***Journal of Engineering and Development*, Vol. 12, No. 4, December (2008)** **ISSN 1813-7822**

Comparison Among Different Methods for Predicting Mass Flow Rate of Refrigerant in Capillary Tubes

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Abstract

Predicting of refrigerant mass flow rate in capillary tube is widely used in numerical simulation and designing of refrigeration and air conditioning systems, so the present study tries to compare the existing analytical and mathematical methods for predicting mass flow rate of refrigerant through capillary tube with experimental data published in previous studies. Assuming adiabatic, homogenous flow rate of refrigerant and neglecting the delay of vaporization region (metastable region) inside the capillary tube. The refrigerant R-22 is used in present study because of the wide range of experimental data and mathematical modeling methods that available.

Three mathematical methods for predicting and modeling mass flow rate in capillary tube were programmed and the results compared with experimental data available. A simple iterative indicator of chock flow condition at exit plane of capillary tube is used during calculations of element by element methods instead of tedious analytical equations. Generally the results show low values of predicted refrigerant mass flow rate compared with experimental data.

Element by element analysis method (present work) predicted mass flow rate with a mean deviation of 10.9% from the experimental data. Zhang and Ding [5] analytical method and Koizumi [1] method predicted mass flow rate with a mean deviation of 11.9% and 37.7% respectively.

الخلاصـــــــــة

حساب معدل التدفق الكتلي لغاز التبريد داخل الأنبوب الشعري يستخدم بشكل واسع في برامج المماثلة العددية وتصميم منظومات تكييف الهواء والتثليج، ولذلك الدراسة الحالية تحاول مقارنه طرق المماثلة التحليلية والرياضية لتخمين التدفق الكتلي لغاز التبريد خلال الأنبوب الشعري مع النتائج العملية المنشورة مفترضا أن الجريان متجانس و معزول مع إهمال منطقه التأخر في التبخير. غاز التبريد R-22 استخدم في الدراسة الحالية بسبب المدى الواسع من النتائج العملية وطرق المماثلة الرياضية المتوفرة.

ثلاث طرق رياضيه لمماثلة وحساب معدل التدفق الكتلي لغاز التبريد داخل الأنبوب الشعري تم برمجتها ومقارنه النتائج مع النتائج العملية المتوفرة. تم استخدام مؤشر تكرار بسيط بدلأ من المعادلات المطولة لتحديد حاله الجريان الحرج (Chocked Flow Condition) في نهاية الأنبوب الشعري خلال الحسابات بطريقه التجزئة.

النتائج اضهرت قيم واطئه لجريان كتله غاز التبريد مقارنه مع القيم العملية. طريقه التحليل بالتجزئة (Element by Element) خمنت معدل التدفق الكتلي بمتوسط انحراف ١٠.٩ % عن القيم العملية. طريقه المماثلة الرياضية Zhang and Ding [5] وطريقه Koizumi [1] خمنت معدل التدفق الكتلي بمتوسط انحراف ١١.٩ % و ٣٧.٧ % على التوالي.

1. Introduction

Capillary tube is one of the main parts of refrigeration system which is used as a throttling device especially in domestic refrigerators and low capacities air conditioning systems. Capillary tube is widely used because it's simple in use, cheap and has no moving parts. Designing capillary tube gets more interest because of mass production in refrigeration and air conditioning systems. There are many methods discussed to predict the mass flow rate of refrigerant inside capillary tubes but till days the method of cut and try is the more reliable one for the manufacturer so much time and labor work is required. The aim of present work is to compare the existing methods for predicting and modeling mass flow rate of refrigerant into capillary tubes with the experimental tests data available to find the more accurate method which is used to predict mass flow rate of refrigerant through capillary tube in designing and modeling computer program for refrigeration and air conditioning systems. The flow of refrigerant through capillary tube assumed to be adiabatic (no heat transfer between the capillary tube and it's surroundings), homogenous (the velocity of liquid and vapor phases are equal) and neglecting the delay of vaporization region.

2. Mathematical Modeling

2-1 Previous Studies

Koizumi and Yokoyama [1] studied the flow of refrigerant inside capillary tubes. The authors have observed the refrigerant flow in a glass capillary tube visually and have reconfirmed it to be homogenous. The pressure and temperature distribution along the capillary tube were measured and they recognized that the starting point of vaporization became delayed. Also they found that a theoretically calculated pressure distribution, presupposing adiabatic and homogenous flow, agreed accurately with measured values, if the delay of vaporization was estimated correctly. A simple method for calculating the length of the vaporization flow region in the capillary tube was developed. The method is limited to adiabatic, homogenous flow and employs a simple analytical integration of momentum equation gets,

$$\mathbf{L_{tp} = N\left[\frac{\exp(-3/4)b}{G^{7/4}}\int_{p_{out}}^{P_r}\exp((-3/4)ap)dp - \frac{G^{1/4}}{g}\int_{\upsilon_r}^{\upsilon_{out}}\upsilon^{-3/4}d\upsilon\right]} \quad \text{.....................} \mathbf{(1)}$$

where: a= - 0.25*10^{-4}, b= - 3.3

$$\mathbf{N = \frac{2gD^{5/4}}{0.3164\upsilon_l^{1/4}}} \quad \text{..} \mathbf{(2)}$$

$$\mathbf{L_l = \frac{2D(P_{in} - P_r)}{f_{in}G^2\upsilon_{in}}} \quad \text{...} \mathbf{(3)}$$

$$\mathbf{f_{in} = 0.3164\left(\frac{G\ D}{\mu_{in}}\right)^{1/4}} \quad \text{..........} \quad \mathbf{(4)}$$

$$\mathbf{L = L_{tp} + L_l} \quad \text{..........} \quad \mathbf{(5)}$$

To calculate mass flow rate of refrigerant through capillary with known length and input and output pressure, the mass flow rate will be assumed initially then length will be calculated from Eq.(5) and compared with actual length, mass flow rate assumed will be corrected until convergence of length values occurs.

Goldstein **[2]** presented a mathematical iterative approach to model the flashing flow in the capillary tube from either liquid or two-phase inlet to either liquid or two-phase outlet, and shows the variable which must be converged to generate balance calculations for a refrigeration system. This technique may be used in a computerized approach to refrigerant system modeling and can be a rather sophisticated alternative to the use of more empirical data or the well known ASHRAE curves. The study doesn’t take into account the delay in vaporization which takes place inside capillary tube.

