The Prediction of Nominal and Off-design Characteristics of Economised Vapour Injection Scroll Compressor-driven Heat Pump

Minh Q. Nguyen[1*] and Neil J. Hewitt[2]

[1]College of Technology, University of Danang, Danang City, Vietnam
[2]Centre for Sustainable Technologies, University of Ulster, UK

Abstract

Economised vapour injection technology based on the integration of a hermetic scroll compressor and a brazed plate heat exchanger is capable of greatly improving vapour compression heat pump efficiency. However there has been a large difference in increased level of performance between off-design and nominal conditions due to the overall heat pump system being designed and built from several components which certainly interact with each other during operation process. The size and configuration of each component are particularly important factors causing the overall system performance to be deviated from nominal condition-based values and subsequently energy losses because of components to be either oversized or undersized unexpectedly. Experimental investigation was conducted to estimate these efficiency deviations in each individual component as well as the whole system under a wide range of working conditions. In comparison with the performance reference predicted by the Copeland Selection Software, the experimental results show a tendency of increasing deviation between the measured and predicted performances when the compressor power is increased while the experimentally measured heating capacities are slightly deviated from the nominal values throughout the operating range.

Keywords*:* Heat pump, Scroll compressor, Economised vapour injection, Heating capacity, Coefficient of performance

1. Introduction

Electric heat pumps are one of a range of heating devices that can be thought of as energy-efficient and environmentally friendly systems. They offer large energy savings due to the fact that a well-designed system will deliver considerably more heat energy than the primary energy used to drive it while also contribute to significant reduction of CO_2 emissions compared to other heating systems. If the electricity is produced from renewable sources, this benefit is further increased. However the energy savings and potential environment benefits offered by electric heat pump have been insufficient to enable them to become the first-choice heating system for domestic and commercial buildings because of inherent energy losses of vapour compression cycle on which heat pump is operated. Therefore improved vapour compression cycles including economised vapour injection (EVI) technique have been developed to overcome restrictions and limitations of the conventional vapour compression cycle in order to eliminate thermodynamic losses and enlarge the operation range of heat pump.

2. Heat pump with EVI technology

The economised vapour injection technology applying to vapour compression heat pump is a novel design concept using either an internal subcooling heat exchanger or a flash tank connected to an immediate pressure injection line of single two-stage scroll compressor. By subcooling the liquid refrigerant the flash gas formed during the expansion process is reduced and subsequently inducing a lower quality of refrigerant entering the evaporator contributing to improved heat transfer performance in the evaporator. On the other hand, by injecting cooled vapour into the scroll compressor at immediate pressure, the compressor work input and discharge temperature are reduced, resulting in decreased power consumption of the compressor and increased heat transfer effectiveness of the condenser. Figure 1 describes schematic principle of such two EVI heat pump cycles with internal subcooling heat exchanger and flash tank and its P-h diagrams.

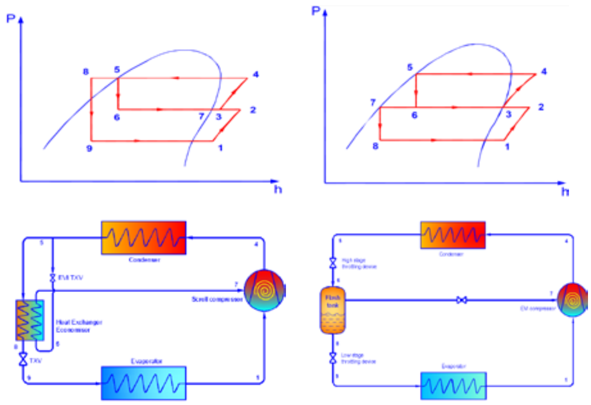

Fig. 1 EVI cycles and P-h diagrams

Many studies have been conducted both theoretically and experimentally to enhance the performance of conventional heat pump by using EVI technology integrated with either internal heat exchanger or flash tank [1-5]. The results showed significant large augmentation in overall efficiency, especially when operating in high temperature lift conditions which are disadvantageous for traditional heat pump. Some other intensive researches also demonstrated much further benefits obtainable from refrigerant injection as well as the effect of varying injection conditions on overall performance and compressor stability [6-7]. However the experimental systems developed in above mentioned

*Corresponding Author: E-mail: ngminh@ud.edu.vn , Tel: +84Z0X511 3894883, Fax: + 84 Z0X 511 389 4884

studies are probably constructed and tested based on off-design conditions which are entirely different from nominal values provided from manufacturer. The present paper predicts experimentally this deviation between nominal and off-design performances of EVI air-source heat pump for heating applications.

