Theoretical investigation of vapor mass fraction measurement methods for two-phase injection compression

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Abstract. The economized vapor injection (EVI) method is used to decrease the discharge temperature of scroll compressors and to improve the cycle performance of vapor compression refrigeration systems by directly injecting refrigerant vapor into the compression chamber. In previous studies, the optimal cycle performance for an air conditioning system using EVI was detected during two-phase injection. However, the exact vapor mass fraction could not be measured directly. For further investigations on two-phase injection systems, accurate vapor mass fraction (VMF) measurements need to be conducted. This paper compares different options for the VMF measurement using pure refrigerants or refrigerant mixtures. It focuses on the achievable accuracy of the VMF measurement, based on the propagation of uncertainty.

1. Introduction

Vapor injection scroll compressors and the economized vapor injection (EVI) method are utilized to enlarge the operation range of single-stage vapor compression heat pump systems. During EVI operation a defined amount of subcooled liquid refrigerant is extracted after the condenser (upstream extraction) or after the economizer (downstream extraction), expanded to the injection pressure and evaporated in the economizer. This leads to a further subcooling of the liquid refrigerant after the condenser. After its evaporation at injection pressure, the refrigerant is directly injected into the compression chamber. Figure 1 shows an EVI cycle with downstream extraction and a heat exchanger economizer that was modelled and tested by Moesch et al. [1]. The authors investigated EVI for air conditioning (A/C) systems using R-407C. Their results indicate that two-phase injection with a high vapor mass fraction (VMF) leads to an optimal performance of the air conditioning system. However, for two-phase operation a reliable VMF measurement method is required. There is already a variety of published VMF methods based on flow measurements and two-phase properties. Wang et al. [2] measured the VMF at the evaporator outlet of an R-134a A/C system using a gas/liquid separator and measuring the saturated gas flow rate. The overall uncertainty of this method was not given by the authors. Mitra et al. [3] used a tunable diode laser to measure the specific volume from which they derived the VMF of a two-phase H₂O flow. Based on their experimental results, the authors claim to achieve 1% accuracy for the derived VMF. However, the uncertainty for different fluids or applications cannot be derived from their data.

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To narrow down the achievable uncertainty of different VMF measurement methods and their applicability in regard to the existing EVI setup and future standardized EVI performance tests, the authors conducted a theoretical uncertainty investigation based on the required sensors of each method.

This paper presents four different VMF methods that are based on heat balances, fluid properties and fluid separation. It provides an input on the methods’ correlations and their theoretical uncertainties for a given reference point.

2. Study on different VMF methods

2.1. VMF measurement methods

The VMF or vapor quality of two-phase flows is generally defined by Equation (1), where \( \dot{m} \) represents the mass flow rate of the two-phase refrigerant flow and \( \dot{m}'' \) is the mass flow rate of the saturated vapor.

\[
\dot{x} = \frac{\dot{m}''}{\dot{m}} \quad (1)
\]

Another definition of the VMF is based on fluid properties in an equilibrium state and is given by Equation (2), where \( h \) is the enthalpy of the two-phase refrigerant flow, \( h'' \) is the enthalpy of the saturated liquid refrigerant as \( h' \) and the enthalpy of the saturated vapor refrigerant. Strictly speaking this definition is only valid for homogeneous flow approaches, where both fluid phases are assumed to have the same flow velocity, or for stationary applications (e.g. closed vessels or tanks).

\[
x = \frac{h - h'}{h'' - h'} \quad (2)
\]

The four investigated VMF methods are described in the following subsubsections. The described Calorimeter method and Direct PT method are based on Equation (2), the Direct PD method and the Separation method are based on Equation (1).