Stoecker **[3]** modified a purely analytical technique to take advantage of digital computer based on fundamental laws and influenced by proposal of Hopkins and Cooper; this method may be used to design the capillary tubes for new refrigeration systems. The computed value of capillary tube length shows a good agreement with ASHRAE curves for designing capillary tubes.

Li et. al. **[4]** developed a mathematical model for a steady-state, two phase flow in capillary tubes, considering the thermodynamic non equilibrium phenomenon during vaporization and the relative velocity between the liquid and vapor. A comparison is in good agreement with experimental data obtained from two phase flow of R-12 flowing through capillary tubes which shows that the model predicts and can be used for selection of capillary tubes of refrigerating systems using R-12 as a working fluid.

Zhang and Ding **[5]** approximate analytic solution of capillary tube may be used for theoretical analysis and engineering calculation. In this work, two kinds of approximate analytic solutions of adiabatic capillary tube have been developed assuming homogenous flow and neglecting delay of vaporization, the chocked flow condition is taken into account without iterative calculations.

1. Non chocked flow condition

$$\mathbf{m^{\bullet} = \frac{\pi D^2}{4}\left[\frac{\left(P_{in}^{*}-1\right)-\frac{f_{in,p}}{f_{tp,p}}\left[\frac{P_{out}^{*}-1}{1-\beta}-\frac{\beta}{(1-\beta)^2}\ln\left[\beta+(1-\beta)P_{out}^{*}\right]\right]}{\frac{L.f_{in,p}}{2D}-\frac{f_{in,p}}{f_{tp,p}}\ln\left[\frac{P_{out}^{*}}{\beta+(1-\beta)P_{out}^{*}}\right]}\left(\frac{P_r}{\upsilon_r}\right)\right]^{1/2}} \quad \text{..........} \quad \mathbf{(6)}$$

where:

$$\beta=\frac{\left(1.63*10^{5}/P_{l}^{0.72}\right)P_{l}^{*}}{1+\left(1.63*10^{5}/P_{l}^{0.72}\right)\left(P_{l}^{0.72}-1\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

C_1=0.23, C_2=0.216, $P_{in}^{*}=P_{in}/P_{r}$, $P_{out}^{*}=P_{out}/P_{r}$, $P_{l}^{*}=P_{l}/P_{r}$

In two phase region viscosity is calculated as:

$$\frac{1}{\mu_{tp}}=\frac{x}{\mu_{v}}+\frac{1-x}{\mu_{l}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

2. Chocked flow condition

$$m^{\bullet}=\frac{\pi D^{2}}{4}\left[\frac{\left(P_{in}^{*}-1\right)-\frac{f_{in,p}}{f_{tp,p}}\left[\frac{\sqrt{\beta}G_{P}^{*}-1}{1-\beta}-\frac{\beta}{(1-\beta)^{2}}\ln\left[\beta+(1-\beta)\sqrt{\beta}G_{P}^{*}\right]\right]}{\frac{L.f_{in,p}}{2D}-\frac{f_{in,p}}{f_{tp,p}}\ln\left[\frac{\sqrt{\beta}G_{p}^{*}}{\beta+(1-\beta)\sqrt{\beta}G_{p}^{*}}\right]}\left(\frac{P_{r}}{\upsilon_{r}}\right)\right]^{1/2} \quad \ldots\ldots\ldots\ldots \text{(9)}$$

$$G_{p}=\left[\frac{2}{C_{1}}\left(\frac{D^{1+C_{2}}}{L}\right)\left(\frac{P_{r}}{\upsilon_{r}\mu_{in}^{C_{2}}}\right)\left\{P_{in}^{*}-1-\left(\frac{1+\beta(\ln\beta-1)}{(1-\beta)^{2}}\right)\right\}\right]^{\frac{1}{2-C2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

$$G^{*}=G\sqrt{\upsilon_{r}/P_{r}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(11)}$$

$$P_{ch}^{*}=\sqrt{\beta}G^{*} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(12)}$$

To find mass flow rate, predictor chocked mass flux will be calculated using Eq.(10) and chocked pressure calculated also using Eq.(12) if chocked pressure greater than evaporative pressure (chocked flow condition) ,then mass flow rate will be calculated using Eq.(9), else it will be calculated using Eq.(6) as non chocked flow condition.

2-2 Element by Element Analysis Scheme (Present Work)

The present work will use the technique called element by element analysis scheme. This scheme divides the capillary tube into specified number of elements. The output condition (Thermodynamics and Thermophysical properties of refrigerant) of a specified element is the input conditions of the second element. This technique is similar to method used by Stoecker [3] and Goldstein [2] but the present work will depend on a simple numerical iterative indicator of chocked flow condition at exit of capillary tube and assuming homogenous adiabatic throttling flow and neglecting the metastable region (delay of vaporization). This phenomenon (chocked flow) is similar to flow in a convergence nozzle when the outlet pressure has been reduced until sonic velocity occurs at the throat, further reduction in the discharge pressure fails to increase the flow rate through the nozzle [3]. Similarly in capillary tube when the chocked flow occurs at exit plane, the pressure drop of refrigerant at exit plane close to maximum value and mass flow rate of refrigerant will be constant, in other words a negligible change of mass flow rate gives maximum and constant pressure drop as shown in **Fig.(1)**. The **Fig.(1)** shows the relation between pressure drop of refrigerant at exit plane and the change of mass flow rate of refrigerant (the change of mass flow rate is a continuous operation during computer calculations until the balance occurs between the assumed and calculated values). Mathematically the simple iterative indicator is presented from the definition of chocked flow phenomenon and the behavior of flow indicated by **Fig.(1)** to be used as a simple indicator for chocked flow as follows,

$$\frac{\Delta m^{\bullet}}{\Delta P_{out}} \approx 0 \quad \text{(At chock flow condition)} \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(13)}$$

where:

