Energy and Exergy Analyses of Heat Pump Cycle with Refrigerant Injection Technology

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ABSTRACT

The effect of refrigerant injection techniques on the performance of heat pump system based on exergy analysis was studied theoretically. Three refrigerant injection techniques were used; the first was achieved by injected vapour in volume ratios from 1 to 7% in the accumulator. The second was injection liquid refrigerant in the discharge line with the aid of Liquid Pressure Amplification (LPA) pump, with volume ratios from 1 to 10%. The third was a hybrid injection with volume ratios of injected vapour and liquid varied from 1 to 3% and 1 to 10%; respectively. The following improvements in cycle performance were observed. For vapour injection technique, the best ratio of injection was 5%, the exergy destruction reduced by 21% and exergy efficiency enhanced by 14.6%. For liquid injection technique the best ratio of injection was 6%, the reduction in exergy destruction was 34% while the exergy efficiency increased by about 21.4%. The hybrid injection technique increased the exergy efficiency by 23% when the volume ratio of vapour and liquid injections are 3% each. The effect of condensing pressure on the cycle performance was studied also. The optimum exergy efficiency of the cycle was 54.55% achieved when the condensing pressure was 15 bars.

Keywords: refrigerant injection, LPA technology, exergy, heat pump

تحليل الطاقة وجودتها لمضخة حرارية ذات تقنية حقن مائع التثليج

عبدالهادي نعمة خليفة
استاذ
الكلية التقنية الهندسية – بغداد

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الخلاصة

دراسة نظرية لبيان تأثير تقنيات حقن وسيط التبريد على أداء المضخة الحرارية وفقا لتحليل الاكسيرجي. تم أستخدام ثلاث تقنيات لحقن وسيط التبريد، الاولى أنجزت عن طريق حقن البخار بنسبة حجمية من 1 الى 7% داخل مجمع السائل. في الثانية تم حقن سائل وسيط التبريد خلال خط الدفع بأستخدام مضخة تضخيم ضغط السائل مع نسب حجمية من 1 الى 10%. التقنية الثالثة كانت الحقن المزدوج بنسب حجمية للبخار والسائل المحقونين من 1 الى 3% و 1 الى 10% على التعاقب. لوحظت التحسينات التالية في الدورة، لتقنية حقن البخار كانت افضل نسبة للحقن 5%، قلت الاكسيرجي الضائعةالى 21% وتحسن كفاءة الاكسيرجي الى 14.6%. لتقنية حقن السائل كانت افضل نسبة للحقن 6%، قلت الاكسيرجي الضائعة الى 34% بينما تحسنت كفاءة الاكسيرجي الى 21.4%. في تقنية الحقن المزدوج ازدادت كفاءة الاكسيرجي الى 23% عندما كانت النسبة الحجمية للبخار والسائل المحقونين 3% لكل منهما. تمت دراسة تأثير ضغط التكثيف على اداء الدورة ايضاً. أقصى كفاءة

اكسيرجي للدورة 54.55% تم الحصول عليها عندما كان ضغط التكثيف 15 بار.

الكلمات الرئيسة: حقن وسيط التبريد، تقنية LPA، اكسيرجي، مضخة حرارية

1. INTRODUCTION

It is known that all real thermodynamics cycles are irreversible due to heat transfer, friction, throttling, mixing and non-isentropic compression or expansion. The irreversibilities in cycle components caused entropy generation within each one of them, which leads to destruct exergy flowed and transported to the system. As the individual exergy destruction is identified, the source of thermodynamics inefficiencies can be defined, and the performance of each cycle components, as well as, the overall cycle performance can be evaluated and improved. Many works calculated and investigated the exergy destruction in vapour compression refrigeration cycle. **Torrella, et al., 2010** described a Second Law Analysis based on experimental data of a two-stage vapour compression facility driven by a compound compressor for medium and low-capacity refrigeration applications. The experimental analysis is performed for an evaporating temperature range between -36ºC and -20ºC and for a condensing temperature range between 30ºC and 47ºC using the refrigerant R-404A. The exergetic analysis of a vapour compression refrigeration system with selected refrigerants was introduced by **Reddy, et al., 2012**. They computed various parameters such as COP and exergetic efficiency in the system. Effects of condenser temperature, evaporator temperature and sub-cooling of condenser outlet, supper-heating of evaporator outlet and effectiveness of vapour liquid heat exchanger were also computed and discussed. It was found that R134a has the better performance in all respect, whereas R407C refrigerant has poor performance. The Voorhees' compression process was studied by **Morosuk, et al., 2012**. The Voorhees compression process is achieved at constant total volume with the help of injection of working fluid in the beginning of the compression process. They presented a conventional and an advanced exergetic analysis for Voorhees' compression process. This work focused theoretically on the exergy destruction and exergy efficiency of suggested heat pump cycle. A heat pump of 5 ton capacity, charged with R-22, was modified by injection of refrigerant in different phases and different locations in the cycle. The Engineering Equation Solver (EES) software was used to simulate the cycle.