2.1.1. Calorimeter Method. A schematic of the Calorimeter method is shown in Figure 2. It uses the available heat exchanger economizer as a secondary fluid calorimeter as described in ASHRAE Standard 41.9 [4]. Instead of a secondary fluid though, which is usually water or brine, the subcooled liquid flow exiting the condenser (state point 4-2) is used to evaporate the extracted refrigerant flow at state point 4-1, which is the injected flow \( \dot{m}_{\text{inj}} \). The enthalpy of the injected flow is calculated based
on an energy balance across the economizer as shown in Equation (3), where $h_{\text{inj}}$ represents the enthalpy of the injected two-phase flow, $T_{4,1}$ and $T_{4,2}$ are the measured temperatures, $p_{4,1}$ and $p_{4,2}$ are the measured pressures, $\dot{m}_C$ and $\dot{m}_E$ are the measured mass flow rates, and $\varphi_{\text{amb}}$ is the relative heat loss to ambient.

$$h_{\text{inj}} = \frac{\dot{m}_C \cdot \left[ h(p_{4,2}, T_{4,2}) - h(p_{4,1}, T_{4,1}) \right] \cdot (1 - \varphi_{\text{amb}})}{\dot{m}_C - \dot{m}_E} + h(p_{4,1}, T_{4,1})$$  (3)

This method requires two mass flow meters, three pressure sensors and two temperature sensors and is therefore more costly. The relative heat loss to ambient $\varphi_{\text{amb}}$ is not measured and therefore seen as an unknown parameter. This method is not applicable for other economizers, such as flash tanks. However, for EVI applications with closed heat exchanger economizers, it provides a reliable way to determine the injection enthalpy.

2.1.2. Direct PT Method. The Direct PT method is shown in Figure 3. It uses the temperature glide during the phase change of R-407C. The enthalpy of the injected two-phase flow is directly calculated based on the measured injection pressure $p_{\text{inj}}$ and injection temperature $T_{\text{inj}}$ (see Equation (4)).

$$h_{\text{inj}} = h(p_{\text{inj}}, T_{\text{inj}})$$  (4)

This method only requires one pressure sensor and one temperature sensor and is therefore the preferable method in terms of cost-effectiveness. It is only applicable to EVI systems with zeotropic refrigerant mixtures with a certain temperature glide and does not interfere with the EVI system.
2.1.3. Direct PD Method. The Direct PD method uses a similar approach as reported in [3] and measures the density of the two-phase flow as shown in Figure 4. According to [5], the average density of a heterogeneous two-phase flow is defined by Equation (5), where \( \alpha \) represents the void fraction, \( \rho' \) is the density of saturated liquid refrigerant and \( \rho'' \) is the density of saturated vapor refrigerant.

\[
\rho_{\text{inj}} = \rho'(p_{\text{inj}}) \cdot \alpha + \rho''(p_{\text{inj}}) \cdot (1 - \alpha)
\]  

The vapor mass fraction or quality for a two-phase flow is defined by Equation (6), where \( S \) is called the velocity ratio or slip and represents the ratio of the vapor refrigerant velocity to the liquid refrigerant velocity.

\[
\dot{x}_{\text{inj}} = \left[ 1 + \frac{1}{S} \cdot \frac{1 - \alpha}{\alpha} \cdot \rho'(p_{\text{inj}}) \right]^{-1}
\]  

Merging Equations (6) and (5), the void fraction can be eliminated and the VMF for the Direct PD method can be defined as follows.

\[
\dot{x}_{\text{inj}} = S \cdot \left[ \frac{1}{\rho_{\text{inj}}} - \frac{1}{\rho''(p_{\text{inj}})} \right] \cdot \left[ \frac{S}{\rho'(p_{\text{inj}})} + \frac{1 - S}{\rho_{\text{inj}}} - \frac{1}{\rho''(p_{\text{inj}})} \right]^{-1}
\]  

There are different approaches for the velocity ratio \( S \). Zivi [6] analytically investigated an annular flow based on its minimal total kinetic energy and suggested Equation (8) for the estimation of \( S \).

\[
S = \left( \frac{\rho'}{\rho''} \right)^{1/3}
\]  

Chisholm [7] used an annular flow theory and a homogeneous approach for the fluid density. This resulted in the correlation in Equation (9), where \( x \) represents the vapor quality.