$\Delta m^{\bullet}$ = *Change of mass flow rate (kg/s)*

ΔP_{out} = *Pressure drop at exit plane (pa)*

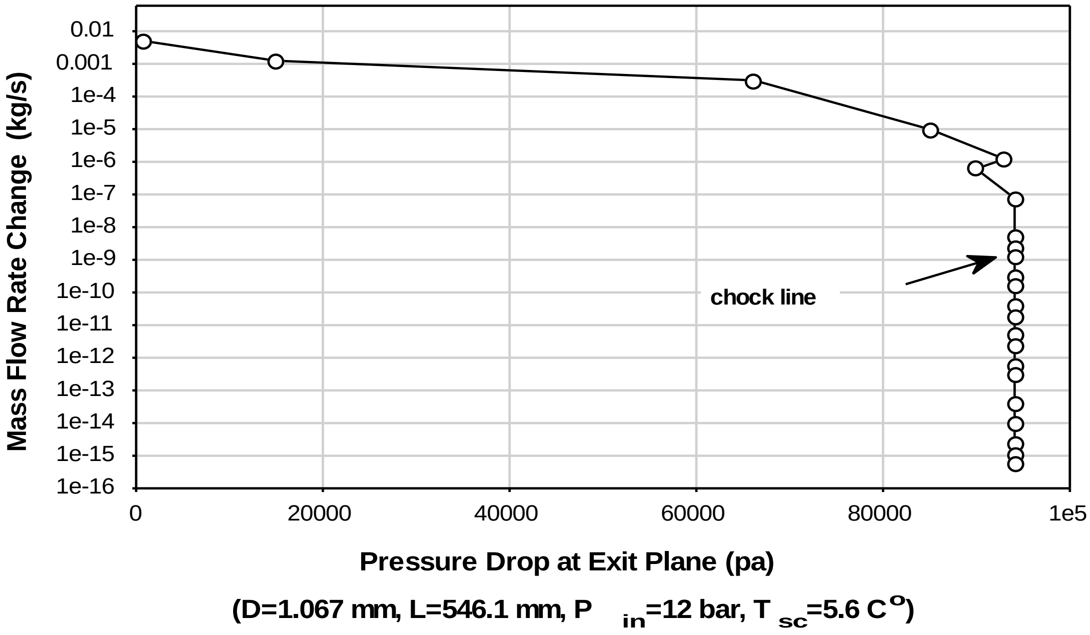


Figure (1) Chocked flow condition (present work)

2-2-1 Calculation Scheme

Flow chart of calculations of element by element analysis scheme is illustrated in **Fig.(2)**. At first the required input data must be entered to the program and then mass flow rate of refrigerant through the capillary will be assumed. If the input condition of refrigerant into capillary was liquid then the length of liquid region (single phase region) will be calculated using Eq.(3).After that the length of two phase region will be calculated and divided into number of elements. The input condition of two phase region is the output condition of liquid region else it's the input condition of capillary if the refrigerant entering capillary at two phase condition. The pressure out of the element will be assumed and the properties of refrigerant exiting element will be calculated, the actual output pressure of element during two phase region may be calculated using Eq.(14) [6], that presented depending on proposals of Wallis [7].

$$\mathbf{P_o = P_i - \left[\frac{f_{tp}\cdot\Delta l\cdot G^2}{2D}\right]\cdot\left[\upsilon_{lo} + \frac{(x_i + x_o)}{2}\right]\cdot(\upsilon_{ro} - \upsilon_{lo}) + \left[G^2\cdot(\upsilon_{vo} - \upsilon_{lo})\cdot(x_o - x_i)\right]} \quad \text{………………… (14)}$$

The calculated value of the pressure will be compared with assumed value and the assumed value will be corrected each time until convergence occurs between assumed and calculated values. This scheme will continue to the next element assuming the input condition of the element is the output condition of the previous one. This procedure continued to the end of capillary tube. At the exit of capillary the pressure out is calculated and compared with the actual pressure output of capillary, if the convergence occurs between the two values the program will end, else the program will check if chock condition occurs using the simple iterative indicator or mass flow rate assumed will be changed by binary search method and program will be restarted again.