2. EXERGY ANALYSIS

A heat pump cycle of 5 ton capacity, shown in **Fig. 1** was modified by installing liquid receiver, accumulator, secondary expansion valve and Liquid Pressure Amplification (LPA) pump. An attempt to improve the exergetic behaviour are done by three methods, the first by injection R-22 vapour in suction line, the volume ratio of injected vapour varied from 1 to 7% of the total refrigerant charge. The second by injecting liquid refrigerant in the discharge line, the ratio of injected liquid varied from 1 to 10% of the total refrigerant volume. While in third method, a hybrid injection is used, in which both vapour and liquid refrigerant is injected in the cycle at the same time. The volume ratios of injected vapour and liquid are varied from 1 to 3%, and 1 to 10% respectively. The thermal mathematical model for the energy analysis was adopted from the work of **Khalifa, et al**. The exergy analysis of this suggested cycle is as follows;

The exergy and energy analysis of compressor are as follows **Borgnakke, and Sonntag, 2009**:

Power consumed by compressor is:

$$\dot{W}_{comp.} = \dot{m}_{comp}.(h_2 - h_1) \quad (1)$$

The exergy destruction in compressor is:

$$\Psi_{dest.comp.} = \dot{m}_{comp} T_o (s_2 - s_1) \quad (2)$$

The exergy efficiency of compressor is the ratio of reversible to actual work, **Dincer, and Marc, 2013**.

$$\eta_{ex_{comp.}} = \frac{W_{rev.}}{W_{in}} = 1 - \frac{\Psi_{dest.comp.}}{W_{comp.}} \quad (3)$$

The rate of heat rejected from condenser is:

$$\dot{Q}_{cond.} = \dot{m}_{cond.}.(h_4 - h_3) \quad (4)$$

and the exergy destruction in the condenser is:

$$\Psi_{dest.cond.} = \dot{m}_{cond.}.T_o(s_3 - s_4) - \frac{\dot{Q}_{cond.}}{T_{Cond}} \quad (5)$$

The exergy efficiency of condenser is the ratio of exergy flow due to heat transfer to the total exergy flow through condenser due to mass flow rate, **Borgnakke, and Sonntag, 2009.**

$$\eta_{ex_{cond}} = \frac{Q_{cond}\left(1 - \frac{T_o}{T_{cond}}\right)}{\dot{m}_{cond.}(\psi_3 - \psi_4)} = 1 - \frac{\Psi_{dest.cond.}}{\dot{m}_{cond.}(\psi_3 - \psi_4)} \quad (6)$$

The power consumed by LPA pump is:

$$\dot{W}_{pump} = \dot{m}_{liquid}(h_5 - h_4) \quad (7)$$

and the exergy destruction and exergy efficiency of the pump are:

$$\Psi_{dest.pump.} = \dot{m}_{liquid} T_o (s_5 - s_4) \quad (8)$$

$$\eta_{ex_{pump}} = \frac{W_{rev.}}{W_{in}} = 1 - \frac{\Psi_{dest.pump}}{\dot{W}_{pump}} \quad (9)$$

The exergy destruction in capillary tube is:

$$\Psi_{dest.cap.tube} = \dot{m}_{evap} T_o (s_6 - s_5) \quad (10)$$

The exergy efficiency of the expansion device is zero, which is more meaningful since none of the expended exergy is recovered. An expansion valve is highly irreversible as the pressure of the refrigerant is decreased with no product output, **Dincer, and Marc, 2013**.