\[
S = \left[ 1 - x \cdot \left( 1 - \frac{\rho'}{\rho''} \right) \right]^{1/2}
\]  

This method requires one pressure sensor and one density sensor for two-phase flows. The density measurement is based on a Coriolis flow meter and thus, the costs will be between the Direct PD Method and the Calorimeter Method. For this investigation the velocity ratio \( S \) is assumed to be an unknown parameter since the authors have no information on the accuracy of the Equations (8) and (9). This method is applicable for both pure refrigerants and refrigerant mixtures and may be applied to alternative economizers such as a flash tank as well. The pressure loss over the density sensor might interfere with the injection process.

![Figure 4. Direct PD Method](image)

2.1.4. Separation Method. The Separation Method is similar to the approach presented in [2] and uses an additional vessel to separate the saturated vapor refrigerant flow from the saturated liquid refrigerant flow as shown in Figure 5. This allows a direct measurement of the vapor refrigerant flow.

The VMF of the injection two-phase flow is then defined by Equation (10), where \( \dot{V}_{\text{inj},l} \) represents the measured volume flow of the saturated liquid refrigerant, \( p_{\text{inj}} \) is the measured injection pressure, and \( \dot{m}_C \) and \( \dot{m}_E \) are the measured mass flow rates.
\[
\dot{m}_i = \frac{\rho_i \left( \frac{p_{inj}}{\bar{p}_{inj}} \right) v_{inj}}{\dot{m}_c - \dot{m}_E} \tag{10}
\]

This method uses three flow meters and one pressure sensor and its costs are between the Direct PD Method and the Calorimeter Method. It can be applied to any EVI configuration and refrigerant. Due to the separation of the injected flow this method interferes significantly with the injection process. For accurate measurements a stable filling of the separator needs to be guaranteed.

2.2. Approach for uncertainty analysis

The uncertainty of the VMF method results from the uncertainty of each measured parameter and its propagation. The propagation of uncertainty was conducted using the Taylor Series Method (TSM) described by Coleman and Steele [8]. The TSM is defined by Equation (11), where \( U_x \) represents the uncertainty of the VMF calculation, \( U_{Y,i} \) is the uncertainty of each measured parameter and \( \frac{\partial x}{\partial Y_i} \) is the partial derivative of the VMF correlation for each parameter.

\[
U_x = \left[ \sum_{i=1}^{n} \left( \frac{\partial x}{\partial Y_i} \cdot U_{Y,i} \right)^2 \right]^{0.5} \tag{11}
\]

The relative uncertainty contribution of each parameter \( \varepsilon_{Y,i} \) is given by Equation (12).

\[
\varepsilon_{Y,i} = \left( \frac{\partial x}{\partial Y_i} \cdot U_{Y,i} \right)^2 \left[ \sum_{i=1}^{n} \left( \frac{\partial x}{\partial Y_i} \cdot U_{Y,i} \right)^2 \right]^{-1} \tag{12}
\]

The partial derivatives are numerically approximated by the central-difference approach in Equation (13) as defined in [8], where \( \Delta Y \) represents the finite difference, \( Y_i^0 \) are the referenced measured parameters, and \( Z^0 \) is the referenced unknown parameter.

\[
\frac{\partial x}{\partial Y_i} \bigg|_{Y_i^0,...,Y_j^0=const} \approx \frac{x \left( Y_i^0 + \Delta Y_i, Y_j^0, ..., Y_n^0, Z^0 \right) - x \left( Y_i^0 - \Delta Y_i, Y_j^0, ..., Y_n^0, Z^0 \right)}{2 \cdot \Delta Y_i} \tag{13}
\]

**Figure 5. Separation Method**
The uncertainty of each parameter \( U_{Y_i} \) depends on the measuring device. Table 1 lists the uncertainty range of different sensors based on manufacturer data and European standards ([9], [10]).

