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Uncertainty Analysis of the Experimental Results of Air Conditioner Performance due to Uncertainty of Equation of States

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ABSTRACT

In previous literature, the uncertainty analyses of experimental results of air conditioners usually ignored the uncertainty due to the equation of state (EoS) of the refrigerants. One possible reason was that the uncertainty reported in the EoS literature was much smaller than the one of the measurement. However, with the advancement of the measurement technologies, the impact of measurement uncertainty on the air conditioner performance calculation is lowered and becomes on par with that of the EoS. Simultaneously, new research findings give more comprehensive understanding of the EoS uncertainties, such as that the uncertainty of EoS reported in previous studies was underestimated under some conditions. To examine if the uncertainty of experimental results of a thermal system are significantly affected by the new findings, an uncertainty analysis is carried out with experimental data of an air conditioner using propane. The results show that the uncertainty of EoS has a more significant impact on experimental results involving saturation temperature such as subcooling and superheat measurement than the uncertainties of the measurement, while its impact on the uncertainty of the measured heat transfer rate is still not as significant in most cases.

1. INTRODUCTION

Uncertainty analyses of air conditioner performance mainly focus on propagating experimental measurement uncertainties to the output results of the cycle. For example, ASME Performance Test Code 30 (ASME, 2016) only considered measurement uncertainty and changes in the environment as the only sources of uncertainties to the test results of heat exchangers. Payne et al. (1999) only quantified uncertainties due to measurement sensors in an air conditioner experiment. Considering measurement uncertainties only may miss other important sources of uncertainties in air conditioner experiments such as the uncertainties of equation of state (EoS) that is used to estimate thermodynamic properties in the analyses. For example, Cheung et al. (2017) showed that the uncertainty of EoS may contribute to the uncertainty of saturation temperature more than the uncertainty of the pressure transducers. Cheung and Wang (2018) also demonstrated that the uncertainties of heat transfer rate due to sensors have the same order of magnitude as the uncertainties propagated from the EoS of the refrigerant used in the air conditioner. These examples show that other uncertainty sources such as the uncertainty of EoS of refrigerant properties that may also be important to experimental analyses of performance of air conditioners.

The aforementioned studies used the uncertainties recorded in the literature of EoS (Lemmon, 2003) but did not utilize new methods to quantify the impact of uncertainties by the EoS. For example, Feistel et al. (2016) calculated uncertainties of EoS based on uncertainties of experimental results in the literature by refitting EoS with generalized least-squares method to quantify the uncertainty of EoS of steam. Frutiger et al. (2016) conducted a similar study using Monte Carlo method to quantify the effects of uncertainties of EoS of various refrigerants on organic Rankine cycle power outputs. Unlike the uncertainties reported in the literature of EoS that were calculated solely based on the EoS accuracy (Lemmon, 2003), these studies calculated the uncertainties of EoS based on statistical methods (JCGM 2008; Coleman and Steele, 2009) that are more appropriate than the accuracy of the models. These methods should be able to account for the effects of uncertainties of EoS to experiments of air conditioners more reasonably than ones in Cheung et al. (2017) and Cheung and Wang (2018).

In this study, the effects of uncertainties of EoS on the uncertainties of the air conditioner performance are studied by using an uncertainty calculation method of EoS based on Seber and Wild (1989). The method was used to derive the uncertainty calculation method of Helmholtz-energy-based EoS in Cheung et al. (2018). This study applied the technique to the air conditioner test result in Abdelaziz et al. (2015) as a case study to examine the effect of uncertainty of EoS to the experimental analyses of air conditioner performance.

2. CALCULATION METHOD OF EOS UNCERTAINTY

Cheung et al. (2018) developed a method to calculate uncertainty of Helmholtz-energy-based EoS based on the uncertainty calculation method of a regression model in Seber and Wild (1989) and demonstrated the method using the EoS of propane in Lemmon et al. (2009). Regression models are mathematical models that estimate a value of a dependent variable based on some independent variables and a set of parameters. These parameters are estimated from a set of training data with observations of dependent variables and independent variables in the system to be modeled. Its mathematical description is shown in Equations (1) and (2).

$$y_{pred} = f(\vec{x}, \vec{\beta}) \tag{1}$$

$$\vec{\beta} = g(X_{train}, \vec{y}_{train}) \tag{2}$$

where y_{pred} is the predicted dependent variable, $\vec{x}$is a vector of independent variables, $\vec{\beta}$is a vector of parameters, $X_{train}$is a matrix of independent variables in the training data and $\vec{y}_{train}$is a vector of dependent variables in the training data.