The rate of heat absorbed by evaporator is:

$$Q_{evap.} = \dot{m}_{evap.}(h_6 - h_7) \quad (11)$$

and the exergy destruction and exergy efficiency of evaporator is, **Borgnakke, and Sonntag, 2009.**:

$$\Psi_{dest.evap.} = \dot{m}_{evap.} T_o (s_7 - s_6) - \frac{Q_{evap.}}{T_{evap.}} \tag{12}$$

$$\eta_{ex.evap} = \frac{-Q_{evap}\left(1 - \frac{T_o}{T_{evap}}\right)}{\dot{m}_{evap.}(\psi_6 - \psi_7)} = 1 - \frac{\Psi_{dest.evap.}}{\dot{m}_{evap.}(\psi_6 - \psi_7)} \tag{13}$$

The overall exergy efficiency of the cycle is the ratio of actual COP to Carnot COP **Dincer, and Marc, 2013**:

$$\eta_{Overall} = \frac{COP}{COP_{Carnot}} \tag{14}$$

$$COP = \frac{Q_{evap.}}{\dot{W}_{Comp.} + \dot{W}_{pump}} \tag{15}$$

$$COP_{Carnot} = \frac{T_{cond.}}{T_{cond.} - T_{evap.}} \tag{16}$$

The energy and the exergy models were programmed using the EES software suitable for solving thermal models equations efficiently and according to the flowchart shown in **Fig. 2**.

3. RESULTS AND DISCUSSIONS

To validate the current mathematical model, a comparison was made with available experimental data from **Khalifa et al 2015** as shown in **Fig. 3**. The figure depicts a reasonable qualitative and quantitative agreement to render the results of the current model acceptable. Condensing pressure affects both discharge temperature, suction temperature as well as, power consumed by the cycle, as the condensing pressure increases the balance point of the cycle shifts to another one. The shifting of balance affects exergetic behaviour of the all cycle components as shown in **Fig. 4**. From the figure it can be seen that for a given condensing pressure, the highest exergy destruction occurs in capillary tube, since the expansion of refrigerant through capillary tube produces no work. As the condensing pressure increases, discharge and suction temperatures increased also, thus entropy generation within condenser increased leading to increase condenser exergy destruction. The evaporator is the only cycle component that recovers its exergy as condensing pressure increases, due to high efficient heat transfer between low evaporation temperature and environment. From the figure it can be seen that, the optimum condensing temperature for a given VCR cycle operating under Baghdad condition is about 40^{o}C that corresponds to condensing pressure of about 15 bars, this condensing pressure can give higher exergy efficiency as shown in **Fig. 5**. While **Fig. 6** shows the effect of volume ratio of injected vapour on the exergy destruction in heat pump components. It can be seen from the figure that, the injection of vapour can recover the exergy for all cycle components, except evaporator, since the reduction in refrigerant mass flow rate through evaporator reduces the heat pump capacity. As a result of injected vapour, in the ratio of 5%, the system overall exergy destruction is minimized by 21%, and the overall heat pump exergy efficiency is increased by about 14.6%, as shown in **Fig. 7** and **Fig. 8** respectively. **Fig. 9** shows the effect of LPA and liquid injection technologies on the exergy destruction of modified heat pump system components. The figure shows that the exergy destruction of the compressor decreased when applying these two technologies; due to reducing the compressor work as a result of decrease the pressure ratio. Then the exergy destruction is further reduced with the increasing in the volume ratio of liquid injected; as a result of decrease the inlet temperature to the compressor. It is observed from the figure that the exergy destruction of the expansion device reduces with increase in the volume ratio of liquid injecte. While the exergy destruction in the evaporator shows insignifcant effect until the injected liquid ratio becomes more than 5%, it is believed that the injection of liquid in the discharge line has a little effect on the suction temperature with the ratio limits mentioned above. The exergy destruction through evaporator tends to reduce as liquid injection percentage increases more than 5%. **Fig. 10** shows the effect of volume ratio of injected liquid on the total exergy destruction of modified heat pump system. The total exergy destruction decreased about 14.71 % by LPA pump with no injection, and by about 40.26 % as a result of injected liquid in the ratio of 10%. The reduction in exergy destruction improves the overall exergy efficiency of heat pump; until the injected liquid ratio reaches 5%, after this ratio the overall exergy efficiency tends to reduce, as shown in **Fig. 11**. The exergetic behaviour of heat pump with hybrid injection shows the same trend as mentioned in vapour and liquid injection, as shown in **Fig. 12**, **13**, and **14** for different volume ratios of injected vapour of 1, 2 and 3%. **Fig. 15** shows the effect of volume ratio of injected vapour in hybrid injection, it can be seen from the figure that the ratio 1% of injected vapour gives minimum PF for the cycle for all liquid injected ratios, while ratio of 2% for vapour injected appears efficient when the ratio of injected liquid is more than 3%. Finally when injected vapour is in the ratio of 3%, the injected liquid should not exceed 3%.