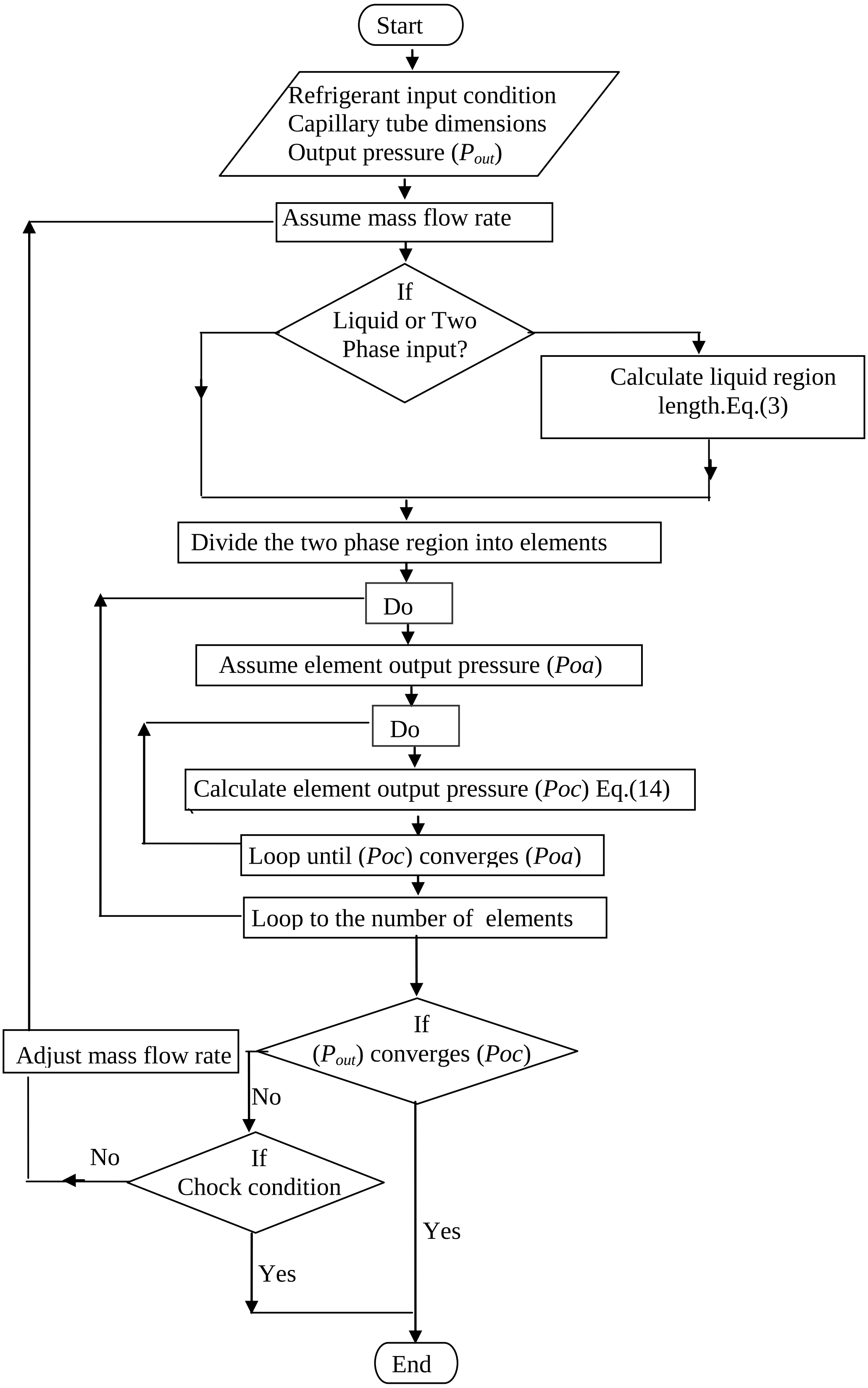


Figure (2) Flow chart of element by element scheme

3. Experimental Data

Kuehl and Goldschmidt [8] experimentally tested several length and diameter combinations using a test loop that provides control of the sub cooling, and condenser and evaporator pressures using R-22 as a working fluid. Tests were also performed to measure the distribution of the pressure drops and to determine the effect of coiling on the restriction characteristics of the capillary tube. The inlet pressure was varied between 12.41 to 22.06 bar and subcooling between 5.6 to 11.1 C°. All tests where run with the evaporator pressure at or below 3.45 bar. The dimensions of capillary tubes tested illustrated in **Table (1)**.

Table (1) Capillary tube dimensions

D (mm)	L (mm)
1.067	546, 800, 1054
1.245	546, 800, 1054, 1308, 1562
1.373	546, 800, 1054, 1308, 1562
1.499	546, 800, 1054, 1308, 1562
1.626	546, 800, 1054, 1308, 1562

The data of tests where fitted to following equations:

$$L = 2.225-2.474\,\phi+0.503\,\phi^2 \text{ (mm)}, D = 1.067 \text{ mm} \quad \ldots\ldots (15)$$

$$L = 5.827-7.816\,\phi+2.835\,\phi^2 \text{ (mm)}, D = 1.245 \text{ mm} \quad \ldots\ldots (16)$$

$$L = 6.236-7.061\,\phi+2.139\,\phi^2 \text{ (mm)}, D = 1.373 \text{ mm} \quad \ldots\ldots (17)$$

$$L = 6.243-5.657\,\phi+1.39\,\phi^2 \text{ (mm)}, D = 1.499 \text{ mm} \quad \ldots\ldots (18)$$

$$L = 4.744-3.045\,\phi+0.518\,\phi^2 \text{ (mm)}, D = 1.626 \text{ mm} \quad \ldots\ldots (19)$$

where: $\phi = m^{\bullet} / m^{\bullet}_{sc}$

$$m^{\bullet}_{sc} = 1.049\, P_{in}^{\,0.494} \quad \text{(kg/h)} \quad , T_{sc} = 5.6 \;C^{\circ} \quad \ldots\ldots (20)$$

$$m^{\bullet}_{sc} = 1.299\, P_{in}^{\,0.473} \quad \text{(kg/h)} \quad , T_{sc} = 8.3 \;C^{\circ} \quad \ldots\ldots (21)$$

$$m^{\bullet}_{sc} = 1.837\, P_{in}^{\,0.434} \quad \text{(kg/h)} \quad , T_{sc} = 11.1 \;C^{\circ} \quad \ldots\ldots (22)$$

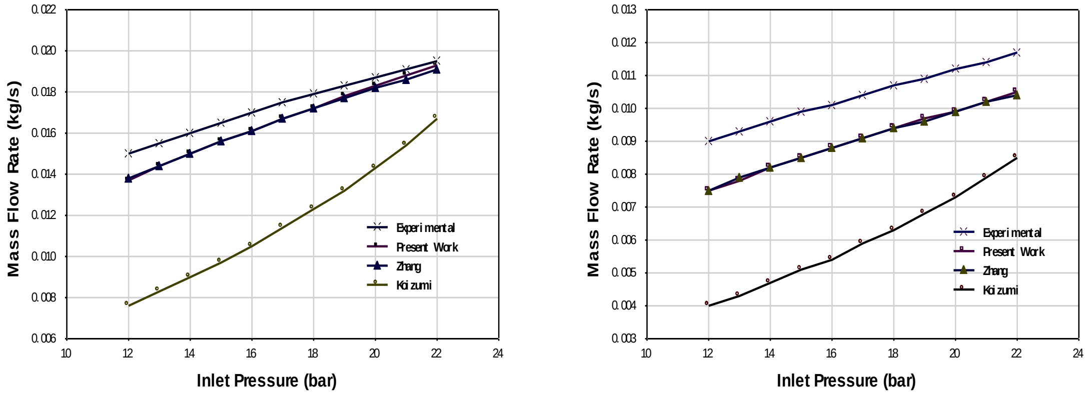
To calculate the mass flow rate of refrigerant in case of known dimensions and operating conditions, at first mass flow rate will be assumed and the length of capillary tube will be calculated using the equations above according the dimensions and operating conditions of capillary tube. The calculated value will be compared with actual value of length. The value of mass rate assumed will be corrected until convergence of values occurs. After convergence of values exists the value of mass flow rate will be fixed.