The choices of the mathematical form in Equation (1) and the training data used to estimate the parameters in Equation (2) is subjected to the model developers and the limitations of resources to obtain the training data. Depending on the criteria of the choices, the results of the estimation of Equation (1) may vary. Seber and Wild (1989) provide a method to calculate the uncertainty of the model prediction by calculating the confidence interval of the estimation of the dependent variable by Equations (3), (4) and (5).

$$\Delta y_{pred} = \sqrt{diag\left(COV(y_{pred})\right)}\, t(n-m, \gamma_t/2) \tag{3}$$

$$COV(y_{pred}) = \vec{J}(\vec{x}, \vec{\beta})COV(\vec{\beta})\vec{J}(\vec{x}, \vec{\beta})^T \tag{4}$$

$$COV(\vec{\beta}) = \left(\frac{SSE}{n-m}\right)^2 \left(J(X_{train}, \vec{\beta})J(X_{train}, \vec{\beta})^T\right)^{-1} \tag{5}$$

where Δy_{pred} is the uncertainty of y_{pred}, $COV(y_{pred})$ is the covariance matrix of y_{pred}, $diag\left(COV(y_{pred})\right)$ is the diagonal entries of the matrix, $t(n-m, \gamma_t/2)$ is the Student t-statistics with n-m degree of freedom and Type I error γ_t, $\vec{J}(\vec{x}, \vec{\beta})$ is the Jacobian vector of $f(\vec{x}, \vec{\beta})$ with respect to $\vec{\beta}$, SSE is the sum of square of errors of the regression model, n is the number of training data points and m is the number of coefficients.

Equations (3), (4) and (5) show how the uncertainty of a dependent variable from a regression model can be calculated based on the training data, the estimated parameter and the sum of square error of the regression model. Details of the calculation method can be found in Seber and Wild (1989).

To use the technique for the uncertainty calculation of the Helmholtz-energy-based EoS (HEoS) of thermodynamic properties of pure substances, the mathematical form of the HEoS has to be understood. The HEoS can be described by a nonlinear equation of dimensionless Helmholtz energy α as a function of temperature T, density ρ and parameters θ_{EoS} as shown in Equation (6).

$$\alpha = f(T, \rho, \theta_{EoS}) \tag{6}$$

By calculating the dimensionless Helmholtz energy, other thermodynamic properties can be calculated by explicit equations depending on the model parameters, dimensionless Helmholtz energy, its partial derivatives, temperature and density values (Lemmon et al., 2009). If the temperature or density values are unknown, numerical methods will be used with the equations to calculate the temperature, density and Helmholtz energy values before calculating other thermodynamic properties. To describe the transformation between vapor and liquid due to a change of temperature and density of the pure substance, Maxwell's criteria are used to find the temperature and density that defines the transition between vapor, liquid-vapor mixture and liquid (Bejan, 2006).

Although Equation (6) is a nonlinear equation, multiple features of HEoS hinder the direct application of the method in Seber and Wild (1989) for the uncertainty of HEoS. These features are:

- Training data of HEoS contain multiple types of dependent variables such as pressure and specific heat capacity but the uncertainty calculation method in Seber and Wild (1989) is made to be applied to a model using one type of dependent variable only;
- Seber and Wild (1989) only provides a method to calculate uncertainties of dependent variables, but applications of HEoS may also the uncertainties of temperature and density values that are independent variables in Equation (6). An uncertainty calculation method of HEoS should also calculate these uncertainties;
- The differences of values of some properties such as enthalpy and entropy are more important than the magnitude of a single property value, so it is important to account for the correlation between the uncertainties of properties to accurately describe the uncertainties of the differences of these properties;
- The calculation of uncertainties of properties at saturation depends on the use of the Maxwell's criteria which contain a set of implicit equations. A method to propagate the uncertainties of Equation (6) through the Maxwell's criteria is needed to calculate the uncertainties of the properties at saturation;
- The training process involves the differences of Gibbs energy of saturated liquid and vapor at vapor pressure data points instead of the measured and predicted vapor pressure (Bell et al. 2018).