4. CONCLUSIONS

1- The condensing pressure in Iraq should be in the range of 14 to 15 bars; this range gives maximum exergy efficiency which equals about 54.55%.

2- The best volume ratios of injected refrigerant are as follows:

a- 5% of injected vapour reduces the total exergy destruction by about 21% and increases the total exergy efficiency by 14.6%.

b- 5% of injected liquid enhances the exergy efficiency by about 19.6% and deteriorates the exergy destruction by 30.3%.

c- At 3% volume ratio for both vapour and liquid, at these ratios cycle exergy efficiency increases by 22%.

REFRENCES

- Borgnakke, Claus, and Sonntag, Richard, 2009, "*Fundamentals of Thermodynamics*", 7th edition, John Wiley & Sons.
- Dincer, Ibrahim, and Marc A. Rosen., 2013, *Exergy: energy, environment and sustainable development*. Elsevier Ltd., 2nd edition.
- Khalifa, A. N., Faraj, J. J., and Hasan, H. K. *Theoretical Study of Refrigerant Injection Technology Effect on Heat Pump Cycle Performance*, to be published in the Journal of Engineering and Technology, University of Technology.
- Khalifa, A. N., Faraj, J. J., and Hasan, H. K., 2015., *Performance study of heat pump system with refrigerant injection*. International Journal of Thermal Technologies, Vol. 5, No. 1, PP, 1-6.
- Morosuk, T., Tsatsaronis, G., & Zhang, C., 2012, *Conventional thermodynamic and advanced exergetic analysis of a refrigeration machine using a Voorhees compression process*, Energy Conversion and Management, Vol. 60, PP. 143-151.

- Reddy, V. S., Panwar, N. L., & Kaushik, S. C., 2012, *Exergetic analysis of a vapour compression refrigeration system with R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A*. Clean Technologies and Environmental Policy, Vol. 14, No. 1, PP. 47-53.
- Torrella, E., Llopis, R., Cabello, R., Sanchez, D., & Larumbe, J. A., 2010, *Second-law analysis of two-stage vapour compression refrigeration plants.* International Journal of Exergy, Vol. 7, No. 6, PP. 641-653.

NOMENCLATURE:

Symbols

h= specific enthalpy, kJ/kg.
$\dot{m}$= mass flow rate, kg/s.
$\dot{Q}$= rate of heat transfer, kW.
s= specific entropy, kJ/kg. K.
T= temperature, K.
$\dot{W}$= rate of work, kW.
Ψ= flow availability, kJ/kg.
η= efficiency, %.

Subscripts

cond.= condenser
dest.= destruction
evap.= evaporator
ex. = exergy
cap. tube= capillary tube
rev.= reversible
o= dead state

