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Error Propagation on a Hybrid Evaporator Model

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Error propagation calculation using Monte Carlo method (MC) is applied to the heat transfer rate (Q) predicted by a hybrid model. This Q permitted us to evaluate an evaporator used in a vapour compression refrigeration system. A hybrid model reported in literature was used in order to obtain error propagation in the heat transfer rate prediction. This model used the temperatures, the mass flow rates and the enthalpies for the evaporator. The influence of each operation variable over the standard deviation of a heat transfer rate (s_Q) was assessed.

1. Introduction

Evaporation is an important phenomenon that occurs in many engineering applications, ranging from refrigeration systems and heat pumps, to thermal devices and nuclear systems. Detailed knowledge of the various thermal-hydraulics phenomena in an evaporator device is necessary in order to fulfil its complete design of every component. According to Ding et al. (2009) the evaporator can be modelled with different levels of complexity: black-box, ε-NTU and distributed models. Many works reported in literature are aimed to control and optimization of thermal devices, for instance Vasickaninova et al. (2010, 2011) describe a strategy of control based in artificial neural networks (ANN) and one simplified nonlinear dynamic model of heat exchanger.
The hybrid approach is a reasonably alternative for modelling, optimization and control of thermal devices. The methodology involves energy and material balance, structure of empirical models and a method of solution. Jin et al. (2007) developed a hybrid model of a cooling tower foreseen for control and optimization. Ding et al. (2009) presented a hybrid model to describe heat transfer rate of an evaporator, as a new form to modelling thermal devices in real time. In many cases, the influence of each operating variable of the thermal performance using a physical model (empirical or theoretical) is based a simple comparison between the prediction (without the weight of variable studied) and the experimental results. All previous, without taking into account the respective

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uncertainties in the variables evaluated. To remedy this situation, appropriate confidence intervals of Q should be experimentally determined.

Traditionally, error propagation is determined with equations proposed by (Bevington and Robinson, 2003). Error propagation from Monte Carlo method represents an alternative that consists of repeated calculation of a quantity, varying each time the input data randomly within their stated prediction limits. Indeed, Colorado et al. (2011) used the Monte Carlo method to propagate errors on performance prediction by ANN in a water purification system integrated to an absorption heat transformer.

Consequently, the objective of the present work is to present an influence of each operating variable of (s_Q) obtained by hybrid modelling, using the Monte Carlo method. The model of the evaporator was developed by Ding et al. (2009) for Q prediction on an evaporator foreseen for refrigeration applications. However, the hybrid model was developed without considering errors in the inlet variables. Therefore, in this work specific level of errors in the inlet variables were considered to obtain standard deviation estimates of heat transfer rate values.

2. Experimental Data

The test facility was located in a process instrumentation laboratory of Nanyang Technological University of Singapore. This experimental rig, shown in fig. 1, is made up of a semi-hermetic reciprocating compressor, an air-cooled finned-tube condenser followed by a liquid receiver, three electronic expansion valves and three evaporators (one air-cooled finned-tube evaporator and two electronic evaporators; In this case, the air-cooled evaporator is used only.) followed by an accumulator.

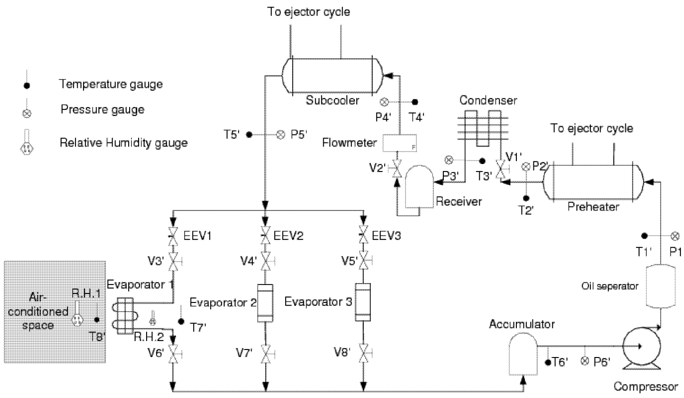

Fig. 1. Sketch of the experimental test section.

Table 1: Some experimental results (A-G) for the 6 inlet parameters of the evaporator a vapour compressor system.