In order to deal with these issues, the method in Cheung et al. (2018) modifies the uncertainty calculation method in Seber and Wild (1989) with the following measures:

- Normalizing the Jaocbian matrix in Equation (5);
- Using the Kline and McClintock (1953) method and the finite difference method (Nocedal and Wright, 2006) to propagate the uncertainty of EoS of other properties such as pressure and entropy to the temperature and density values;
- Calculating the covariance of differences of dependent variables in Equation (4) instead of the covariance of a single dependent variable to calculate the uncertainties of differences of properties;
- Using the Kline and McClintock (1953) method to calculate the uncertainties of saturation densities by propagating the uncertainties from Equation (6) through the equations in the Maxwell criteria for the uncertainties of other saturation properties;
- Involving Gibbs energy of vapor pressure data points in the Jacobian vectors and the calculation of SSE.

The detailed mathematical description of the modification can be found in Cheung et al. (2018). With the modified method, the uncertainty of HEoS can be calculated, and the effects of uncertainties to the performance metric of air conditioners can be quantified.

3. DESCRIPTION OF TEST SETUP AND PERFORMANCE ANALYSIS

Abdelaziz et al. (2015) conducted an experiment of the performance of a 5.25kW split air conditioner using propane in a pair of environmental chambers as shown in **Figure 1**.

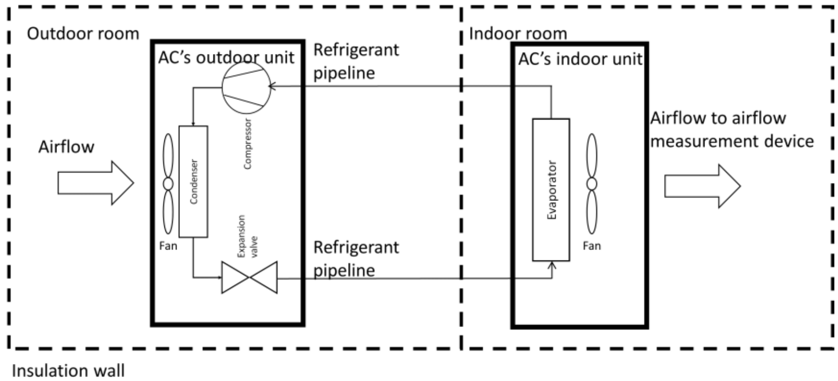

Figure 1: Test setup of a split air conditioner in environmental chambers

To quantify the performance of the air conditioner comprehensively, the study tested its steady-state performance under 6 different conditions as shown in **Table 1**.

Table 1: Testing conditions of the split air conditioner

Test condition	**AHRI B**	**AHRI A**	**T3***	**T3**	**Hot**	**Extreme**
Outdoor temperature [°C]	27.8	35	46	46	52	55
Indoor dry-bulb temperature [°C]	26.7	26.7	26.7	29	29	29
Indoor wet-bulb temperature [°C]	19.4	19.4	19	19	19	19

The performance of the air conditioner was quantified by measuring the temperature, pressure and flows of air as well as refrigerant at multiple locations of the setup. Since this paper only involved the uncertainty calculation method of refrigerant properties but no the air properties, only the refrigerant-side measurement was investigated. The information of the sensors for the refrigerant-side measurement are listed in **Table 2**.

Table 2: Uncertainty of sensors on the refrigerant-side of the air conditioner

Type of sensor	**Measurement**	**Accuracy**
T-type thermocouple	Refrigerant temperature	±0.28°C
Pressure transducer	Pressure in refrigerant pipes	±0.08% of reading
Coriolis mass flowmeter	Refrigerant mass flow rate	±0.1% of reading

The measurement by sensors in **Table 2** collected data for the calculation of the air conditioner performance metrics as shown in Equations (7), (8) and (9).

$$\dot{Q} = \dot{m}\left(h_{evap,out}\left(T_{evap,out}, p_{evap,out}\right) - h_{cond,out}\left(T_{cond,out}, p_{cond,out}\right)\right) \tag{7}$$

$$SH = T_{evap,out} - T_{evap,out,sat}\left(p_{evap,out}\right) \tag{8}$$

$$SC = T_{cond,out,sat}\left(p_{cond,out}\right) - T_{cond,out} \tag{9}$$

where $\dot{Q}$ is cooling capacity, $\dot{m}$ is refrigerant mass flow rate, h is enthalpy, p is pressure, evap,out refers to a variable at the evaporator outlet, cond,out refers to a variable at the condenser outlet, SH is superheat, SC is subcooling and sat refers to a variable for a substance at saturation.