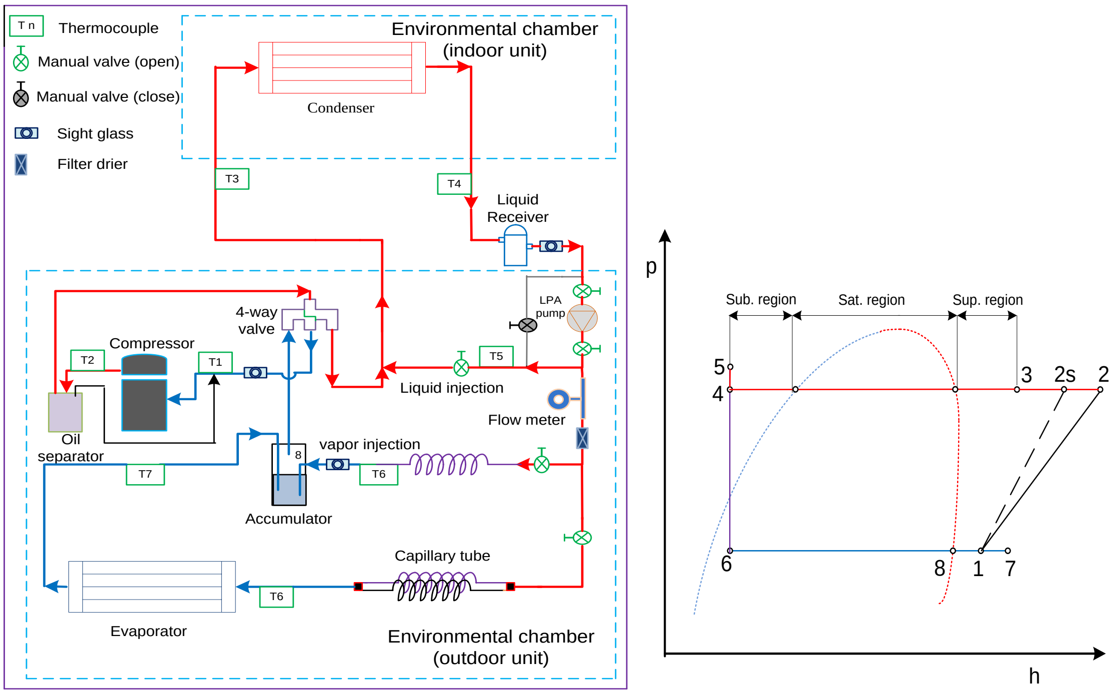

Figure 1. Schematic and P-h diagrams of heat pump cycle with LPA and hybrid injection technologies.

