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NUMERICAL SIMULATION OF REFRIGERANT FLOW AND HEAT TRANSFER IN A NON-ADIABATIC CAPILLARY TUBE IN REFRIGERATOR

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Abstract - A numerical simulation model is developed to design an efficient Non-Adiabatic Capillary Tube (NACT) heat exchanger to obtain specific vapor quality at its outlet. Refrigerant flow and heat transfer inside heat exchanger has been modeled through a set of governing equation by conserving mass, momentum and energy. The model analyses three discrete regions of capillary tube namely i) adiabatic inlet region, ii) heat exchanger region and iii) adiabatic exit region. Governing physical equations are considered in these regions based on single-phase or two-phase flow inside capillary tube. The effect of metastability has been incorporated in the model. Finite difference method is used for solution of governing equations to obtain pressure, temperature and vapor volume fraction in capillary tube and temperature of suction line. The model is validated with experimental results available in the literature. Parametric analysis has been performed to study the effect of diameter of capillary tube and the degree of sub-cooling on performance parameters. Concentric and lateral capillary tube heat exchanger configurations are compared. It has been found that lateral heat exchanger configuration gives better heat transfer performance.

Keywords - Refrigeration, Capillary Tube Heat Exchanger, Nact, Metastability

I. INTRODUCTION

Capillary tube is an expansion device used in refrigeration and air conditioning. Refrigerant undergoes expansion in capillary tube connected between condenser and evaporator. A capillary tube without heat exchanger arrangement is called Adiabatic Capillary Tube (ACT). In ACT, refrigerant expands adiabatically and enters the two-phase domain with higher vapor content. In alternate arrangement, suction line of compressor is in contact with capillary tube forming a Non-Adiabatic Capillary Tube (NACT) heat exchanger. NACT results in lower vapor quality at the outlet of the refrigerator due to heat loss to suction line fluid. This results in improvement in COP of the system due to reduced enthalpy at evaporator inlet. Design and verification of a NACT heat exchanger performance through prototyping & testinginvolveslead time for physical hardware, scheduling and running the tests apart fromthe cost implications in the respective activities. Therefore, a digital prototype of NACT heat exchanger is developed to accelerate product design and gain physical insights. Initially a 3D numerical simulation model is developed in commercial analysis software ANSYS Fluent®; however, it is later replaced with an in-house 1D solver to reduce turnaround time. Literature study is carried out for validating developed model before deploying it for design of heat exchanger. Mendoncaet. al. [1] experimentally measured the temperature profile in capillary tube and suction line in lateral heat exchanger arrangement. Meloet. al. [2] measured the same from experimental study where capillary tube was concentrically inside the suction line. Prajapati et al. [3] applied three-dimensional computational fluid dynamics (CFD) approach to find the onset of vaporization with R-134 refrigerant in an adiabatic capillary tube and observed the location for flashing.Chen and Lin [4] experimentally observed metastable flow of R-134a refrigerant. Garcia-Valladares [5] studied numerically the effect of metastability in the flow and heat transfer with the help of correlation of metastable pressure of vaporization given by Chen and Lin [4].

In this present study, fluid flow and heat transfer in NACT is modeled from conservation equations considering the effect of metastability. Model results are validated with test data published in literature with good accuracy. A parametric study is performed to determine effect of design parameters on heat exchange process. This helped to determine design parameters to achieve desired heat exchanger performance and specified quality of refrigerant at capillary tube outlet. Concentric and lateral capillary tube heat exchanger arrangement is analyzed with the developed model. The lateral capillary tube arrangement gives better heat transfer performance which is in line with published literature.

II. MATHEMATICAL MODELING OF NACT

NACThasa heat exchanger arrangement with suction line as shown in Fig. 1. Heat transfer from capillary tube to suction line results in enthalpy drop of the liquidrefrigerant. Based on the configuration of heat transfer, NACT heat exchanger is divided in three sub domains as below

(i) Adiabatic entry region (A-B in Fig. 2)
(ii) Heat exchanger region (B-C in Fig.2)

(iii) Adiabatic exit region (C-D in Fig. 2)

In each of the above mentioned sub domains, governing equations have been derived by conserving mass, momentum and energy of the refrigerant flowing through it.

