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NUMERICAL SIMULATION OF THE FLOW OF NATURAL[1] REFRIGERANTS IN A CAPILLARY TUBE

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ABSTRACT

Traditionally, capillary tubes are designed for CFC12 and HCFC22 as working fluids. Due to the public concerns on the depletion of the ozone layer and greenhouse effect, CFCs and HCFCs are falling into disuse. As a result, a number of natural refrigerants including HC600a, HC290 and a mixture of HC290 and HC600a.etc, have emerged as promising CFC-free alternatives to CFCs. Characteristic of the flow of such natural refrigerants in a capillary is analyzed, and a adiabatic homogenous model accounting for the metastable phenomenon is established to simulated the flow of natural refrigerants in a capillary in this paper. The results agree well with the experimental data that verified the model established in this paper.

NOMENCLATURE

A : area
G : mass flow rate
l : length
v : specific volume
P : pressure
T : temperature
μ : dynamic viscosity
ζ : resistance coefficient
d : diameter
h: specific enthalpy
k : borltzman constant
m: mass flux
x : quality
Φ : gasification coefficient
σ : surface tension
υ : kinetic viscosity

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Subscript

f : liquid g : vapor

INTRODUCTION

Capillary tube is widely used as a throttling component in small refrigeration apparatus such as domestic refrigerator, air-conditioners, heat pumps, etc, for its simple configuration, high reliability and low price. However, the ability of capillary tube to adjust the mass flow rate is limited and the mass flow rate cannot be adjusted according to the system load to a great extent.

As for a given refrigeration equipment, the capillary tube has optimum inner diameter and length. If there were some departure of the actual size from the optimum one, the performance of the system would be affected markedly. Therefore, it is extremely important to set suitable geometric dimension for the capillary tube in course of designing such refrigeration apparatus.

Nowadays, during the process of designing of such refrigeration apparatus, first, diagram and analogy method are used to estimate inner diameter and length of capillary tube, then experimental method are used to adjust the size of capillary. In addition, the above methods are suitable for such refrigerants as CFC12、HCFC22 and CFC502[1] [2]. Due to the increasing public concern about ozonosphere depletion and greenhouse effect, CFCs and HCFCs are falling into disuse. As a result, a number of natural refrigerants including HC600a, HC290 and a mixture of HC290 and HC600a.etc, have emerged as promising CFC free alternatives to CFCs. In this paper, a mathematical model is established to simulate the flow of new refrigerants in capillary tubes, in this model, the effect of metastable phenomenon on the calculation of the size of the capillary is accounted.

SELECTION OF NATURAL REFRIGERANTS

During the selection process of natural refrigerants, refrigeration capacity and energy consumption are two most important criteria in addition to environmental indexes. On the premise that there is no or only a little modification to the configuration dimension of compressors, the selection criterion is that such properties as standard boiling point and refrigeration capacity of the selected refrigerants should be similar to their predecessors. With consideration of possibility of the application of the natural refrigerants, the thermodynamic properties of some HFCs and natural refrigerants are listed in Table. 1, that can be used as a reference for the selection of natural refrigerants.

Table 1：Thermodynamic properties of refrigerants

	CFC12	HFC134a	HC290	HC600a
ODP	1.0	0	0	0
GWP	3.1	0.27	0.01	0.01
Molecular weight	120.9	102.0	44.1	58.1
Standard boiling point (℃)	-29.8	-26.1	-42.1	-11.6
Critical temperature (℃)	112.0	101.1	96.7	134.7
Condensation pressure (+40 ℃，bar)	10.088	10.164	15.89	5.319

Evaporation pressure (-30℃, bar)	1.0041	0.8436	1.85	0.468
Theoretical exhaust temperature (℃)	120-125	125-130	105-110	100-105
Lubricating oil	Mineral oil	Ester oil	Mineral oil	Mineral oil
Sensitivity to impurity	Sensitive	Highly sensitive	Sensitive	Sensitive
Water dissolvability	Scarcely any	Very dissolvable	Scarcely any	Scarcely any
Request for vacuum degree	Average	High	Average	Average
Material compatibility	Good	Bad	Good	Good

HC290, HC 600a and the blend of HC290 and HC 600a all can alternate CFC12. Among these refrigerants, the evaporation pressure of HC290 is higher than that of CFC12 and the evaporation pressure of HC600a is lower than that of CFC12. However, the evaporation pressure and the refrigeration capacity of the non-azeotropic refrigerant mixture HC290/HC 600a with proper ratio is similar to those of CFC12. In this paper, aiming at the flow characteristics of HC290 and HC 600a in capillary tubes, a mathematical model is established to simulate the flow of pure refrigerants.