4. Refrigerant Properties

The refrigerant used in present study is R-22 which is widely used in air conditioners. Wide range of experimental data of this refrigerant could be found in previous studies, which gives us a good tool for comparison with the results obtained by theoretical modeling method. The present study depends on the thermodynamic relations and equation of state presented by Japanese Association and published by ASHRAE [9] and the computer program which built by Kazim [10] to calculate the refrigerant thermodynamic and thermophysical properties.

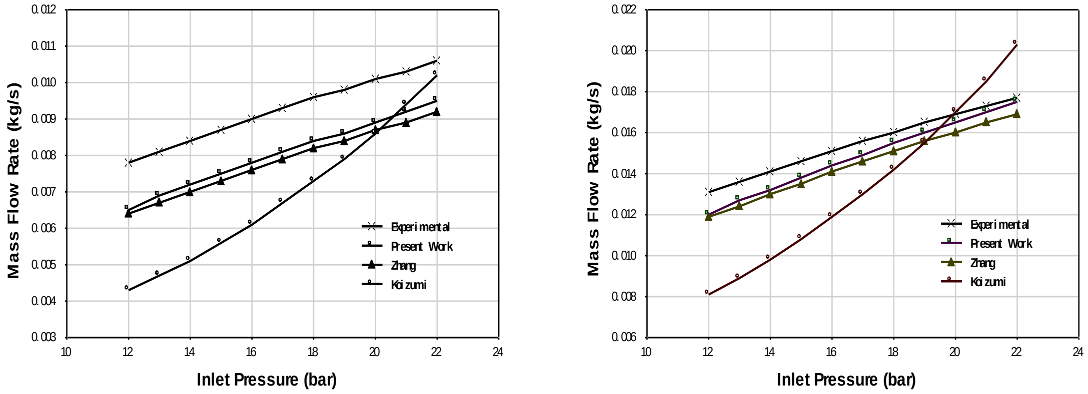
5. Results and Discussions

A wide range of capillary tubes dimensions were studied during the present study as mentioned in **Table (1)** with the same operating conditions (input, output pressure and degree of subcool) of experiments that studied by Kuehl and Goldschmidt [8].Three methods of predicting mass flow rate of refrigerant through capillary tube (Koizumi [1], present work, Zhang and Ding [5]) and experimental data of Kuehl and Goldschmidt [8] were programmed using Visual studio 6.0 language and the results of them were compared. **Figure (3)** shows the relation between mass flow rate and changing of input pressure of capillary tube at different cases. Mass flow rate increases with increasing the input pressure of capillary tube, Koizumi [1] method gives the lowest values of mass flow rate, while the present work (element by element method) and Zhang and Ding [5] analytical method are looking coincide and they seem close to experimental data. **Figure (4)** shows the relation between changing of length of capillary tube with mass flow rate of refrigerant flowing into it at different conditions, mass flow rate decreases with increasing the length and it's obvious that the present work and Zhang and Ding [5] in a good agreement with experimental data but Koizumi [1] method gives lower values. **Figure (5)** describes the behavior of mass flow rate with changing the tube diameter at different conditions, mass flow rate increases with increasing tube diameter and it's clear that the present work and Zhang and Ding [5] shows good agreement with experimental data. **Figure (6)** shows the relation between mass flow rate of refrigerant and degree of subcool, mass flow rate increases with increasing degree of subcool, the present work and Zhang and Ding [5] give values of mass flow rate close to experimental data. **Figure (7)** shows the scatter plot of the experimental and predicted data collected from the present study. Mean deviation factor is used to compare the level of agreement for the predicted values with the experimental data.



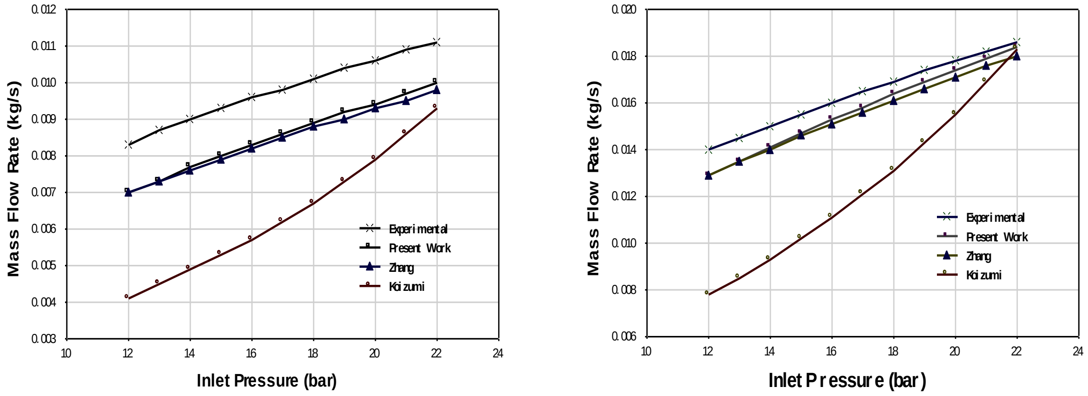
(a) D=1.626 mm , L=1.562 m , T_{sc}=11.1 C^{o}

(b) D=1.067 mm , L=0.546 m , T_{sc}=11.1 C^{o}



(c) D=1.067 mm , L=0.546 m , T_{sc}=5.6 C^{o}

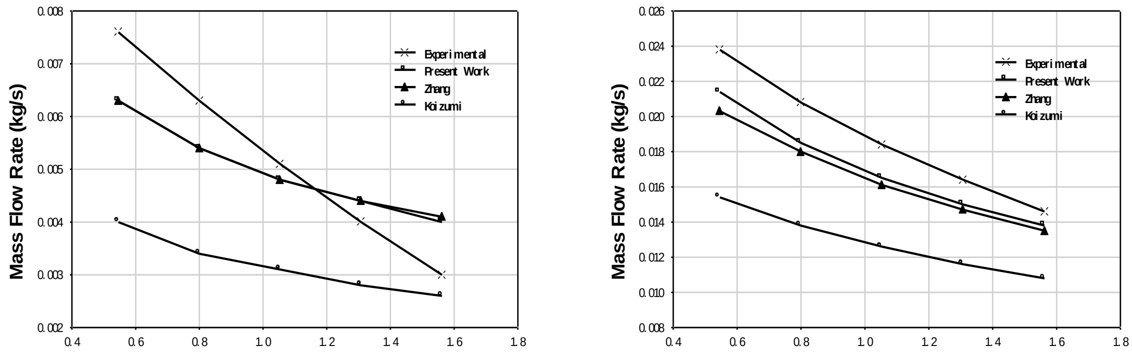
(d) D=1.626 mm , L=1.562 m , T_{sc}=5.6 C^{o}