Table 1. Uncertainties of various measuring devices

| Measured property | Measurement Principle | Measurement range | Uncertainty range |
|-------------------|-----------------------|-------------------|------------------|
| Temperature       | Type T thermocouple   | -40 to 350 °C     | ± 0.5 °C to ± 1.0 °C |
|                   | Type J thermocouple   | -40 to 750 °C     | ± 1.5 °C to ± 2.5 °C |
|                   | Platinum resistance   | -196 to 600 °C    | ± 0.1 °C to ± 0.6 °C |
| Pressure          | Semi-conductor        | variable          | ± 1 % |
|                   | Piezo-resistance      | variable          | ± 0.05 % FS to 4.0 % FS |
| Density           | Coriolis              | 400 to 2500 kg/m³ | ± 0.5 kg/m³ to ± 5.0 kg/m³ |
| Mass flow         | Coriolis              | variable          | ± 0.15 % to ± 1.0 % |
| Volume flow       | Float-type            | variable          | ± 1.0 % to ± 4.0 % |
| Vortex frequency  |                      | variable          | ± 1.0 % to ± 2.0 % |

\( ^a \) Based on European standards  
\( ^b \) Based on manufacturer data

2.3. Reference state

A comparative investigation of the VMF methods was conducted for a mutual reference state for all measured parameters \( Y_i^0 \), unknown parameters \( Z^0 \), and measurement uncertainties \( U_{Y_i}^0 \).

The referenced measured parameters are based on the EVI system described in [1] for the refrigerant mixture R-407C, a VMF of \( x = 0.95 \), and an injection pressure of \( p_{inj} = 10 \text{ bar(a)} \). Further, the authors assumed a condensing dew point temperature of \( t_{c,dew} = 50 ^\circ \text{C} \), a subcooling after the condenser of \( \Delta T_{SC} = 2 \text{ K} \), and a minimal temperature difference at the economizer of \( \Delta T_{min} = 2 \text{ K} \). State 4-1 at the economizer outlet can be calculated using Equation (14).

\[ h(T_{4,1}, p_{4,1}^0) = h(T_{4,1}^0 - \Delta T_{min}^0, p_{inj}^0) \]  

(14)

The referenced suction mass flow rate \( \dot{m}_E^0 \) results from Equation (15) and is based on a scroll compressor with a theoretical displacement volume flow of \( V_{th} = 14.1 \text{ m}^3/\text{h} \), a volumetric efficiency of \( \omega_v = 0.9 \), a evaporator dew point temperature of \( T_{E,dew} = 5 ^\circ \text{C} \), and a suction superheat of \( \Delta T_{SH} = 10 ^\circ \text{K} \).

\[ \dot{m}_E^0 = V_{th} \cdot \omega_v \cdot \rho(T_E + \Delta T_{SH}, p_{E,dew}) \]  

(15)

The referenced condenser mass flow rate \( \dot{m}_C^0 \) is derived from Equation (3) assuming no heat losses and the referenced enthalpy of the injected refrigerant as stated in Equation (16).

\[ h_{inj}^0 = h(p_{inj}^0, x_{inj}^0) \]  

(16)

The values for the referenced measured parameters \( Y_i^0 \) are summarized in Table 2. The refrigerant properties were calculated using RefProp [11].

Table 2. Reference state for measured parameters

| \( p_{4-2, 4-1}^0 \) [bar(a)] | \( p_{inj}^0 \) [bar(a)] | \( T_{4-2}^0 \) [K] | \( T_{4-1}^0 \) [K] | \( T_{inj}^0 \) [K] | \( \rho_{inj}^0 \) [kg/m³] | \( \dot{m}_E^0 \) [kg/s] | \( \dot{m}_C^0 \) [kg/s] | \( \dot{V}_{inj,g}^0 \) [10⁴ m³/s] |
|-----------------------------|------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 19.88                       | 10.00                  | 316.5             | 293.9             | 297.2             | 44.94             | 0.09675           | 0.07767           | 4.226             |