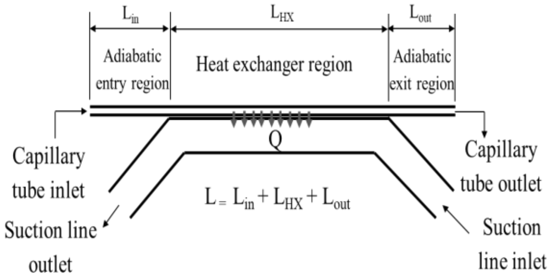


Fig. 1. Schematic of non-adiabatic capillary tube

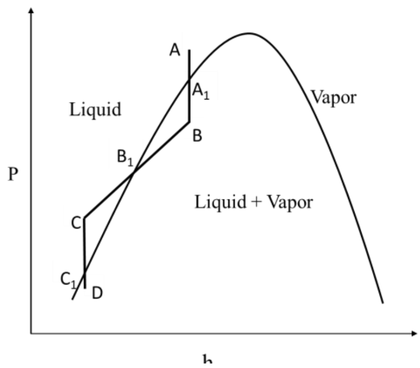


Fig. 2.P-h diagram of non-adiabatic capillary tube

2.1.Adiabatic entry region

Adiabatic entry region starts from condenser and continues tillthe start of heat exchanger region. Capillary tube and Suction line are physically separated. This adiabatic flow can be single phase liquid flow (region A-A_1 in Fig.2) or two-phase mixture (region A_1-B in Fig.2). Flow and heat transfer physics will be governed by the following equations.

(i) Conservation of mass:$\dot{m} = \text{constant}$

(ii) Conservation of Momentum:

$$-\frac{dP}{dz} = f\frac{vG^2}{2D_c} + \frac{G^2 dv}{dz}$$

Pressure drop consists of two parts, first due to friction at the walls and later from the inertial pressure drop. Inertial loss will be insignificant due to negligible change in density in single phase flows.

(iii) Conservation of Energy:$\frac{dh}{dz} = -\frac{G_c^2}{2}\frac{dv^2}{dz}$

As there is no heat transfer in this domain,loss of enthalpy comes only from work done by inertial force.

2.2.Heat exchanger region

In this region heat is extracted from the capillary tube to the suction line vapor. Refrigerant in capillary tube can be two-phase mixture (region B-B1 in Fig.2) or single phase (region B1-C in Fig.2) liquid depending on the rate of heat extraction. The governing equation for mass and momentum conservation remains same as in adiabatic entry region. The energy conservation equation is given below:

(i) Conservation of Energy:

$$\frac{dh}{dz} = -\frac{U_c \pi D_c (T_c - T_s)}{m_c} - \frac{G_c^2}{2}\frac{dv^2}{dz}$$

Rate of change of enthalpy consists of two parts: heat extraction by suction vapor and loss of energy due to inertial work done. In single phase heat transfer, enthalpy drop due to inertial work diminishes.

2.3.Adiabatic exit region

The flow and heat transfer in adiabatic exit region islike adiabatic entry region. There will be no heat transfer from the capillary tube. It can be single phase flow (region C-C1 in Fig.2)or two-phase flow (region C1-Din Fig.2). The governing equationsarelike adiabatic entry region.

III. SOLUTION PROCEDURE

Governing equations are discretized on one dimensional grid of the capillary tube and suction line. Solution of governing equations on grid is obtained with numerical technique. Taking a boundary condition at the start of the domain, solution for mass, momentum and energy are obtained for next grid points. Gradients for grid point are calculated with the help of central difference scheme using the values at adjacent grid points. The solution algorithm is shown in Fig.3.