(e) D=1.067 mm , L=0.546 m , T_{sc}=8.3 C^{o}

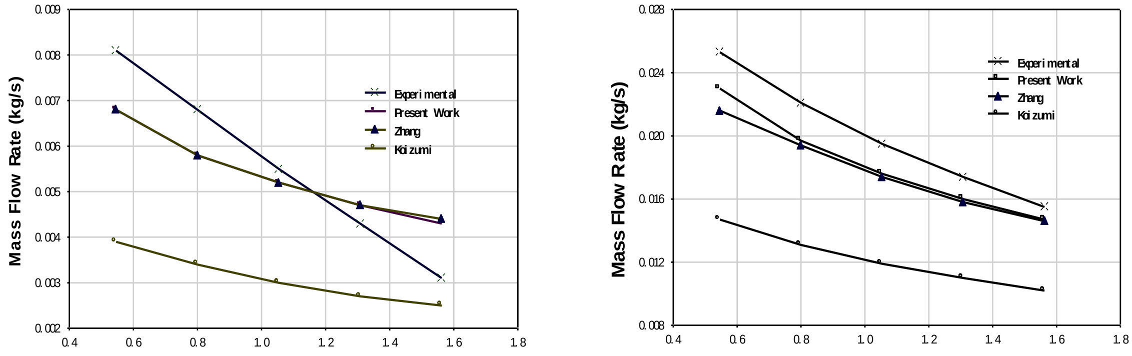
(f) D=1.626 mm , L=1.562 m , T_{sc}=8.3 C^{o}

Figure (3) The relation between mass flow rate and input pressure at different cases



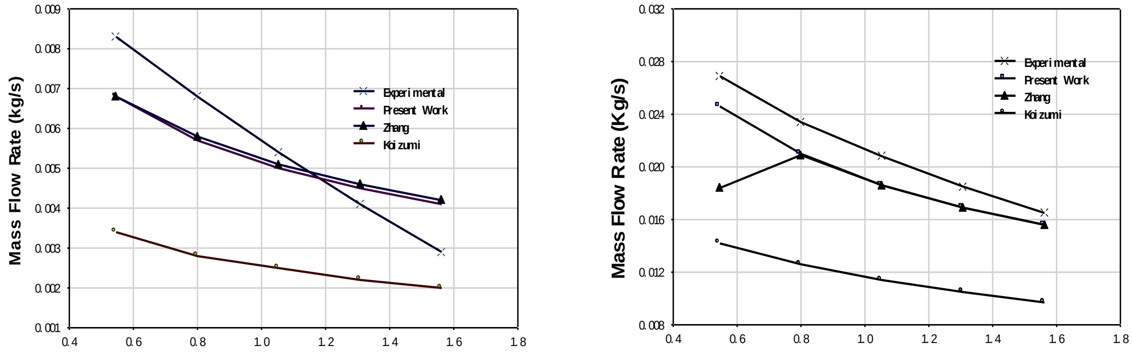
(a) D=1.067 mm, P_{in}=10 bar, T_{SC}=5.6 C^{o}

(b) D=1.626 mm, P_{in}=15 bar, T_{SC}=5.6 C^{o}



(c) D=1.067 mm, P_{in}=10 bar, T_{sc}=8.3 C^{o}

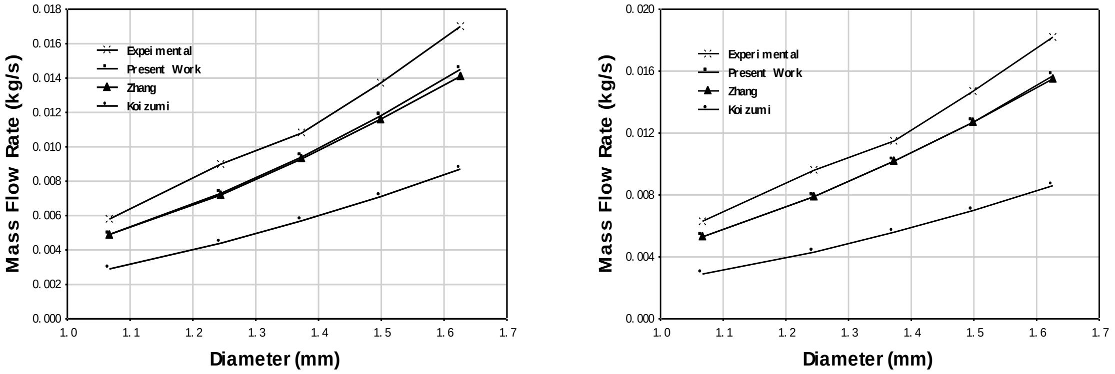
(d) D=1.626 mm, P_{in}=15 bar, T_{SC}=8.3 C^{o}



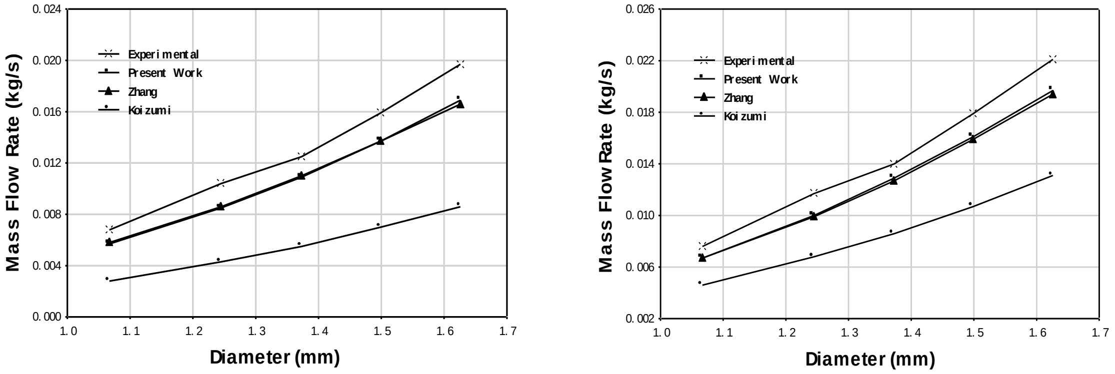
(e) D=1.067 mm, P_{in}=10 bar, T_{sc}=11.1 C^{o}

