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Modelling of Flashing in Capillary Tubes using Homogeneous Equilibrium Approach

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Abstract

A model for the two phase flow of refrigerant through a capillary tube has been developed. This model assumes mechanical & thermal equilibrium between the phases. The flashing phenomenon occurs when a liquid is out of thermodynamic equilibrium such as sudden changes in the pressure or temperature of a liquid system. The rate of flashing is modeled as proportional to the deviation from the equilibrium vapor pressure. Results of this model compared with experimental data for flow through capillary tube. Also this model is used to calculate the critical flow rate for various inlet conditions. The predictions are compared with experimental data. The concordance between the predictions and the experiments has been discussed in this paper.

Keywords: Refrigeration; Capillary Tube; Two Phase Flow; Flashing; Choking; R12, R134a; CFD

1. Introduction

Capillary tubes are extensively used as expansion devices in refrigeration industry due to their simplicity, reliability and low cost. A capillary tube is a long & narrow tube of constant diameter which serves as a pressure
reduction device between the condenser and evaporator in the refrigeration cycle. It also acts as a flow metering
device due to flashing. Flashing is the sudden change of phase from a liquid to vapor due to the local pressure falling
below the saturated vapor pressure. The point where the first bubble is formed is known as bubble point. Post the
bubble point, there is two phase flow of liquid-vapor under non equilibrium conditions with nonlinear pressure drop.
The onset of vapor significantly restricts the flow rate across the capillary tube and thus it acts as flow regulator. For
a given inlet pressure the flow rate increases monotonically as the outlet pressure is reduced. The mass flow rate is
insensitive to a reduction of the outlet pressure beyond a critical value. From manufacturing point of view main
concern for these systems is the determination of the length and diameter of the tube when a refrigeration capacity
and the parameters at the inlet and exit of the capillary tubes are given.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>p</td>
<td>Pressure</td>
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<tr>
<td>V</td>
<td>Velocity Vector</td>
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<tr>
<td>R_B</td>
<td>Nucleation site radius</td>
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<tr>
<td>R_e</td>
<td>Mass transfer rate</td>
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<tr>
<td>F</td>
<td>Flash coefficient</td>
</tr>
<tr>
<td>C</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>m</td>
<td>Volumetric Mass Source</td>
</tr>
<tr>
<td>E</td>
<td>Total Energy</td>
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Greek Letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>α</td>
<td>Phase volume fraction</td>
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<tr>
<td>ρ</td>
<td>Fluid density</td>
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Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>i</td>
<td>inlet</td>
</tr>
<tr>
<td>m</td>
<td>Mixture</td>
</tr>
<tr>
<td>l, v</td>
<td>liquid, vapor</td>
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Various researchers carried out experiments to study characteristics of flow through capillary tubes. Work of
Whitesel [5,6], Mikol et al. [7], Ghosal et al.[8], Chen et al[9] and Lin et al[10] has helped to understand the effect
of parameters like frictional pressure drop, two-phase flow system with mass transfer etc. on critical flow rate. As
two phase flow of refrigerant is quite complicated through a narrow capillary tube, it is difficult to solve equations
describing the complex phenomenon by analytical method. Therefore numerical simulation of this physics has very
important to role to play in design of capillary tubes. Goldstein [11] developed a thermodynamic equilibrium model
to model the flashing flow through capillary tube. Maczek et al [12] used a non-adiabatic, non-equilibrium two phase
flow method. Lin et al.[13] presented a steady state two phase flow model considering the non-equilibrium
phenomenon during vaporization and relative velocity between the liquid and vapor.

In current study, a homogeneous model has been developed to model flow through capillary tubes. This paper
presents prediction of the pressure drop in capillary tube for different operating conditions and comparison with
experimental data of Chen et al [9]. Also the critical maximum flow rate predictions for different inlet conditions are
compared with experimental data (ASHRAE 2006). Simulations have been carried out using ANSYS Fluent [1].

2. Mathematical Modeling

In current study, a homogenous model is used which assumes local equilibrium over short spatial length scales and
treats the mixture of phases as a pseudo fluid. The model solves continuity, momentum & energy equations for the
mixture, and the volume fraction equations for the secondary phase.
2.1. Governing equations

The mixture multiphase model (Mixture Model Theory [1]) is used to model the two phase flow through capillary tube. The model solves continuity, momentum, and energy equations for the mixture, the volume fraction equations for the secondary phase.