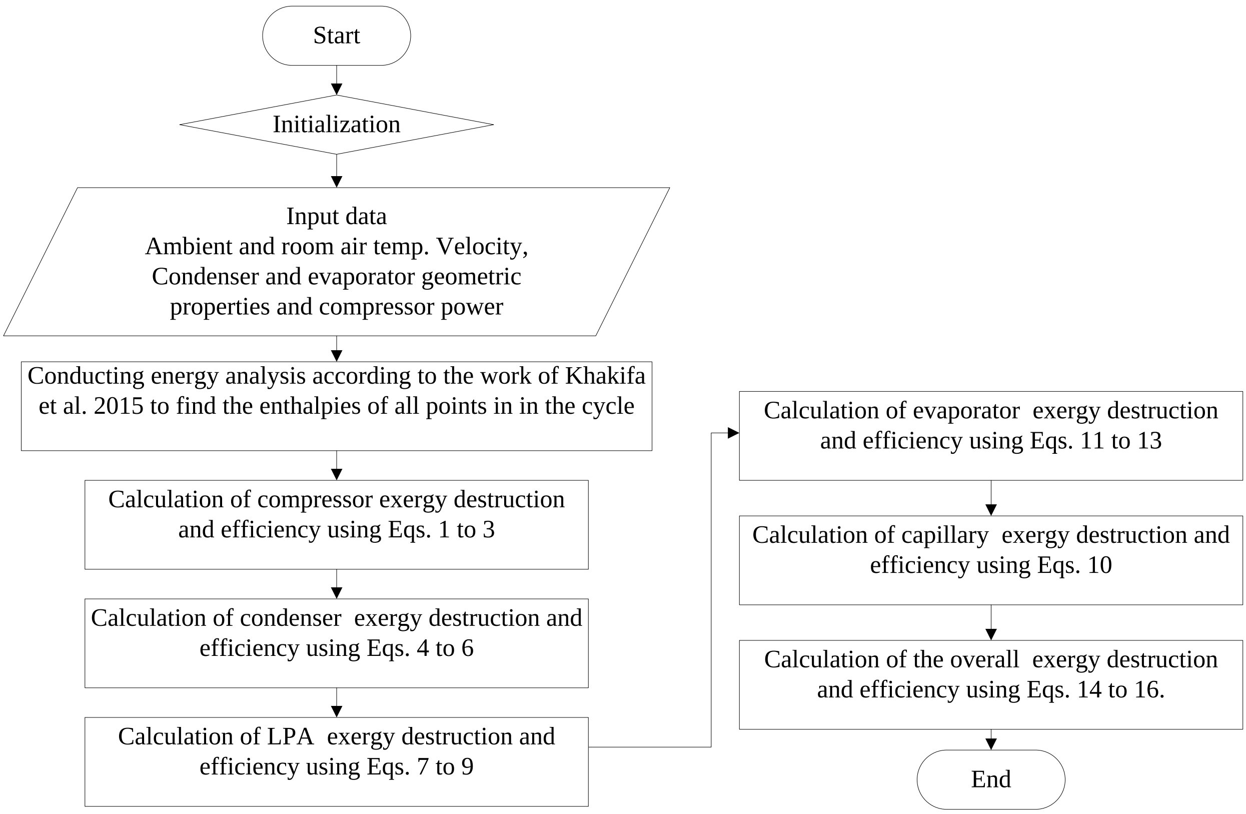

Figure 2. Flowchart of the EES program.

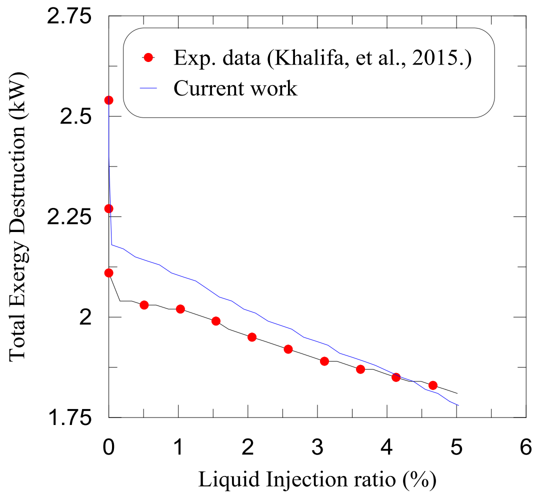

Figure 3. Comparison between current model and experimental data from Khalifa et al., 2015.

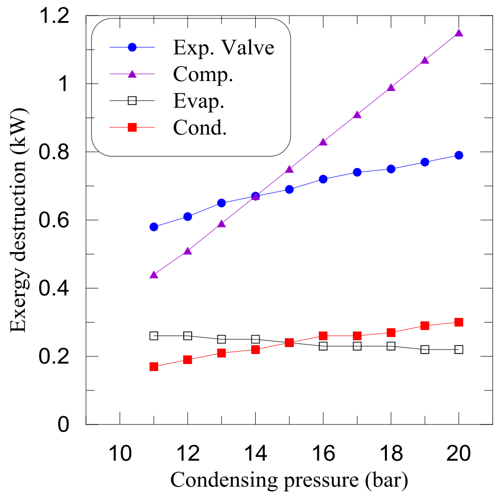

Figure 4. The variation of exergy destruction of components vs condensing pressure.

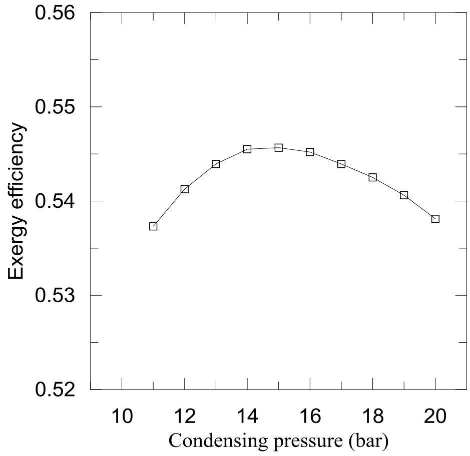

Figure 5. The variation of total exergy efficiency vs condensing pressure.