The referenced unknown parameters \( Z^0 \) are representative for ideal conditions. For the Calorimeter Method the reference heat losses are zero (\( q_{amb}^0 = 0 \% \)) assuming an ideally insulated heat exchanger economizer and injection line. For the Direct PD Method the reference slip ratio is based on a homogeneous flow (\( S^0 = 1 \)) which suggests that both vapor and liquid travel at the same velocity.
The referenced measurement uncertainties are based on the best sensor uncertainty available in Table 2 and are summarized in Table 3. For this investigation, the pressure range of all pressure sensors is assumed to be 35 bars.

| $U_ρ^0$ | $U_T^0$ | $U_ρ^0$ | $U_m^0$ | $U_V^0$ |
|---------|---------|---------|---------|---------|
| [bar]   | [K]     | [kg/m³] | [kg/s]  | [m/s]   |
| ±0.0175 | ±0.1    | ±0.5    | ±0.0015 | ±0.01   |

2.4. Approach for comparative investigation

The comparative investigation is divided into the distribution analysis, the sensitivity analysis, and unknown analysis.

The distribution analysis is based on Equations (11) and (12) and calculates the overall uncertainty $U_x$ of each method as well as the relative uncertainty contribution of each sensor type at the reference state 0. The result indicates the importance of each sensor for the VMF measurement as well as the lowest achievable VMF uncertainty for each method.

The sensitivity analysis is based on Equation (11) and compares the impact of a changing measurement uncertainty of a particular sensor type. For the analysis the uncertainties of the investigated sensor is varied within the range of the common uncertainties listed in Table 2 while the other sensor types remain at their referenced uncertainty $U_{x,ij}^0$. This analysis simulates the impact of low accuracy sensors or altering sensor uncertainties on the overall uncertainty of the VMF method.

For the unknown analysis, the unknown parameters are varied within a reasonable range and their effect on the reference state is determined by Equation (17), where $Z$ represents the investigated unknown parameter, are the referenced measured parameters as, and $Z_0$ is the referenced unknown parameter.

$$\Delta x = x\left(X_1^0, ..., X_n^0, Z\right) - x\left(X_1^0, ..., X_n^0, Z_0\right)$$

(17)

For the Calorimeter method the relative ambient heat loss is varied within a range of $-5\% \leq \varphi_{amb} \leq +5\%$ as both heat gain and heat loss seem reasonable. For the Direct PD method the velocity ratio range is based on the estimated velocity ratios from Equations (8) and (9). Based on the reference injection pressure and the refrigerant R-407C the density ratio $\rho'/\rho''$ yields to 27.2 which leads to $S_{Chisholm} = 3.00$ and $S_{Chisholm} = 5.09$. The velocity ratio $S$ was therefore varied within a range of $1 \leq S \leq 10$.

3. Results of the comparative investigation

3.1. Results of the distribution analysis

The results of the distribution analysis are shown in Figure 6. The figure indicates that only three methods are preferable for the VMF measurement at the EVI system and that each method with mass flow measurements can be improved. At the reference state, the Direct PT Method shows the highest uncertainty with $U_x = \pm 0.021$ kg/kg and is therefore not preferable for the VMF measurement. The uncertainties of the other methods are comparable at the reference state and range from $\pm 0.0098$ kg/kg to $\pm 0.0134$ kg/kg.

The VMF uncertainty of the Calorimeter Method is mainly affected by the uncertainty of the mass flow measurement ($\varepsilon_m = 68.74\%$) and the uncertainty of the temperature measurement ($\varepsilon_t = 31.23\%$). The distribution of the mass flow measurement is caused by injected mass flow which is determined from a mass flow difference measurement. A direct mass flow measurement of the injected mass flow would decrease the overall VMF uncertainty. The distribution of the pressure measurement uncertainty can be neglected for the Calorimeter Method since the calculated enthalpies in Equations (2) and (3) are based on liquid phase refrigerant and thus the enthalpy is mainly temperature.
dependent. For the Direct PT Method the temperature measurement shows the major distribution to the overall VMF uncertainty with $\varepsilon_T = 73.35\%$ and $\varepsilon_p = 26.65\%$. Compared to the other methods, the pressure has a significant impact on the Direct PT Method due to the temperature glide of R-407C. The uncertainty of the Direct PD method mainly results from the density measurement which distributes $\varepsilon_\rho = 97.4\%$. For the Separation Method both volume flow measurement and mass flow measurement have the main influence on the overall uncertainty with $\varepsilon_V = 50.37\%$ and $\varepsilon_m = 47.97\%$. Again, the mass low measurement distribution can be reduced when measuring the injected mass flow rate directly.