Continuity Equation:
\[ \frac{\partial (\rho_m)}{\partial t} + \nabla \cdot (\rho_m \vec{V}_m) = 0 \]  

where \( \rho_m \) is the mixture density given by \( \rho_m = \alpha_l \rho_l + \alpha_v \rho_v \)

Volume Fraction Equation:
\[ \frac{\partial}{\partial t} (\alpha_v \rho_v) + \nabla \cdot (\alpha_v \rho_v \vec{V}_m) = \dot{m}_{l\rightarrow v} - \dot{m}_{v\rightarrow l} \]  

where \( \dot{m}_{l\rightarrow v} \) and \( \dot{m}_{v\rightarrow l} \) are source terms due to mass transfer between the liquid and vapor phase.

Momentum Equation
\[ \frac{\partial (\rho_m \vec{V}_m)}{\partial t} + \nabla \cdot (\rho_m \vec{V}_m \vec{V}_m) = -\nabla p + \nabla \cdot \left[ \mu_m \left( \nabla \vec{V}_m + \nabla \vec{V}_m^T \right) \right] \]  

where \( \mu_m \) is the mixture viscosity defined as: \( \mu_m = \alpha_l \mu_l + \alpha_v \mu_v + \mu_{t,m} \) and \( \mu_{t,m} \) is mixture turbulent viscosity.

Energy Equation
\[ \frac{\partial}{\partial t} \sum_{k=1}^{L_v} (\alpha_k \rho_k \vec{E}_k) + \nabla \cdot \sum_{k=1}^{L_v} (\alpha_k \vec{V}_m (\rho_k \vec{E}_k + p)) = \nabla \cdot (K_{eff} \nabla T) + S_E \]  

where \( S_E \) is the volumetric heat source/sink due to phase change and \( K_{eff} \) is the effective conductivity given by: \( K_{eff} = \alpha_l K_l + \alpha_v K_v + K_{t,m} \)

2.2. Mixture Speed of Sound

The sound speed of a two phase mixture is dramatically different from the sound speed of either pure component. Also it is very important to model the compressibility effects accurately to predict critical flow condition. Inverse of effective bulk modulus \( (\rho_m C_m^2) \) of mixture is equal to an average of the inverse bulk moduli of the components weighted according to their volume fractions.

\[ \frac{1}{\rho_m C_m^2} = \frac{\alpha_v}{\rho_v C_v^2} + \frac{\alpha_l}{\rho_l C_l^2} \]  

2.3. Liquid Flashing Model

Mass transfer between the phases due to changes in the thermodynamics is modelled through a User Defined Function (UDF) based on the cavitation model (Zwart-Gerber-Belamri). Mass transfer is driven by the difference in local pressure and saturation pressure. Saturation pressure is taken as a function of temperature. The mass transfer rate per unit volume is given as

\[ R_e = F \frac{3 \alpha_{nuc} (1 - \alpha_v) \rho_v}{R_B} \frac{2|P_B - P|}{3 \rho_l} \]  

where, \( P_B \) is the vapor saturation pressure at the liquid temperature and \( F \) is an empirical flash coefficient that needs to be determined by fitting experimental data to model predictions. More details about Zwart et al. cavitation model are available in ANSYS Fluent documentation [1].
3. Results & Discussion

In the design of a capillary tube the main parameters affecting the flow conditions are: inlet pressure & temperature, exit pressure, mass flow rate, diameter and length of tube. In current study, pressure based coupled solver has been used and axi-symmetric steady state solution has been carried out. Multiphase Mixture model, Realizable k-epsilon turbulence model with scalable wall function treatment has been used. Density, Thermal Conductivity, Viscosity and Speed of Sound are considered as function of temperature and pressure implemented via User Defined Functions. Properties have been taken from NIST Standard Reference Data. For numerical calculation the following cases are considered:

3.1. Application 1

In this study for given inlet pressure, inlet temperature and exit pressure, critical mass flow rate will be predicted for different flash coefficients. As discussed in section 2.3 “Flash Coefficient” is the parameter which needs to be tuned for particular fluid. So in current study we have carried out simulations for different flash coefficients till we get constant mass flow rate with respect to flashing coefficients. A capillary tube of the diameter 0.66 mm and length 1.5 m has been modeled. Two cases were simulated for R-12 flow through capillary tubes:

Inlet condition 1) G=3306 kg/s-m², Pi = 9.67 bar and Ti =31.4 C.