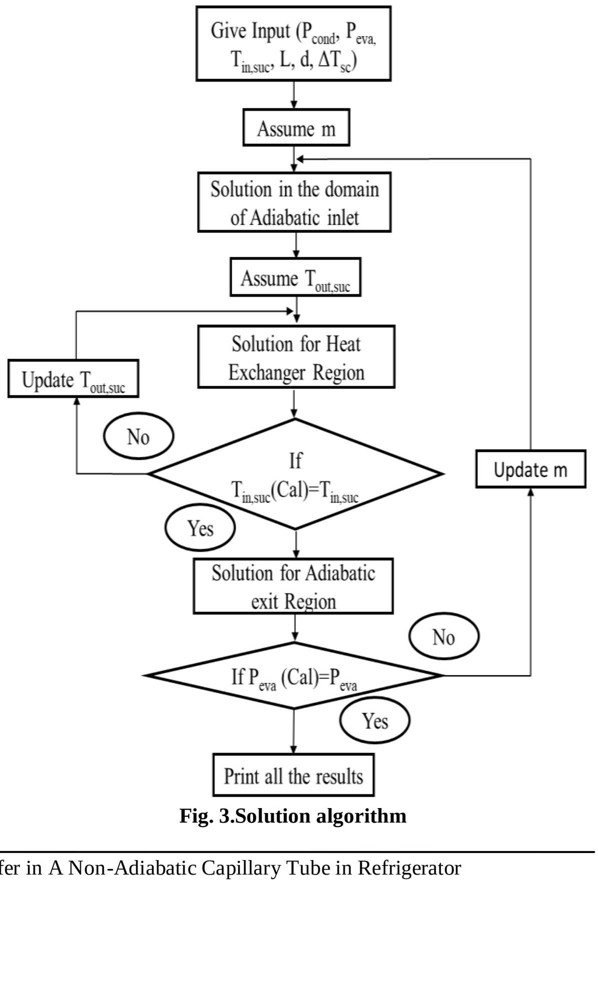


Fig. 3.Solution algorithm

IV. VALIDATION OF SIMULATION RESULTS

Temperature distribution in concentric internal capillary tube with refrigerant R-134a is compared with the experimental results from Meloet. al. in Fig. 4. There is good agreement between experimental results and numerical results of the present case for two different condenser pressures. Fig. 5 shows comparison of the model results with experimental results of Mendoncaet. al. [4] for lateral capillary tube configuration. Three regions of the capillary tube namely i) adiabatic inlet, ii) heat exchanger and iii) adiabatic outlet are represented in Fig.4.

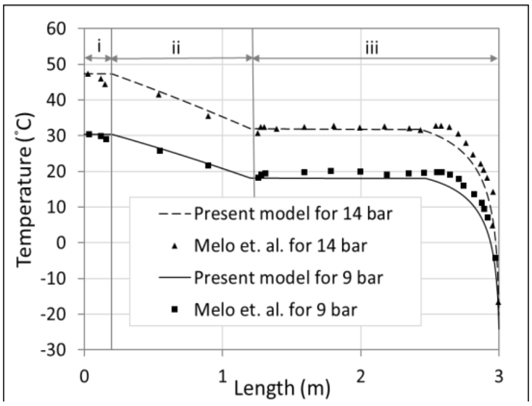


Fig. 4. Validation temperature profile with experimental results given in Meloet. al. [4]

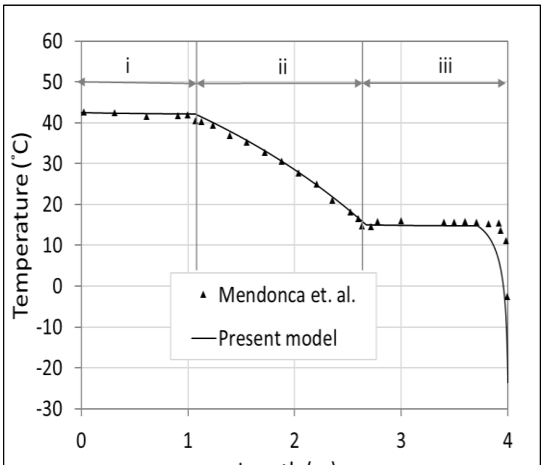


Fig. 5. Validation temperature profile with Mendonca et. al.[4]

V. RESULTS AND DISCUSSION

5.1. Effect Of Metastability On Onset Of Vaporization

Metastability is the property of refrigerant which causes onset of vaporization of refrigerant lower than saturation pressure. Refrigerant can stay in single phase at its saturation pressure. The length of single phase flow below saturation pressure is called as metastable region. Fig. 6 represents the effect of metastability on volume fraction for refrigerant R134 where suction tube is laterally connected with capillary tube.The increase in volume fraction in adiabatic exit region starts little late which confirms late onset of vaporization with metastable condition.