MATHEMATICAL MODEL

Analysis of the Flow of Natural Refrigerants in Capillary Tubes

The flow process of natural refrigerant in capillary tubes is similar to those of CFCs. The refrigerant enters the capillary often as subcooled liquid, during the flow process of refrigerant in the capillary, the pressure of refrigerant decreases linearly and the temperature keeps constant till the saturation point, then enters a metastable liquid region, behind of this region, refrigerant evaporates, and the pressure and temperature drop rapidly, at last refrigerant flows out of capillary as two-phase mixture.

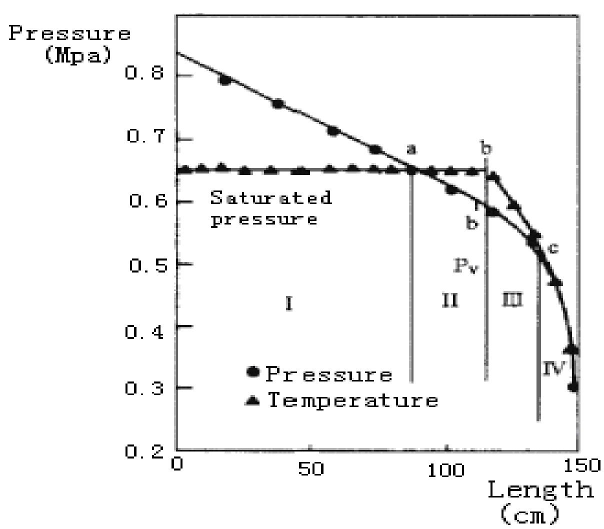

Figure.1 distributions of temperature and pressure of refrigerant along the capillary

Figure.1 illustrates the distribution of pressure and temperature of refrigerant along the capillary, according to which the flow process can be divided into the following four regions according to Mikol E .P' results:

- I Subcooled liquid region: The pressure drops linearly and the temperature remains constant, the refrigerant exists as subcooled liquid.
- II Metastable liquid region: The pressure still drops linearly and the temperature remains constant, but the pressure is lower than the saturation pressure corresponding to the temperature. The refrigerant exists as superheated liquid.
- III Metastable two-phase flow region: The refrigerant evaporates and both the temperature and the pressure drops rapidly, the refrigerant exists as a mixture of vapor and superheated liquid.
- IV Thermodynamic equilibrium two-phase flow region: The pressure and the temperature drops rapidly continuously, the vapor and the liquid are in a equilibrium state.

According to the flow characteristics of natural refrigerant in capillary tube, appropriate assumptions are presented before establishing the mathematical model:

- Homogenous flow
- Adiabatic
- One dimensional
- Steady flow
- Constant sectional area and even coarseness degree

Mathematic Model

Control Volume

The control volume is showed in Figure 2.

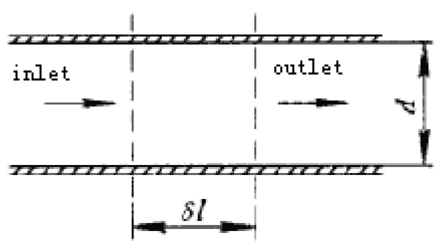

Figure. 2 control volume

Local pressure drop at the inlet

When refrigerant flows out of condenser and into capillary, local resistance loss will arise the abrupt reduction of the tube diameter. The local resistance loss coefficient is showed as follows:

$$\zeta = 0.5(1- A_2 / A_1) \quad (1)$$

The local pressure drop is:

$$\Delta P = P_{liquidline} - P_{inlet} = \zeta \cdot G^2 v_f / 2 \quad (2)$$

where A_1 is intersection area of the tube before capillary's inlet; A_2 is intersection area of the capillary.

Subcooled liquid region

When subcooled refrigerant liquid enters into capillary, the pressure decrease from the inlet pressure P_{inlet} until the corresponding saturated pressure P_{sat} of the inlet temperature.

