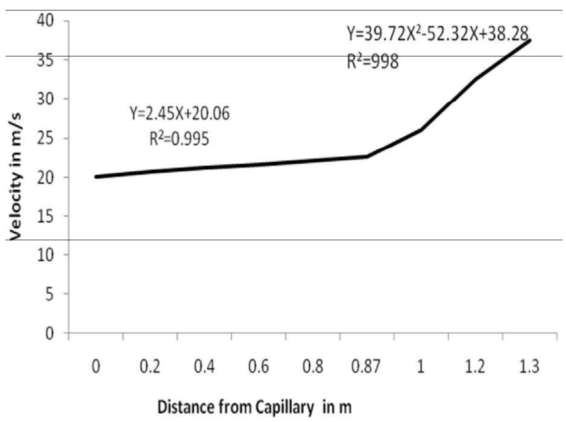
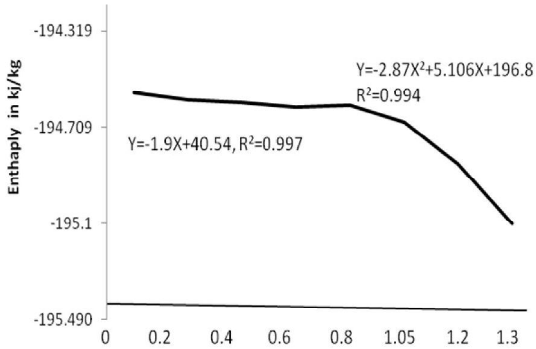


Fig.4 Variation of refrigerant velocity along the capillary length

Variation of quality along the tube length is exhibited in Figure 3. Initially, quality increases at a faster rate since the increments of length needed to drop the saturation pressure become progressively smaller. Further, the inception of vapourization is near the critical point due to unique thermodynamic properties of CO_2 where constant dryness fraction lines are in close proximity unlike in subcritical cycles where the inception of vaporization is away from the critical point. It has correlation between quality (y) and Distance from capillary tube(x) is as y=0.5871*sqrt(x-0.8467) with standard deviation value ranging from -2 to +2 and R-square value is 0.98

Figure 4 and 5 exhibits variation in velocity and enthalpy along the tube length(X). The variations are quite modest up to the saturation point (i.e. in single-phase zone).with linear correlation Velocity=Y=2.45X+20.06 with R^2 value0.995 and standard deviation -1.1to +1.1.while Enthalpy=Y=-1.9X+40.54 with R^2 value0.997 and standard deviation -1to +1 However, they vary sharply in the two-phase region due to the presence of vapour phase. Owing to high vapour density of CO_2, acceleration of the fluid in two-phase region is moderate compared to that for conventional refrigerants. With Non linear Correlation Velocity =Y=39.72X^2-52.32X+38.28 with R^2 value0.998 and standard deviation -1to +1.1.And Enthalpy=Y=2.87X^2-5.1062X+19608 with R^2 value0.995 and standard deviation -1.15to +1.15



Distance from Capillary tube in m

Fig.5 Variation of Enthalpy along the capillary tube

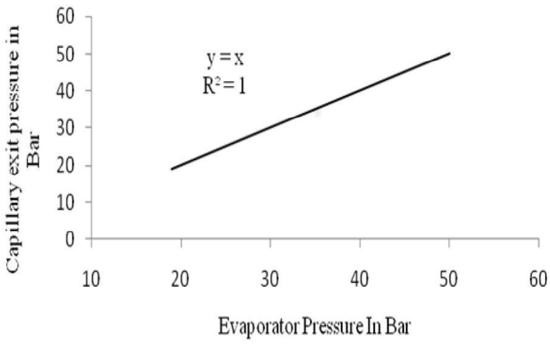


Fig.6 Variation of Capillary exit pressure along the capillary length

Figure 6 and 7 shows variation of the exit pressure nad mass flow rate with evaporating pressure through a capillary tube of 1.55 m length. with linear correlation Capillary exit Pressure =Y=X with R^2 value1 and standard deviation 0.