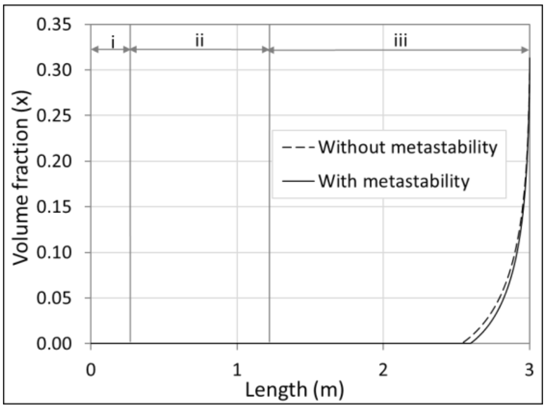


Fig. 6. Effect of metastability on vapor volume fraction

5.2. Comparison Ofconcentric And Lateral Capillary Tube Configuration

Lateral capillary tube heat exchanger arrangement is compared with concentric capillary tube to investigate heat exchange performance. Comparison is carried out for similar geometric dimensions of the tubes and similar operating conditions. Temperature drop in capillary tube refrigerant in lateral tube heat exchanger is more than that of concentric tube heat exchanger as shown in Fig. 7. In lateral configuration heat transfer is more due to low thermal resistance. Because in lateral case entire outer area of suction line tube is available for heat transfer whereas in the concentric case heat transfer happens only through outer surface of capillary tube which is significantly lower than outer surface of suction line.This indicates that lateral capillary tube arrangement is more effective that concentric capillary tube arrangement due to lower thermal resistance.

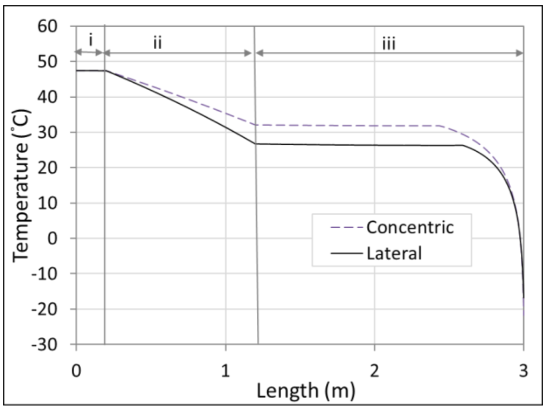


Fig. 7.Temperature distribution of capillary tube for concentric and lateral configuration of heat exchanger

5.3. Parametric Analysis

5.3.1. Effect Of Degree Of Sub-Cooling

Effect of degree of sub-cooling on temperature distribution is evaluated with lateral capillary tube configuration. R-134a is considered as refrigerant with condenser pressure 14 bar and evaporator pressure of 1 bar.Increase in degree of sub-cooling reduces temperature difference between capillary tube and suction line. This results in reduction in suction line outlet temperature and lower mass fraction of vapor at capillary tube outlet as shown in Fig. 8.