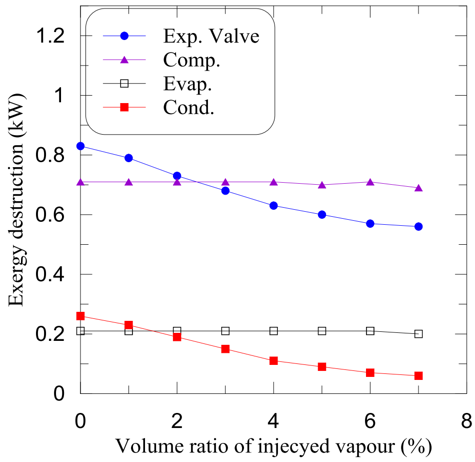

Figure 6. The variation of components exergy destruction vs volume ratio of injected vapour.

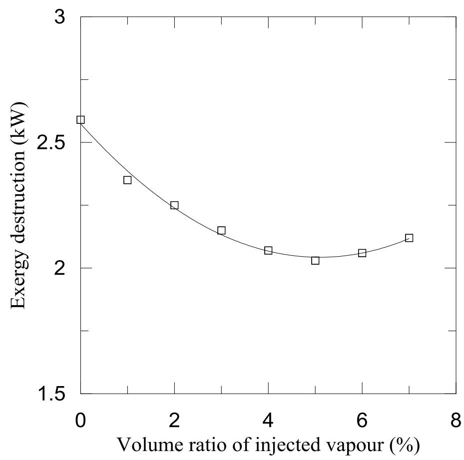

Figure 7. The variation of total exergy destruction vs volume ratio of injected vapour.

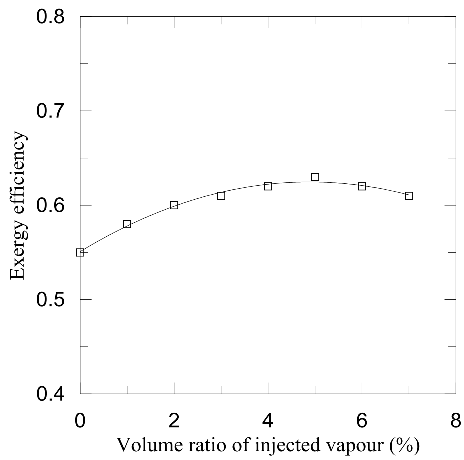

Figure 8. The variation of total exergy efficiency vs volume ratio of injected vapour.

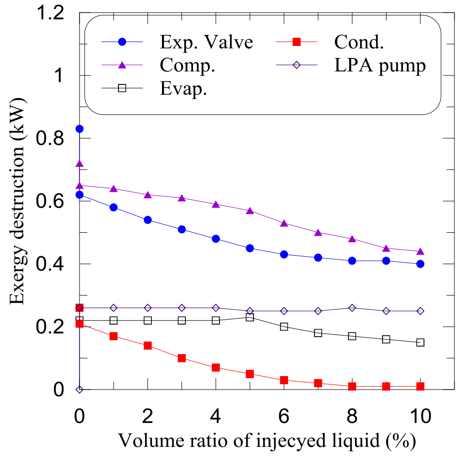

Figure 9. The variation of components exergy destruction vs volume ratio of injected liquid.

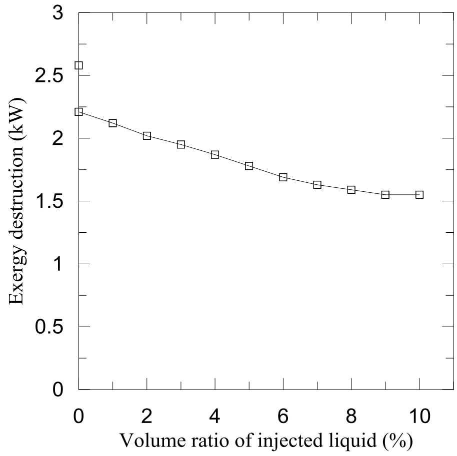

Figure 10. The variation of total exergy destruction of heat pump system vs volume ratio of injected liquid.