(f) D=1.626, P_{in}=15 bar, T_{SC}=11.1 C^{o}

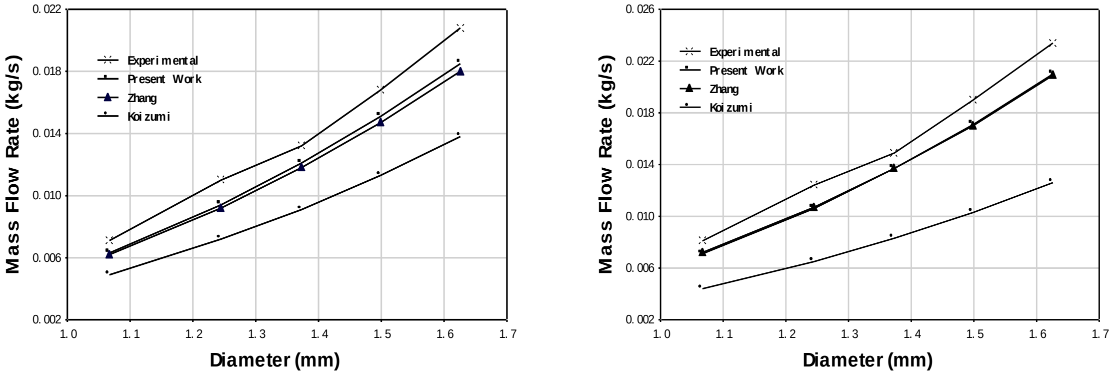
Figure (4) The relation between mass flow rate and length of capillary tube at different cases



(a) L=800.1 mm, P_{in}=10 bar, T_{SC}=5.6 C^o (b) L=800.1 mm, P_{in}=10 bar, T_{SC}=8.3 C^o

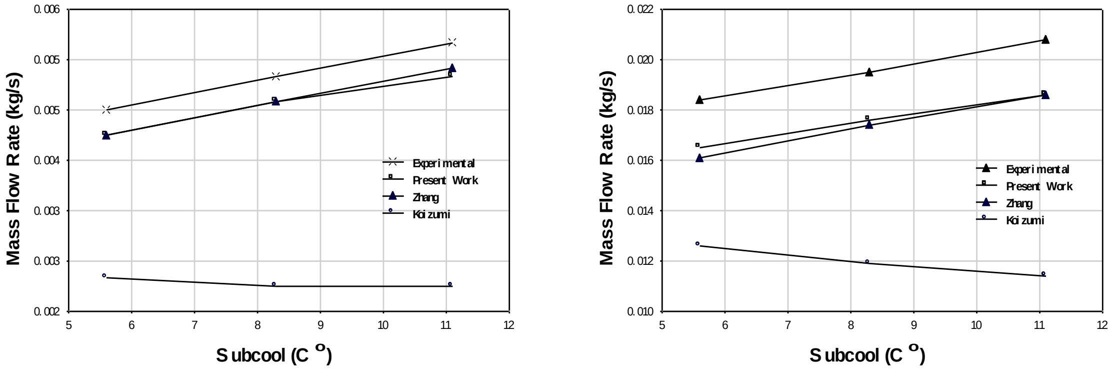


(c) L=800.1 mm, P_{in}=10 bar, T_{SC}=11.1 C^o (d) L=800.1 mm, P_{in}=15 bar, T_{SC}=8.3 C^o

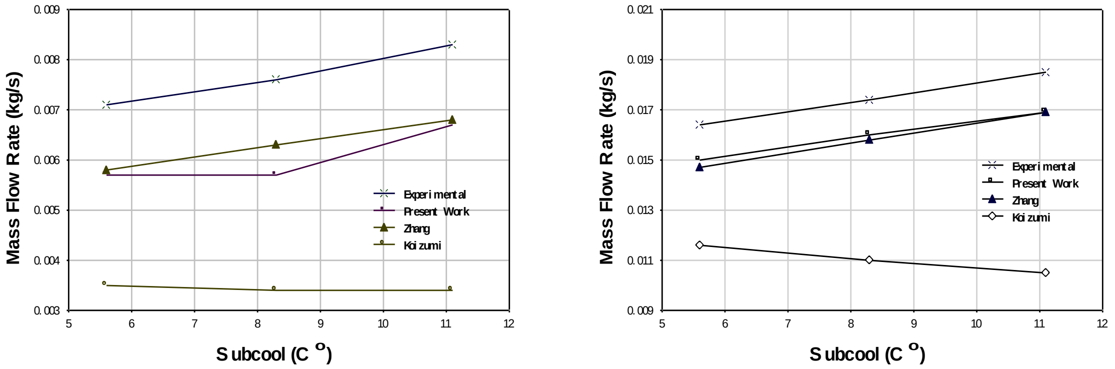


(e) L=800.1 mm, P_{in}=15 bar, T_{SC}=5.6 C^o (f) L=800.1 mm, P_{in}=15 bar, T_{SC}=11.1 C^o

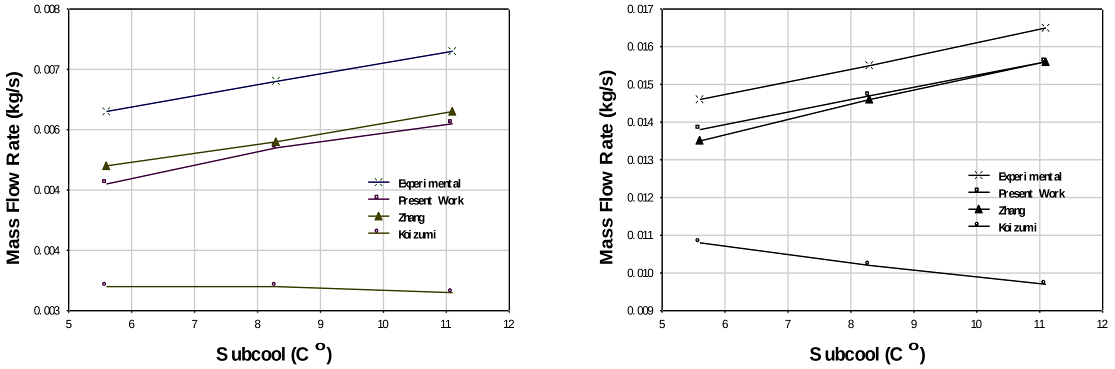
Figure (5) The relation between mass flow rate and the diameter of capillary tube at different cases