Inputs	Unit	A	B	C	D	E	F	G
m_{SF}	kg s^{-1}	0.144	0.153	0.107	0.165	0.138	0.128	0.150
T_{SFi}	^{o}C	25.502	25.528	25.292	25.913	25.487	26.260	26.316
m_{WF}	kg s^{-1}	0.012	0.013	0.014	0.016	0.018	0.022	0.024
T_{sat}	^{o}C	-0.150	2.556	3.995	0.071	3.101	1.837	2.189
P_e	kPa	286.514	318.002	335.913	288.987	324.691	309.350	313.560
H_g	kJ kg^{-1}	398.541	400.105	400.927	398.670	400.417	399.692	399.894
H_{WFi}	kJ kg^{-1}	241.599	241.777	238.404	243.030	240.434	241.865	242.761
Q_{exp}	kW	1.859	2.011	2.194	2.410	2.694	3.222	3.458

The compressor, the condenser fan and the evaporator fan are equipped with variable speed drives such that the rotational speed can be adjusted continuously. The system is moreover equipped with temperature and pressure sensors on each side of the components in the refrigeration cycle. The measurement range of the pressure transducers and the temperature transmitters are 0~16 bar and -40 to 200^{o}C, respectively; and their uncertainty is within ±0.3% and ±0.3 K, respectively. Temperature sensors with the same accuracy are used to measure the inlet and outlet temperature of the secondary media on the evaporator and the condenser respectively. The mass flow of refrigerant in the refrigeration cycle is measured using a flow meter with an uncertainty of ±4%. The working fluid used in this work is R134a.

Table 1 shows some experimental information for a build-up of the hybrid model. The range of Q is from 1.85 to 3.45 kW. A total of 6 variables (2 of temperature, 2 of mass flux and 2 of enthalpy) were used and carefully registered.

3. Evaporator Modelling - A Hybrid Approach

Real time modelling was used to predict the heat transfer rate of evaporator using experimental vapour compression refrigeration information. In this model, hybrid approach methodology was applied according to the one described by Ding et al. (2009). In this research, the model is represented as the governing process fundamental equations based on an energy balance and heat transfer principles. Then, the linear least-squares method as described by Yong (1970) and Strejc (1980) was used to estimate the model parameters. Then, Q equation can be written as the linear equation. The Levenberg-Marquardt method described in Wolfe (1978) and (Nocedal and Wright, 1999) was applied to estimate the model unknown parameters. The optimal model introduces minimal error. In this work, the hybrid model with three parameters was used. A comparison with experimental and simulated data of heat transfer flux was carried out. According to the methodology proposed, the hybrid model is represented by the following equation:

$$Q = \frac{\left(H_g - H_{WFi}\right) m_{WF} + 0.0578 m_{WF}^{0.4146}\left(T_{SFi} - T_{sat}\right)}{1 + 0.4412\left(\frac{m_{WF}}{m_{SF}}\right)^{0.4146}} \quad (1)$$

For equation (1) the standard deviation of Q is unknown as well as the principal variable to influence it.

4. Methodology for Error Propagation Determination

Traditionally, error propagation is determined with equations presented by (Bevington and Robinson, 2003). Nevertheless, the introduction of their equations is an approximate solution for standard deviation determination Verma et al. (2006). Error propagation calculation using Monte Carlo method is a reasonable alternative when the complexity of the model is significant or the standard deviation is unknown. The method (see Fig. 2) is based on repeated calculations of a Q hybrid prediction, changing input datum every time (6 input variables related to the temperatures, to the pressures and to the enthalpies) by a random selection from its error probability distribution. Then, the location of a measurement point for each instrument is shown in Fig. 2. Saturation temperature and vapour enthalpy of the working fluid are functions of pressure evaporator while inlet enthalpy of working fluid is a function of inlet pressure and temperature. In this work, we not considered the influence of thermo-physical properties calculation based in pressure and temperature measurement. We inserted an error directly in the saturation enthalpy and inlet enthalpy of working fluid. The Monte Carlo method required to generate random numbers from a normal distribution to evaluate the input. In this work, the range reported for a parameter can be considered equal to six standard deviations.