3. Experimental apparatus and data reduction

The heat pump prototype tested in the present study was developed based on vapour compression refrigeration system which consists of a Copeland EVI scroll compressor, two brazed plate-type heat exchangers for condenser and internal subcooler, a cylindrical finned tube heat exchanger for evaporator and two thermostatic expansion valves for main and subcooling circuits. Refrigerant R407C was selected with a critical temperature at 86.74^{o}C corresponding to a critical pressure of 46.191bar. The instrumentation was designed to measure temperature, pressure, humidity and flow rate of refrigerant, water and air as well as to monitor operational stability of the overall system during test processes. Data collection and system control were achieved by using a data acquisition system connected to a personal computer. A schematic diagram of such a test apparatus and measuring equipment as well as component layout in the test bed are illustrated in Figures 2 and 3.

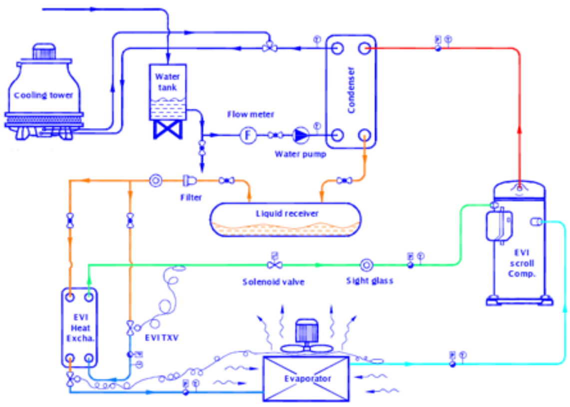

Fig. 2 Schematic diagram of test apparatus

Test conditions and procedures are in accordance with European Standards EN14511-2 and EN14511-3 respectively, regarding the rating and performance of an air-to-water heat pump with an electrically driven compressor. Details of test conditions are listed in Table I.

The operating effectiveness of heat pump system is represented by heating capacity Q_h^w and coefficient of performance COP_h on the water-side that both are calculated based on measured data as follows:

$$Q_h^w = m_w \int C_p^w dT_w = m_w (t_w^{out} - t_w^{in}) \qquad (1)$$

$$COP_h^w = \frac{Q_h^w}{W} \qquad (2)$$

Table I. Test conditions

Order of test	Air-on temperature (^{o}C)	Water-off temperature (^{o}C)
1	-12	60
2	-12	50
3	-7	60
4	-7	50
5	-2	50
6	2	60
7	2	50
8	2	35
9	7	60
10	7	50
11	15	60

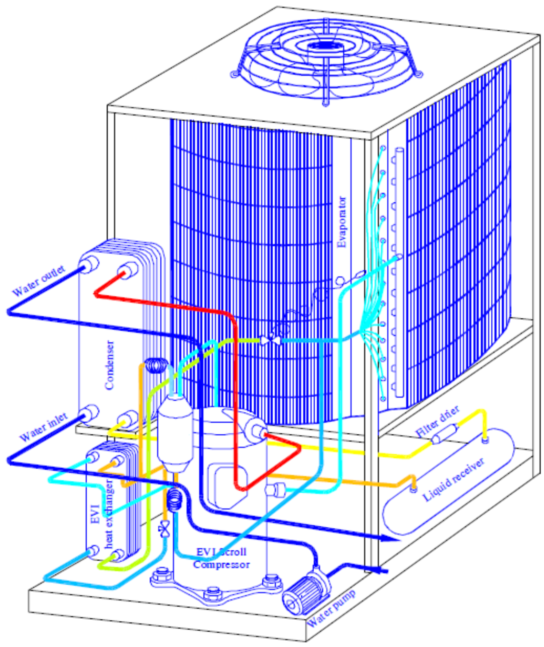

Fig. 3 Layout of components in test bed

In order to verify the validity of the measured data on the water-side, an energy balance using the thermodynamic laws is established in each test to calculate heating capacity Q_h^r and coefficient of performance COP_h^r on the refrigerant-side as follows:

$$Q_h^r = m_r \int C_p^r dT_r = m_r (i_r^{out} - i_r^{in}) \qquad (3)$$

$$COP_h^r = \frac{Q_h^r}{W} \qquad (4)$$

The error in heating capacities calculated on the water-side and refrigerant-side can be determined by the following equation and should be less than 5%:

$$\Delta Q(\%) = \frac{Q_h^r - Q_h^w}{Q_h^w} \times 100 \qquad (5)$$

Fig. 4 Test bed of EVI heat pump

Figure 4 shows a photograph of the experimental apparatus installed and commissioned in a test chamber along with all measuring equipment which are calibrated before embedding to the test system.

4. Results and Discussion

A heat pump system in practice is normally designed and assembled from a number of components provided by several different manufacturers. For instance, with test facilities of heat pump system in this study, EVI scroll compressor is provided by Copeland while SWEP brazed plate heat exchangers are used as the main condenser and internal subcooler. Evaporator and expansion valves are a circular shaped coil heat exchanger and Alco TISE types, respectively. So the operating parameters of each individual component are measured in association with the operation of the overall system. Their performance will be compared with the reference data available in the Copeland Selection Software (CSS) at the same working conditions in order to evaluate whether the operation of each component reaching to its nominal characteristics.

Figure 5 illustrates a comparison of compressor power between the actual measured values and reference values predicted by the CSS. Experimental measurements show higher measured values compared to the predicted values derived from the CCS. The tendency has larger deviation when the compressor power is increased.

It was also found that on average the electricity actually used by compressor is approximately 7% greater than that specified by manufacturer. This is due to higher mass flow rate of refrigerant through EVI subcooler that leads to higher EVI capacity in comparison with the reference value obtained from the CSS. Figure 6 shows this capacity increase which means that EVI subcooler is slightly oversized for integrating to the current EVI compressor under off-design conditions.

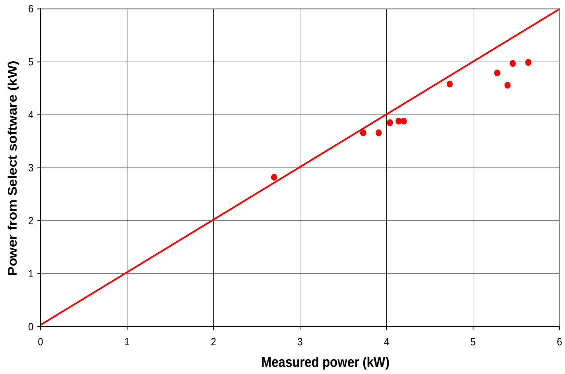

Fig. 5 Measured and predicted compressor power

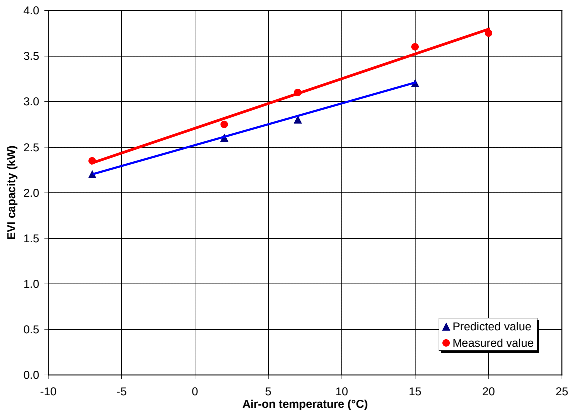

Fig. 6 Measured and predicted heat capacities of EVI subcooler

The performance assessment of SWEP brazed plate heat exchanger was also carried out over a wide range of operating condition. Due to the temperature glide of the refrigerant R407C, the refrigerant temperature for performance evaluation is rated at mid-point state. Figure 7 shows the variation of condenser mid-point temperature difference at several different test conditions of water-off temperature. Due to the condenser designed at the water temperature of 60^{o}C corresponding to the condensing mid-point temperature of 62^{o}C, the measured performance behaviour of the brazed plate heat exchanger have not changed significantly from off-design condition-based performance.

The deviation of condenser mid-point temperature difference over wide range of test conditions is relatively small. This means that the plate heat exchanger used for condenser is designed and sized properly under off-design conditions despite slightly oversized EVI subcooler causing higher refrigerant flow rate through both EVI compressor and condenser that is not still much to affect the condenser operating behaviour.