Equation (7) calculates the cooling capacity of the air conditioner and quantifies the maximum amount of cooling the air conditioner can deliver under the test condition. Equation (8) calculates its superheat, and an appropriate value around 11.1°C indicates that the compressor is running appropriately (Dabiri and Rice, 1981). Equation (9) calculates its subcooling, and a value around 8.3°C indicates that the refrigerant charge level inside an air conditioner is appropriate (AHRI, 2004).

Since the equations depend on measurements of the refrigerant temperature, pressure and mass flow rate, the contribution of the measurement uncertainty to the uncertainty of the performance metrics in Equations (7), (8) and (9) can be calculated by Equations (10), (11) and (12) based on Kline and McClintock (1953).

$$\Delta\dot{Q}_{mea} = \sqrt{\begin{array}{l} \left(\frac{\partial\dot{Q}}{\partial\dot{m}}\Delta\dot{m}_{mea}\right)^2 + \left(\frac{\partial\dot{Q}}{\partial h_{evap,out}}\frac{\partial h_{evap,out}}{\partial T_{evap,out}}\Delta T_{evap,out,mea}\right)^2 \\ \quad + \left(\frac{\partial\dot{Q}}{\partial h_{evap,out}}\frac{\partial h_{evap,out}}{\partial p_{evap,out}}\Delta p_{evap,out,mea}\right)^2 \\ \quad \left(\frac{\partial\dot{Q}}{\partial h_{cond,out}}\frac{\partial h_{cond,out}}{\partial T_{cond,out}}\Delta T_{cond,out,mea}\right)^2 \\ \quad + \left(\frac{\partial\dot{Q}}{\partial h_{cond,out}}\frac{\partial h_{cond,out}}{\partial p_{cond,out}}\Delta p_{cond,out,mea}\right)^2 \end{array}} \tag{10}$$

$$\Delta SH_{mea} = \sqrt{\left(\Delta T_{evap,out,mea}\right)^2 + \left(\frac{\partial T_{evap,out,sat}}{\partial p_{evap,out}}\Delta p_{evap,out,mea}\right)^2} \tag{11}$$

$$\Delta SC_{mea} = \sqrt{\left(\Delta T_{cond,out,mea}\right)^2 + \left(\frac{\partial T_{cond,out,sat}}{\partial p_{cond,out}}\Delta p_{cond,out,mea}\right)^2} \tag{12}$$

where mea refers to a measured variable.

The equations to calculate the performance metrics also depend on the HEoS because enthalpy values and saturation temperature values are calculated from the measurements using the HEoS. The contribution of EoS uncertainties to the uncertainties of performance metrics is quantified by Equations (13), (14) and (15).

$$\Delta\dot{Q}_{EoS} = \dot{m}\Delta\left(h_{evap,out} - h_{cond,out}\right)_{EoS} \tag{13}$$

$$\Delta SH_{EoS} = \Delta T_{evap,out,sat,EoS} \tag{14}$$

$$\Delta SC_{EoS} = \Delta T_{cond,out,sat,EoS} \tag{15}$$

where EoS refers to a variable calculated from EoS

The uncertainties of enthalpy difference and saturation temperature in Equations (13), (14) and (15) are calculated based on the uncertainty calculation method in Section 2.

Other details of instrumentation of sensors, the testing procedure and the measurement data could be found in Abdelaziz et al. (2015).

4. RESULTS AND DISCUSSION

4.1 Cooling capacity

The cooling capacity in each test calculated from Equation (7) and their uncertainties calculated from Equations (10) and (13) are tabulated in Table 3.

Table 3: Heat transfer rates and their uncertainties in various tests

Test condition	AHRI B	AHRI A	T3*	T3	Hot	Extreme
Heat transfer rate [W]	6078	5769	5108	5145	4759	4594
Uncertainty of heat transfer rate due to measurement [W]	19	20	21	21	22	23
Uncertainty of heat transfer rate due to EoS [W]	2	2	2	2	2	2

Table 3 shows that the cooling capacity uncertainties due to EoS are only approximately 10% of the uncertainties due to measurement. This shows that the uncertainties of EoS are insignificant relative to the cooling capacity uncertainties due to measurement. The reason of the small uncertainties due to EoS is the correlation of uncertainties of enthalpy values in Equation (7). The uncertainties of enthalpy values in Equation (7) are found to be highly correlated with each other, and a large part of the uncertainties cancel each other out as their differences are calculated in Equation (7). Hence the uncertainty of the enthalpy difference in Equation (13) and the uncertainties of cooling capacity due to EoS in Table 3 become small.