Inlet condition 2) G=2468 kg/s-m², Pi = 7.17 bar and Ti =23.4 C.

Inlet condition 1 case has been simulated on coarse and fine mesh to get mesh independent solution. Coarse mesh domain has been discretized into 10 by 1650 elements along the radial and axial directions respectively and fine mesh domain has been discretized in to 20 by 3300 elements. Fig 1 shows pressure distribution through capillary tube for two different meshes which shows mesh independence. So coarse mesh has been used for all simulations discussed in this paper.

Table 1 shows critical mass flow rate with different flash coefficients. Simulations show that critical mass flow remains unchanged beyond flash coefficient 0.1.
Table 1. Flash Coefficient vs Mass Flow rate

<table>
<thead>
<tr>
<th>Flash Coeff.</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow Rate (g/s)</td>
<td>1.52</td>
<td>1.32</td>
<td>1.27</td>
<td>1.27</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Fig 2. Pressure Distribution along the axial length (Inlet condition 1)

So the flash coefficient value 0.1 has been considered for all simulations carried out using R12. Fig 2 shows pressure distribution in capillary tube for Inlet condition 1. Pressure distribution matches well with experimental data reported by Chen et al.\[9\]. For sub-cooled inlet conditions, pressure drop is linear till the bubble point; downstream of this point the effective density of the mixture and the subsequent velocity of the mixture varies as a non-linear function of the volume fraction of the gas phase causing a non-linear variation of the pressure drop.

Fig 3: (a) Temperature and (b) Volume Fraction Distribution along the axial length (Inlet condition 1)
with length. For sub-cooled inlet case, temperature is almost constant in liquid length (Fig 3(a)) and then reduces in two phase length. Fig 3(b) shows vapor volume fraction distribution in capillary tube for Inlet condition 1. The vapor volume fraction increases rapidly after flashing inception and goes to very high value up to 0.9.

Fig 4 shows mass flow rates for different outlet pressure for Inlet condition 2. Simulations shows that choked flow condition below 2.5 bar outlet pressure. For both Inlet conditions pressure distribution plot shows bubble point location slightly upstream compared to experimental data and also pressure drop overpredicted, particularly in two phase region. Reason for these differences is that the current model assumes thermal equilibrium between two phases and non-equilibrium effects are not modeled so it leads to early inception of flashing. For both cases homogeneous method overpredicted mass flow by 12% compared to experimental data.

Fig 4. Mass flow rate for different outlet pressure (Inlet condition 2)

Fig 5. Pressure Distribution along the axial length (Inlet condition 2)
3.2. Application 2

In current study, R134a flow through capillary tube has been modeled for different saturation conditions. Choked mass flow rate has been predicted and compared with the data from ASHARE (2006) [2]. A capillary tube of the diameter 0.86mm and length 3.3 m is used. Flash coefficient for these simulations is 0.01. Three sets of simulations have been carried out to get critical flow rate for inlet conditions with 5 K liquid subcooling, saturation condition and 5% vapor quality. The critical flow condition has been obtained by gradually reducing the pressure at outlet.

<table>
<thead>
<tr>
<th>Case No</th>
<th>Conditions</th>
<th>Inlet Pressure (bar)</th>
<th>Inlet Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subcooled</td>
<td>15</td>
<td>323.38</td>
</tr>
<tr>
<td>2</td>
<td>Saturated</td>
<td>15</td>
<td>328.38</td>
</tr>
<tr>
<td>3</td>
<td>5% vapor</td>
<td>15</td>
<td>328.38</td>
</tr>
</tbody>
</table>

Table 2: Inlet conditions for different cases

Figure 6 compares the results from the model against the data from ASHARE. For sub-cooled inlet condition, mass flow rate is predicted within 5%. As we move away from subcooled condition prediction are overpredicted.

4. Conclusion

Homogenous modeling approach along with cavitation model based mass transfer mechanism can be used for modeling of two phase flow through capillary tubes. Though this model overpredicts critical mass flow rate (5 to 12%), predicted flow parameters are in reasonable agreement with experimental data for different refrigerants and inlet conditions. So homogeneous modeling approach can be used to design capillary tubes for refrigeration systems.

References

1. ANSYS FLUENT 15.0 Documentation, 2013.