The comparison of heating capacity basing on the measured values and the reference data predicted by the CSS is illustrated in Figure 8. Both measured and predicted values seem to remain approximately the same during the range of test conditions. The deviation rate is seen to be small, approximately around ±3%.

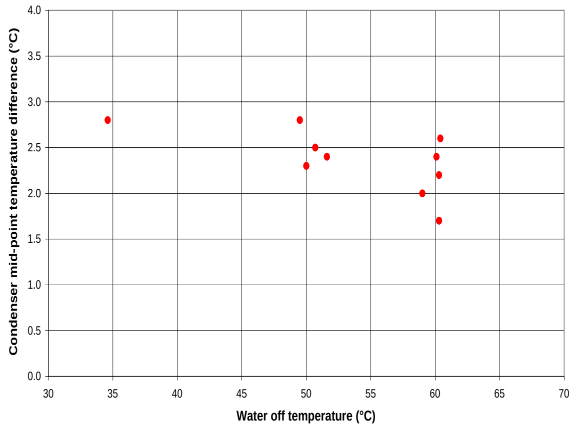

Fig. 7 Condenser mid-point temperature difference

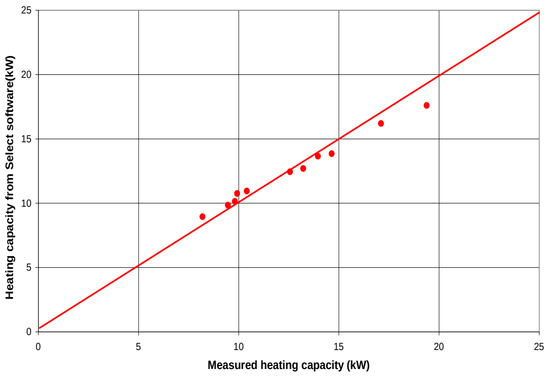

Fig. 8 Measured and predicted heating capacities of condenser

However the deviation behavior is different for every different test condition. For the cases of high heating capacity which is greater than 12kW, the measured value were found to deviate by maximum 3% over the predicted value while the inverse tendency was observed at the range of low heating capacities. This may be contributed by the performance of EVI subcooler which is more oversized when operating in high air-on temperature conditions.

Figure 9 describes the deviation in the overall system performance between actual COP calculated from measured data and nominal COP predicted by the CSS. The results show a significant degradation in the actual performance throughout the range of test conditions. As seen in Figure 5, on average the actual COP is reduced about 5.5% compared to the nominal COP specified by manufacturer. The reduced performance of the overall system is certainly induced by highly increased actual input of compressor power over the predicted power value as already presented above, while the actual heating capacity seems to be kept approximately the same as the predicted value.

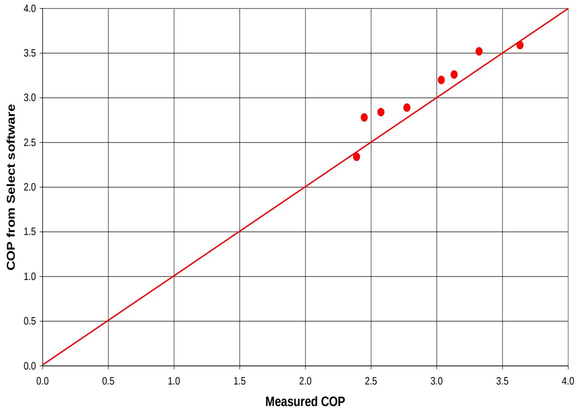

Fig. 9 Actual and predicted COPs of overall system

5. Conclusions

The economised vapour injection technique utilizing in vapour compression cycle has contributed to significant improvements in the performance of air-source heat pump, especially when operating at high temperature lift. However actual increased levels of performance are entirely not similar to those specified by manufacturer under nominal conditions. Although all components of the heat pump system are designed and commissioned basing on off-design conditions which are the same as nominal conditions, the overall system performance is still deviated significantly from the nominal value. This is due to operational interaction among components of system that induces degradation in performance of each individual component and subsequently the overall system. The system modification after design and commission processes is therefore extremely essential to obtain the highest possible efficiency.

6. References

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