4.2 Superheat and subcooling

The superheat and subcooling of air conditioners in various test and their uncertainties are tabulated in Table 4 and Table 5.

Table 4: Superheat and their uncertainties in various tests

Test condition	AHRI B	AHRI A	T3*	T3	Hot	Extreme
Superheat [°C]	5.73	4.21	2.52	2.14	1.34	1.47
Uncertainty of superheat due to measurement [°C]	0.28	0.28	0.28	0.28	0.28	0.28
Uncertainty of superheat due to EoS [°C]	2.08	2.02	1.97	1.96	1.93	1.91

Table 5: Subcooling and their uncertainties in various tests

Test condition	AHRI B	AHRI A	T3*	T3	Hot	Extreme
Subcooling [°C]	7.52	6.75	4.62	4.72	2.97	2.37
Uncertainty of subcooling due to measurement [°C]	0.28	0.28	0.28	0.28	0.28	0.28
Uncertainty of subcooling due to EoS [°C]	1.49	1.46	1.50	1.50	1.55	1.57

Table 4 and Table 5 show that the uncertainties of superheat and subcooling due to EoS are much larger than that of the uncertainties due to measurement. The reason is the Maxwell criteria which are mandates the calculation steps of saturation pressure and the lack of correlation between uncertainties of pressure values. Maxwell criteria determines the saturation pressure by solving Equations (16) and (17) simultaneously.

$$g(T,\rho_l) - g(T,\rho_v) = 0 \tag{16}$$

$$p(T,\rho_l) - p(T,\rho_v) = 0 \tag{17}$$

where g is Gibbs energy.

The solution yields not only the density values of the saturated liquid and vapor but also the Gibbs energy and pressure at saturation. The uncertainty of saturation temperature can then be calculated by converting the pressure difference uncertainty in Equation (17) to the uncertainty of saturation temperature by the Kline and McClinktock (1953) method. The equations show that the uncertainty of saturation temperature is highly dependent on the uncertainty of pressure values calculated at the saturated liquid condition. The high derivative of liquid pressure with respect to density causes high uncertainty of pressure differences in Equation (17). This implies that a small change of measured properties in the liquid region in the training data may lead to a very different liquid pressure value in Equation (17) and hence very different saturation temperature. As a result, the uncertainty of saturation temperature and the uncertainties of subcooling and superheat due to EoS in Table 4 and Table 5 are much larger than that of measurement.

To illustrate that the cause of the large uncertainty is the presence of liquid pressure as a function of density in the Maxwell criteria, the uncertainties of superheat and subcooling due to EoS in Table 4 and Table 5 are also calculated by imposing the uncertainty calculation method of regression model in Seber and Wild (1989) on Equation (18).

$$ln\left(\frac{p_{sat}}{p_c}\right) = \beta_0\left(\frac{T_c}{T_{sat}}\right)\left(1-\frac{T_{sat}}{T_c}\right) + \beta_1\left(\frac{T_c}{T_{sat}}\right)\left(1-\frac{T_{sat}}{T_c}\right)^{1.5} + \beta_2\left(\frac{T_c}{T_{sat}}\right)\left(1-\frac{T_{sat}}{T_c}\right)^{\beta_3} + \beta_4\left(\frac{T_c}{T_{sat}}\right)\left(1-\frac{T_{sat}}{T_c}\right)^{\beta_5} + \beta_6\left(\frac{T_c}{T_{sat}}\right)\left(1-\frac{T_{sat}}{T_c}\right)^{\beta_7} \tag{18}$$

Equation (18) is the anxiliary equation used in Lemmon et al. (2009) that calculates saturation pressure from saturation temperature of propane. It is used to calculate the saturation pressure from temperature, and Equations (3), (4) and (5) can be used to calculate the uncertainty of saturation pressure from Equation (18). The uncertainty of saturation temperature from the EoS can then be calculated from that of saturation pressure by Equation (19) using by the Clausius-Clapeyron relation (Çengel and Boles 2005).

$$\Delta T_{sat} = \left.\frac{dT}{dp}\right|_{sat} \Delta p_{sat} \tag{19}$$

Using Equation (19) to calculate the saturation temperature can help to analyze the cause of high uncertainty in Table 4 and Table 5, because it only describes the relationship between saturation temperature and pressure. It does not depend on liquid pressure as a function of density, and the derivatives of liquid pressure with respect to density and the Maxwell criteria cannot affect the uncertainty of Equation (19). If the uncertainty of superheat and subcooling due to the uncertainty of saturation temperature from Equation (19) is small, it shows that the high uncertainty in Table 4 and Table 5 is a result of the use of Maxwell criteria in HEoS but not the vapor pressure data.