The mass equation is:

$$G = \frac{m}{A} = \text{Constant} \tag{3}$$

The momentum equation is:

$$\Delta p = f\frac{\Delta l}{d} \cdot \frac{G^2 v}{2} \tag{4}$$

$$f = 0.3164 / \mathrm{Re}^{0.25}$$

As the specific volume and velocity of liquid keep unchanged. The length of the subcooled liquid region can be obtained from the above two equations:

$$l_{sc} = \frac{2d(P_{inlet} - P_{sat})}{fG^2 \cdot v_f} \tag{5}$$

Metastable liquid region

Now many researchers observed that refrigerant is still in liquid state though the pressure has dropped below the saturated pressure corresponding to the temperature of the liquid. The pressure difference between the saturated pressure corresponding to the temperature and the actual pressure at the point of inception of vaporization is called as underpressure, which can be calculated according to Chen Z. H and Li R. Y's results:

$$P_u = P_{sat} - P_l = \sqrt{\frac{16\pi\sigma^3}{3kT} \cdot \frac{1}{\Phi\left(1 - \frac{v_l}{v_g}\right)^2}} \tag{6}$$

The length of superheated liquid region is:

$$l_{sh} = \frac{2d(P_{sat} - P_l)}{fG^2 v_f} \tag{7}$$

Two-phase section

Mass conservation equation:

$$dG = 0 \tag{8}$$

Momentum conservation equation:

$$dP + G^2 dv + f\frac{dl}{d} \cdot \frac{G^2 v}{2} = 0 \tag{9}$$

Energy conservation equation

$$dh+\frac{1}{2}\ \mathrm{G}^{2}\ vdv=0 \tag{10}$$

Where,

$$v=v_f(1-x)+v_g x \tag{11}$$

$$h=h_f(1-x)+h_g x \tag{12}$$

$$\mu=\frac{\mu_g\mu_f}{\mu_g+x_g{}^{0.8}(\mu_f-\mu_g)} \tag{13}$$

Modules of calculation program

The main calculation program includes I/O function and is able to call necessary subprograms to calculate the lengths of the subcooled liquid region, superheated liquid region and two-phase region if needed. The total length of these regions is the whole capillary's length. The inlet pressure and inlet temperature are needed during the execution of subprogram in which the length of subcooled liquid region can be calculated

The necessary properties can be calculated by corresponding subprograms, the length of subcooled liquid region can be calculated by equation (5).The length of superheated liquid region is calculated by equation (7), while P_1 is designated as initial value of the subprogram describing two-phase section. The subprogram is established by differential equation to calculate the length of two-phase section.

At the end of the program, it is necessary to evaluate difference between calculated length and initial value, difference between outlet pressure and evaporation pressure, and difference between mass flow rate and critical mass flow rate. If even one difference is satisfactory, the execution can be stopped and the output result is acceptable.