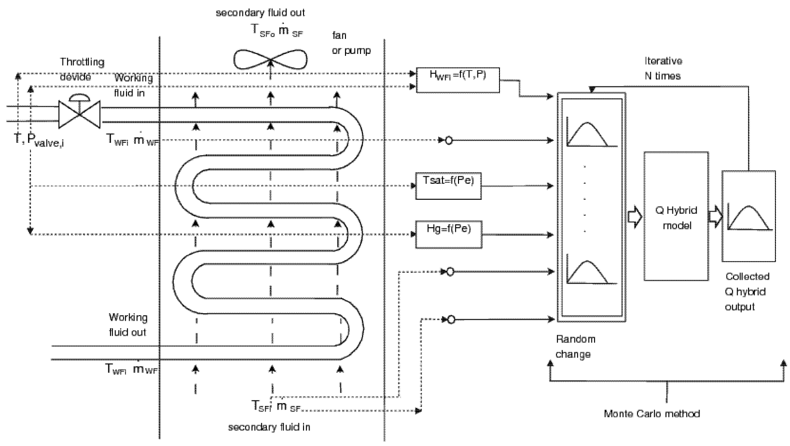

Fig. 2: Schematic representation of the system used to uncertainties analysis on a hybrid model by the Monte Carlo method

Table 2: Contribution of each operation variable of s_Q in %.

Inputs	A	B	C	D	E	F	G
H_g (%)	41.8026	41.928	42.2768	41.8670	42.2082	42.2160	42.1733
H_{WFi} (%)	12.8343	12.7772	12.4276	13.0059	12.6727	12.8874	12.9655
m_{WF} (%)	5.0770	5.0638	5.1719	4.9028	5.0038	4.8052	4.7644
T_{SFi} (%)	0.0736	0.0678	0.0599	0.0566	0.0468	0.0389	0.0352
m_{SF} (%)	0.0245	0.0243	0.0356	0.0261	0.0325	0.0378	0.0342
T_{sat} (%)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Q_{exp} (kW)	1.859	2.011	2.194	2.410	2.694	3.222	3.458
$Q_{sim\text{-}MC}$ (kW)	1.831	1.965	2.088	2.362	2.625	3.102	3.371
s_Q (kW)	0.051	0.055	0.058	0.067	0.074	0.089	0.097

We used the relative standard deviation ($\%RSD = 100\, s/\bar{x}$) for the error incorporated in the operation variables. The iterative model used to determine error propagation has the following sequence: Specify the uncertainty limit of the input layer (temperature, pressure and enthalpy) of Q prediction. Because the actual error estimates were not available, this work assumed the cases for instrumental measurement errors of %RSD = 1. The errors in this case are "typical" error, which might be representative of a routine experiment of the evaporator Verma et al. (2006). Random numbers with normal distribution from the average and standard deviation of every operational variable must be generated. Simulate Q prediction with hybrid model (eq. 1). Determinate the standard deviation and average of Q predicted distribution.

5. Numerical Results

Based on the above mentioned mathematical model (Eq. 1) and *Methodology for error propagation determination* section, a code was developed to estimate the standard deviation of predicted Q. The code has been carefully verified using, whenever possible, equations presented by (Bevington and Robinson, 2003). An excellent agreement was found between the average and standard deviation values obtained from Monte Carlo and traditional method.

The numerical results of Q using the Monte Carlo method with 100,000 random numbers and $\%RSD_{instrument} = 1$ in the equation obtained by hybrid model was used. The effect of each operation variable over s_Q was evaluated. For this analysis, the standard deviation is determined with Monte Carlo method without the error in the variable evaluated ($s_{Q\text{-}v}$) and it's compared with the standard deviation with errors in all input variables (s_{Qtotal}). The case with $\%RSD_{instrument} = 1$ was used and $\left(1 - s_{Q\text{-}v}/s_{Qtotal}\right) \times 100$ was applied. The results are shown in Table 2. The variable with the biggest contribution to the uncertainty of the heat transfer rate predicted is H_g, the contribution is ~42.06% of the total standard deviation. Other contribution important is the H_{WFi} with a ~12.79%. Therefore, the evaporator pressure P_e is the principal operation variable from the point of view of error propagation, because $H_g = f(P_e)$.

6. Conclusion

Error propagation from Monte Carlo method on Q prediction by a hybrid model of an evaporator used in a vapour compression refrigeration system has been successfully developed.
Several experimental conditions have been evaluated within a mean of %RSD = 2.81, for 7 experimental test. The operation variable with the biggest contribution of the standard deviation is the H_g, which is a function of evaporator pressure. Therefore, this level of error in the inlet operation variable is satisfactory to obtain excellent heat transfer predictions. Further investigation of related topics such as the different levels of error in the input operation variables, their influence of the standard deviation and influence of thermo-physical properties calculation would as well be beneficial.

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