(a) D=1.067 mm, L=1.054 m, P_{in}=10 bar (b) D=1.626, L=1.054 m, P_{in}=15 bar



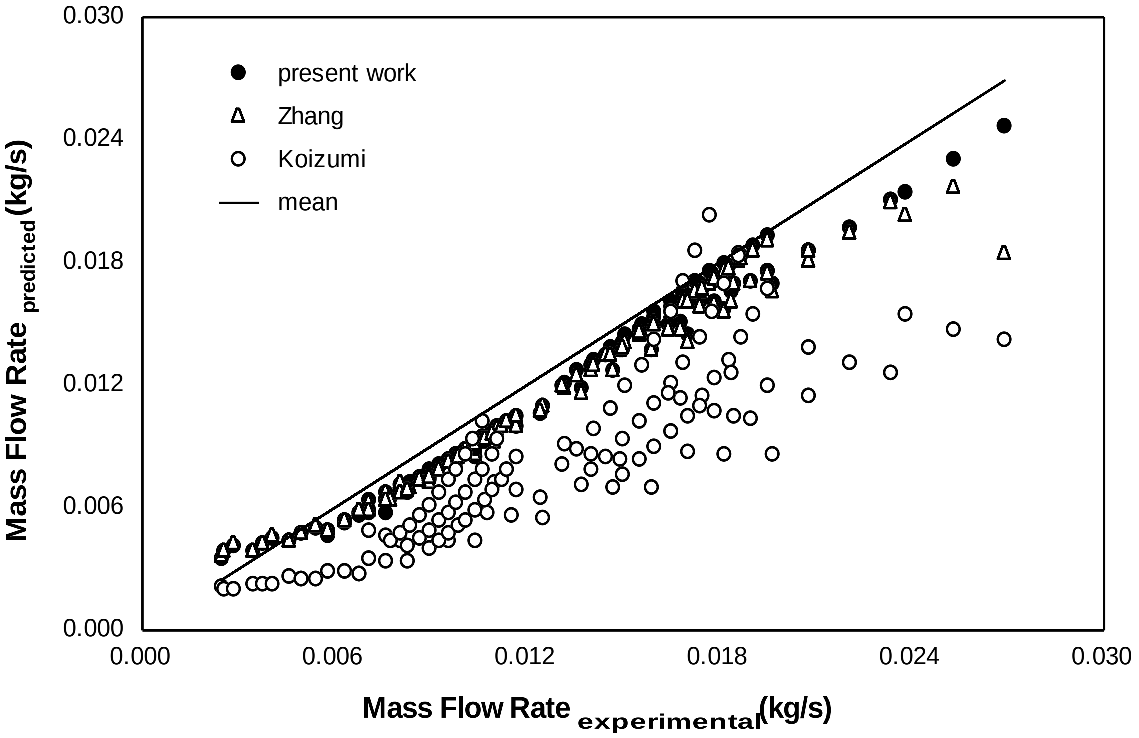
(c) D=1.067mm, L=546.1mm, P_{in}=10 bar (d) D=1.626 mm, L=1.308 m, P_{in}=15 bar



(e) D=1.067mm, L=800.1 mm, P_{in}=10 bar (f) D=1.626 mm, L=1.562 m, P_{in}=15 bar

Figure (6) The relation between mass flow rate and degree of subcool at different cases

Figure (7) shows that the predicted values are lower than experimental data that may be because of neglecting the delay of vaporization region. Neglecting the effect of this region will decrease the total pressure drop occurs inside the capillary tube, so the mass flow rate of refrigerant required will be less than actual value. The present work (element by element analysis) is in good agreement with experimental data, giving mean deviation of 10.9% from the mean (experimental data). Zhang and Ding [5] method gives the results with a mean deviation of 11.9% and Koizumi [1] method give results with a mean deviation of 37.7%.



$$\textbf{Mean Deviation}=\frac{1}{n}\sum_{1}^{n}\left|\frac{(\dot{m}_{predicted}-\dot{m}_{experimental}).100}{\dot{m}_{experimental}}\right| \quad , \ n = no.\ of\ points$$

Figure (7) Comparison of experimental mass flow rate with predicted mass flow rate

6. Conclusions

All the three theoretical methods for predicting mass flow rate and modeling of capillary tubes (Koizumi [1], present work, Zhang and Ding [5]) gave mass flow rate values less than experimental data because of neglecting the effect of delay of vaporization region. To avoid inaccuracy of neglecting the delay of vaporization region, a specified additional pressure drop of liquid region must be added, that will increase mass flow rate. Element by element analysis scheme with the simple iterative indicator of chock flow condition (the present work) gives good agreement with experimental data and stable solution ,the mean deviation of the results was 10.9% .Zhang and Ding [5] method and Koizumi [1] method predicted the mass flow rate of refrigerant with a mean deviation of 11.9 % and 37.7 % respectively.

7. References

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List of Symbols

Symbol	**Description**	**Units**
A	Cross sectional area	m^2
D	Inside diameter of capillary tube	m
f	Friction factor	--
G	Mass flux (G = m• /A)	kg/s
g	Gravity	m/s^2
L	Length of capillary tube	m
Δl	Length of element.	m
m•	Mass flow rate	kg/s
P	Pressure	pa
x	dryness fraction	--
μ	Dynamic viscosity	pa.s
υ	specific volume	m^3/kg

Subscripts

ch	chock flow
i	in to the element
in	input of capillary
l	liquid
o	output of the element
out	output of capillary
p	predictor solution
tp	two phase
r	reference point (start of the two phase region)
sc	subcool
v	vapor