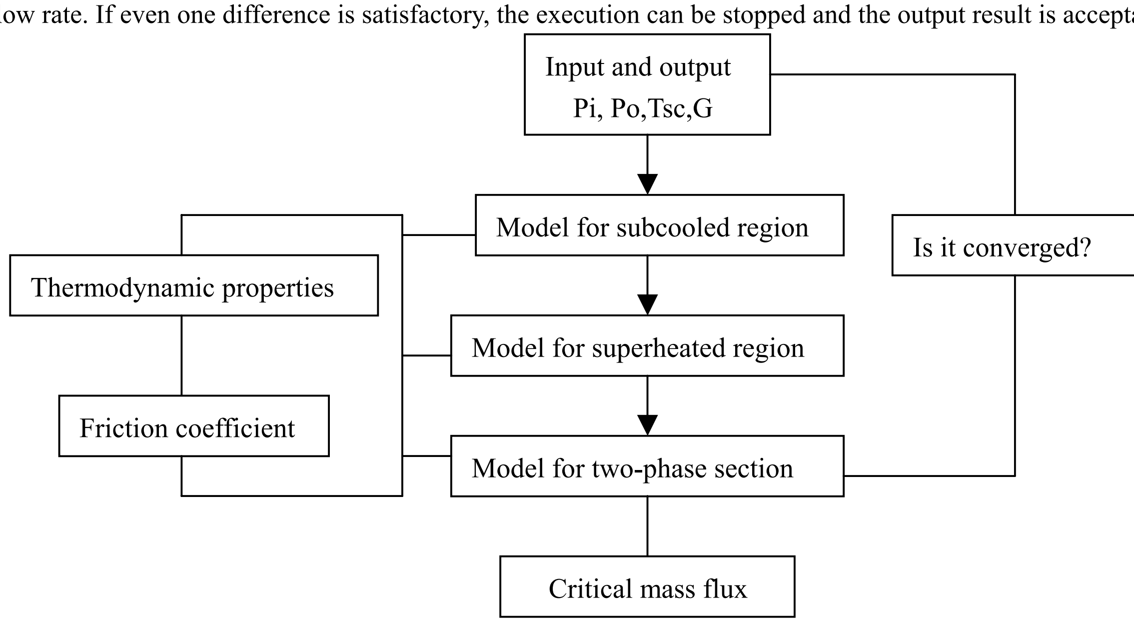

Figure 3. Module of calculation program

The following four cases are very common applicated:

1. Pi, Ti, G, D and l, are known and the outlet pressure Pe is needed to be calculated.
2. Pi, Ti, G, D are known and the length of capillary l is needed to be calculated
3. Pi, Ti, G, l and Pe are known and the tube inner diameter d is needed to be calculated
4. Pi, Ti, G, l, Pe are known and mass flow rate G is needed to be calculated

For the former two cases, the program can be applied directly; with respect to the third case, the initial diameter (d') of the capillary should be assumed, if the calculated outlet pressure (P_e') is higher than the initial pressure P_e, the assumed diameter is too high and should be decreased and continue the calculation, and vice verse; for the fourth case, mass flow rate G' should be assumed firstly. if the calculated outlet pressure P_e' is less than the initial pressure P_e or the calculated length (l') of capillary is less than the initial length l, the assumed mass flow rate is too bigger and need to be decreased and continue the calculation, and vice verse.

RESULT AND DIGUSSION

Aiming at the second case, the length of capillary tube can be determined based on the given working condition and the mass flow rate. Take example for natural refrigerant HC290, the working condition for calculation is as followed: the inlet pressure （P_1 ）is 1.12Mpa, the mass flow rate (G) is 3.15kg/h, the inner diameter of capillary tube(d) is 0.865mm and the subcooled temperature （ΔT） in the inlet is 10℃. The different outlet pressure and the corresponding length of capillary tube are showed in Table.2.

Table.2

Pe（MPa）	Experimental Value (m)	Calculational Value(m)	Discrepancy Value (cm)	Error（%）
1.03	0.50	0.512	1.2	2.4
0.95	1.20	1.150	-5.0	-4.2
0.86	1.80	1.860	6.0	3.3
0.72	2.20	2.235	3.5	1.6
0.60	2.80	2.923	12.23	4.37
0.43	3.50	3.620	12.0	3.43

Based on the configuration dimension of the refrigerant and the working condition, the mass flow rate of natural refrigerant can be calculated and then the mass flow rate is checked whether it can satisfy the refrigeration capacity of the refrigeration apparatus. Take example for HC600a, the calculational values are compared with the recommended experimental values provided by Melo C. and Ferreira R.T.S., which is showed in Table.3.

Table .3

Working condition				Mass flow rate（kg/h）	
d (mm)	l(m)	P_1(MPa)	ΔT(℃)	Experimental	Calculational
1.25	0.765	0.92	10.0	3.56	3.78
1.25	0.765	1.25	6.0	4.65	4.96

1.36	0.520	1.25	8.0	6.62	7.25
1.36	1.650	1.25	8.0	4.56	4.62
1.62	0.765	0.92	6.0	6.65	6.36
1.62	1.650	0.92	10.0	6.68	6.98

From the above two tables, it seems that the discrepancy between the calculational values and the recommended experimental values is not more than 10%, which can satisfy the request of engineering application. Therefore, it is proved that the mathematical model is reliable for natural refrigerant.

CONCLUSION

According to the above analysis, ae one dimensional mathematical model established in this paper turn out to be right and it precision is satisfying in engineering application. Therefore, the models can direct engineering application and experimental investigation of HC600a and HC290, and provide certain reference for the design of capillary tube with these natural refrigerants as well.

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