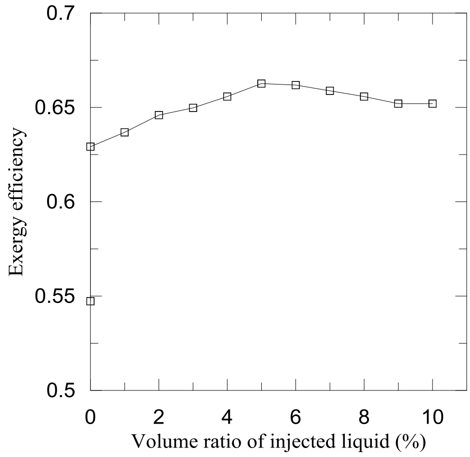

Figure 11. The variation of total exergy efficiency of heat pump system vs volume ratio of injected liquid.

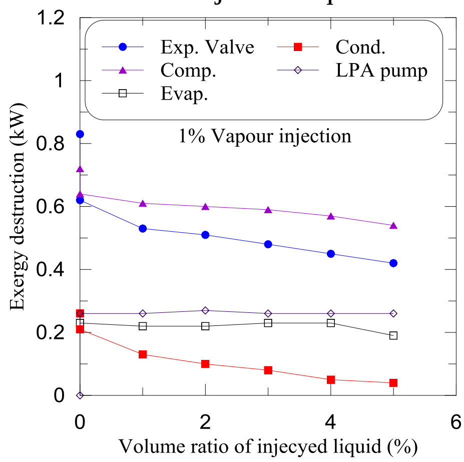

Figure 12. The variation of components exergy destruction vs volume ratio of injected liquid at (1% vapour injection).

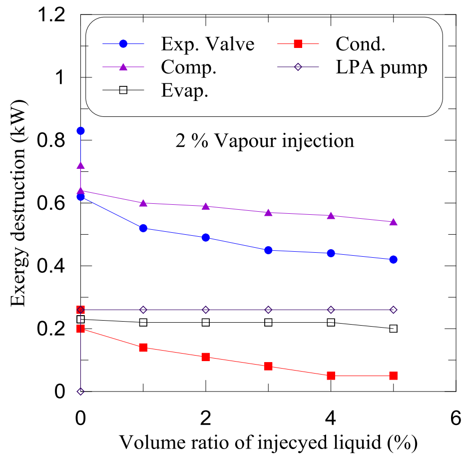

Figure 13. The variation of components exergy destruction vs volume ratio of injected liquid at (2% vapour injection).

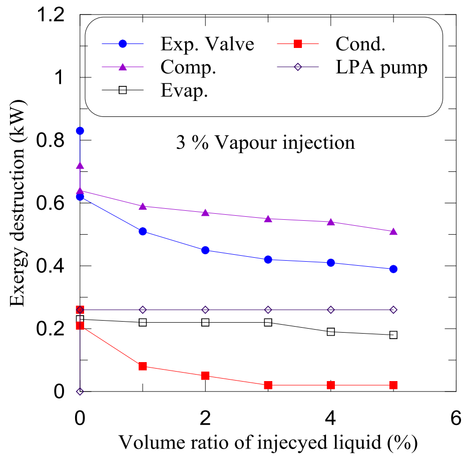

Figure 14. The variation of components exergy destruction vs volume ratio of hybrid injection at (3% vapour injection).

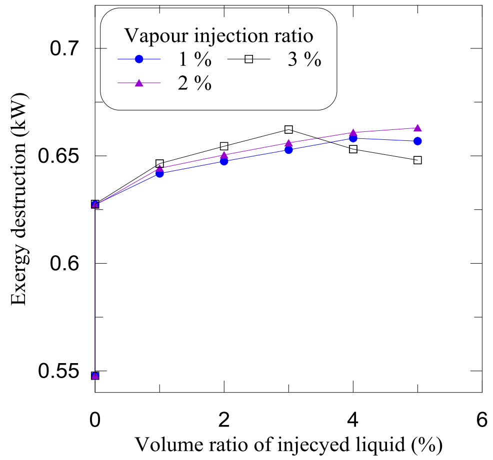

Figure 15. The variation of total exergy efficiency vs volume ratio of hybrid injection.