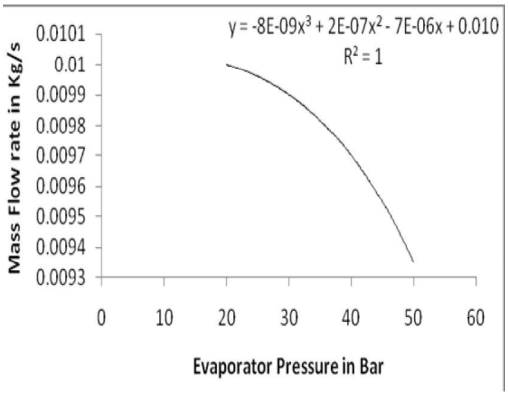


Fig.5 Variation of Mass flow rate along the Evaporating pressure

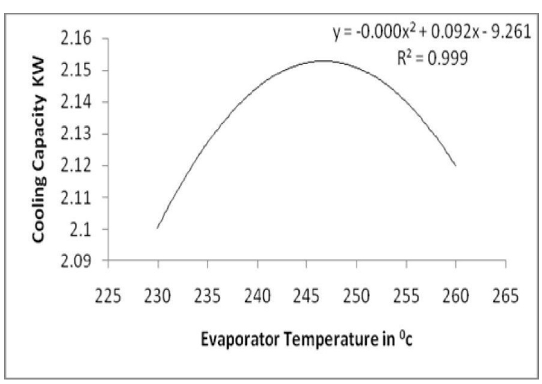
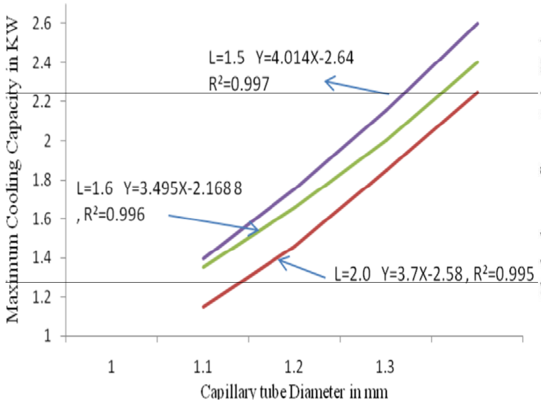
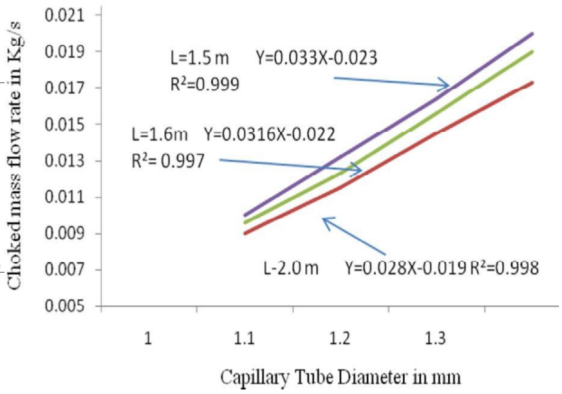


Fig.6 Variation of cooling capacity along the Evaporating pressure

Figure 7 that the absolute change in the refrigeration mass flow rate with the evaporating pressure is marginal. Mass flow rate increases only by 7.5%, as the evaporator pressure decreases by 62.3% from 50 .67 bar (unchoked region) to 19.0 bar (choked region). Hence, when the flow is steady under fixed geometric and inlet conditions, the refrigeration mass flow rate is almost equal to its choked value. it shows correlation $Y=-0.000000008X^3+0.0000002X^2-0.000007X+0.010$ with R^2 value1 and standard deviation 0.

Figure 8 shows the variation of cooling capacity with evaporator temperature for various capillary tube diameters. It can be observed that a lower evaporator temperature brings about a higher cooling capacity, which is inconsistent with traditional refrigeration cycle behaviour. However, cooling capacity decreases after reaching a peak value. This counter-intuitive behaviour is due to the peculiar thermodynamic properties of CO_2.it follows Correlation Cooling capacity $Y= -0.000X^2+0.092X-9.261$ with R^2 value0.999 and standard deviation -0.6 to +0.6





Maximum cooling capacity and choked mass flow rate of refrigerant are shown in Figures 11 and 12, where the capillary tube diameter varies from 1.0 to 1.3 mm and capillary tube length varies from 1.5 to 2.0 m. The trends exhibit that for a given capillary tube diameter, higher cooling capacity can be achieved at lower capillary length due to higher choked mass flow rate of the refrigerant.The Correlation for L=2.0,L=1.6 and L=1.5 is Maximum Cooling Capacity Y=3.7X-2.58 with R^2 value0.995,Y=3.495X-2.1688 with R^2 value0.996 and Y=4.014X-2.64 with R^2 value0.995 respectively

For a given capillary tube length, the cooling capacity almost doubles as the tube diameter increases from 1.0 to 1.3 mm. There is a marginal variation in evaporator pressure by changing the tube diameter for a given tube length and as expected COP remains almost constant

IV. CONCLUSIONS

Analysis of a capillary tube using CO_2 as a refrigerant is different from other refrigerants as the cycle is a transcritical one. Vapour fraction is higher as the inception of vapourization is near the critical point. Variation of pressure and temperature along the tube and calculation of friction factor are unaffected by the choice of viscosity model unlike that in R22 and R134a.

Occurrence of choking in a capillary tube is analysed on the basis of negative entropy change. Before choking occurs, the mass flow rate keeps increasing as the back pressure (or evaporating pressure) is reduced. For a fixed length of capillary, beyond choked flow condition, the mass flow does not change with evaporator pressure. However, in steady flow, the system operates at choked flow conditions since the refrigerant mass flow rate is almost equal to its choked value. It indicates that capillary tube does not correct the flow conditions at varying load conditions.

Due to the peculiar thermodynamic properties of CO_2, a lower evaporating temperature yields larger cooling capacity somewhat counter-intuitively. For a given capillary tube, there is an optimum evaporator temperature, which yields maximum cooling capacity. Without affecting the system COP, higher cooling capacity can be achieved with a relatively larger diameter capillary tube for a given tube length. The analysis presented here has the correlation between various physical parameters which can act as a guideline to select a proper combination of length and diameter of a capillary tube for optimum performance of a transcritical CO_2 refrigeration system.

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