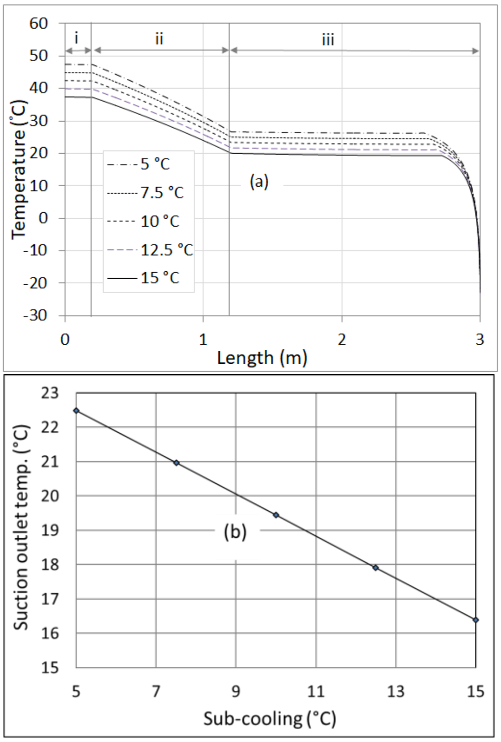
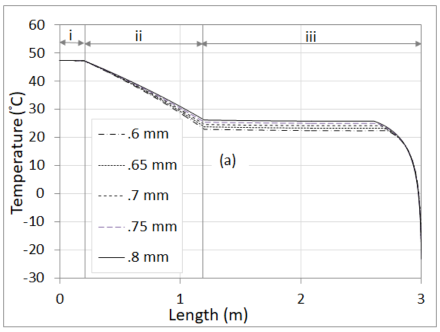


Fig. 8. Effect of degree on sub-cooling on (a) temperature profile and (b) suction line outlet temperature

5.3.2. Effect Capillary Tube Diameter

Effect of capillary tube diameter on temperature profile in suction line and capillary tube in lateral capillary tube configuration is shown in Fig. 9. Refrigerant R-134a with condenser pressure of 14 bar and evaporator pressure of 1bar is considered. It is observed that onset of vaporization approaches more upstream as the diameter increases. The rate of pressure drop increases as the diameter of capillary tube decreases as surface area to volume ratio of capillary tube increases and that gives more viscous pressure drop. For the same reason heat transfer in heat exchanger area increases and is evident from more temperature drop in capillary tube and high suction line outlet temperature with smaller capillary tube diameter.



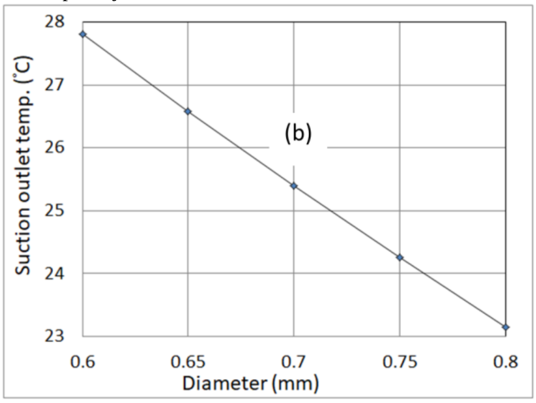


Fig. 9.Effect of capillary tube diameter on (a) temperature profile and (b) suction line outlet temperature

VI. CONCLUSION

In present work, numerical simulation of flow and heat transfer of refrigerant through a non-adiabatic capillary tube has been performed considering meta stable vaporization of refrigerant. The results reveal that onset of vaporization starts further downstream when the effect of metast ability is considered and corresponding mass flowrate of refrigerant increases. It has also been observed that the heat exchanger configuration where capillary tube is placed laterally outside of suction tubes gives higher heat transfer performance compared to concentric configuration. The results further reveal that when the pressure of condenser and evaporator are kept constant, with increase of degree of sub-cooling at the condenser outlet gives delay in onset of vaporization, mass flow rate increases and suction tube outlet temperature increases. The effect of diameter of capillary tube is also studied for the case of constant condenser and evaporator pressure and for a fixed degree of sub-cooling at condenser outlet. The results suggest that with increase in diameter of capillary tube onset of vaporization starts moving upstream, heat transfer rate decreases as temperature drop in in heat exchanger drops and suction line outlet temperature reduces and mass flowrate of refrigerant increases.

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REFRENCE

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SUBSCRIPTS

c = capillary tube
cal = calculated
cond = condenser
eva = evaporator
HX = heat exchanger
in = inlet
NACT = Non-Adiabatic Capillary Tube
out = outlet
sc = sub cooling
suc = suction line
sp =single phase
tp = two phase

LIST OF SYMBOLS

d = diameter of capillary tube (m)
L = length of capillary tube (m)
m = mass flow rate of capillary tube (kg/s)
P = pressure (Pa)
T = temperature (^{0}C)

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