![Figure 6](image.png)

**Figure 6.** Results of the distribution analysis for the Calorimeter method (1), the Direct PT method (2), the Direct PD method (3) and the Separation method (4)

3.2. Results of the sensitivity analysis

The results of the sensitivity analysis are shown in Figure 7. The figure reveals high accuracy VMF measurements for sensor uncertainties close to the reference uncertainties $U_{V,i}$ and that three methods are very sensitive to increased pressure measurement uncertainties.

The Calorimeter Method is sensitive to changes in temperature and mass flow measurement uncertainties. The VMF uncertainty changes with 0.052/K due to $U_T$ and 0.052/% due to $U_m$. The sudden rise in uncertainty of the Calorimeter Method is caused by state point 3 and the small subcooling of 2 K, which leads to an apparent two-phase state when using low accuracy pressure sensors ($U_p > 2.5\%$) or temperature sensors ($U_T > 2K$). The Direct PT Method shows the highest sensitivity of all four methods with 0.090/K due to $U_T$ and 0.105/% due to $U_p$. This high sensitivity is not preferable for accurate VMF measurements and it is caused by the moderate temperature glide of R-407C which is 5.6 K at the referenced injection pressure. However, this sensitivity will be reduced for refrigerants with higher temperature glides as compared to R-407C. The VMF uncertainty of the Direct PD Method varies with 0.022/(kg/m³) for different $U_\rho$ and with 0.035/% for varying $U_p$. The Separation Method is mainly sensitive to pressure and mass flow measurement uncertainties. Its VMF uncertainty varies with 0.058/% for different $U_m$, 0.033/% for different $U_p$ and 0.009/% for different $U_V$. The pressure sensitivity of the Separation Method could be eliminated when using a mass flow meter to measure the saturated refrigerant vapor flow.
3.3. Results of the unknown parameter analysis

The results of the unknown parameter analysis are shown in Figure 8. The unknown heat loss or gain in the Calorimeter method leads to an error of $\Delta x/\Delta \phi_{\text{amb}} = \mp 0.009\%$. Therefore, the heat loss has to be determined during the Calorimeter method since the error to the VMF measurement is unneglectable. The variation of the velocity ratio $S$ leads to an underestimation of the VMF at the maximum of $\Delta x = 0.05$ kg/kg. This is due to the definition of $\dot{x}_{\text{inj}}$ in Equation (6), which yields to $\dot{x}_{\text{inj}} = 1$ for $S \to \infty$. For $S = S_{\text{Zivi}} = 3.00$, the underestimation is $\Delta x = 0.033$ kg/kg and $S = S_{\text{Chisholm}} = 5.09$ leads to an underestimation of $\Delta x = 0.040$ kg/kg. The assumption of a homogeneous flow ($S = 1$) is therefore not sufficient. Without any information on the velocity ratio, the Direct PD Method can only narrow down the range of possible VMF values and is therefore not applicable for accurate VMF measurements.

Figure 8. Results of the unknown analysis
4. Conclusion

The uncertainty investigation in this paper revealed that three of the four investigated VMF methods are generally applicable for VMF measurements. The achievable VMF uncertainty for the investigated reference state and R-407C as the refrigerant ranged from ±0.0098 kg/kg to ±0.021 kg/kg. Each method showed different sensitivity to changing sensor uncertainties and generally required high accuracy sensors for low VMF uncertainties. For future two-phase injection operation of EVI systems, the limits of the VMF measurement accuracy need to be taken into account for a reliable injection control.

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