To calculate the uncertainty of saturation temperature from Equation (19), the covariance matrix of the coefficients in Equation was first calculated using the 1376 phase boundary pressure data points of propane listed in Cheung et al. (2018). The data were also used to calculate the Jacobian matrices and vectors in Equations (4) and (5) to find the uncertainty of the saturation pressure. The uncertainties of saturation temperature, superheat and subcooling can be calculated using Equation (19). The results are tabulated in Table 6.

Table 6: Uncertainties of subcooling and superheat in various tests based on Equation (19)

Test condition	**AHRI B**	**AHRI A**	**T3***	**T3**	**Hot**	**Extreme**
Uncertainty of superheat due to EoS [°C]	0.10	0.10	0.10	0.10	0.10	0.10
Uncertainty of subcooling due to EoS [°C]	0.11	0.12	0.13	0.13	0.15	0.15

The superheat and subcooling values in Table 6 are much smaller than that in Table 4 and Table 5. This shows that the cause of the high uncertainty of EoS in Table 4 and Table 5 is the use of Maxwell criteria in HEoS. If the Maxwell's criteria are not used to calculate the saturation temperature, the saturation temperature values from an HEoS will not be influenced by the high sensitivity of the pressure values of liquid with respect to density, and the uncertainty of saturation temperature can be lowered significantly.

Although the uncertainties in Table 6 are smaller than the ones in Table 4 and Table 5, the values of uncertainties in Table 6 are still approximately 42% of the uncertainties of superheat and subcooling due to measurement in Table 4 and Table 5. This shows that the uncertainties of EoS are significant to the uncertainties of superheat and subcooling values evaluated from experiments of air conditioners.

The validation results and other details of the anxiliary equation such as its theoretical background can be found in Lemmon et al. (2009).

6. CONCLUSIONS

To conclude, the effects of uncertainty of HEoS on the uncertainty of air conditioner performance metric from laboratory experiments are evaluated. The study was conducted by applying the uncertainty calculation method of HEoS of propane properties on the uncertainty calculation of the performance metrics of an air conditioner tested in a laboratory. While the results show that the uncertainty of EoS is negligible in the calculation of the air conditioner's cooling capacity, it is significant to the calculation of the superheat and subcooling from the experimental results of the air conditioner. If the saturation temperature is calculated based on the Maxwell's criteria, the uncertainty of the superheat and subcooling values are dominated by the uncertainty of EoS due to the high sensitivity of liquid pressure with density. However, if the saturation temperature is calculated from an anxiliary polynomial, the uncertainty of superheat and subcooling values due to HEoS will only be around 42% of that due to measurement.

NOMENCLATURE

COV(x)	covariance of variable x	(–)
$COV(\vec{x})$	covariance matrix of vector x	(US$)
diag(**X**)	diagonal elements of matrix X	(–)
f	function	(–)
g	Gibbs energy	(J/kg)
h	enthalpy	(J/kg)
$\vec{J}$	Jacobian vector	(–)
J	Jacobian matrix	(–)
m	number of parameters	(–)
$\dot{m}$	mass flow rate	(kg/s)
n	number of data points	(–)
p	pressure	(Pa)
$\dot{Q}$	cooling capacity	(W)
SC	subcooling	(°C)
SH	superheat	(°C)
SSE	sum of square error	(–)
t	Student t statistics	(–)
T	temperature	(°C)
$\vec{x}$	independent variable vector	(–)
X	independent variable matrix	(–)
y	dependent variable	(–)
$\vec{y}$	dependent variable vector	(–)

Greek

α	dimensionless Helmholtz energy	(–)
β	regression model parameter	(–)
$\vec{\beta}$	regression model parameter vector	(–)
γ_t	p-value for Student t statistics	(–)
Δx	uncertainty of variable x	(–)
ρ	density	(kg/m^3)

Subscript

c	critical
cond	condenser
evap	evaporator
EoS	equation of state
mea	measurement
out	outlet

pred	predicted
sat	saturation

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