

Research Article

Performance Study of Heat Pump System with Refrigerant Injection

Abdul Hadi N. Khalifa^{*,†}, Johain J. Faraj[†] and Hayder K. Hasan[†]

[†]Engineering Technical College, Middle Technical University, Baghdad-Iraq

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Abstract

The current work investigated the performance improvement that can be achieved on heat pump system, through using refrigerant injection technology. A 5 tons heat pump system charged with R22 was modified by adding secondary expansion valve, Liquid Pressure Amplification (LPA) pump, accumulator and receiver. The heat pump performance was improved through three approaches. The first approach was accomplished by injected refrigerant vapour into the accumulator to mix with superheated vapour leaving evaporator. The volume ratio of injected vapour was 1 to 4%. The second was achieved by injected liquid refrigerant from condenser exit by an LPA pump, to the discharge line in a volume ratio of 1 to 5%. A hybrid injection was the third approach, in which both vapour and liquid were injected in suction and discharge lines simultaneously, the vapour volume ratio varied from 1% to 2% while keeping the liquid ratios as above. It was found that, injected vapour in the ratio of 4% improved both cycle PF and overall exergy efficiency by about 2.47% and 3.2% respectively, reduces suction temperature from (-4.89°C) to (-12.48°C) and discharge temperature by 12.74%. The optimum ratio of injected vapour was 3% since an additional increase in the ratio to 4% shows less effect on all the key variables. Injected liquid in the ratio of 3% improved both cycle PF and overall exergy efficiency by about 27.1% and 18.37% respectively, reduces the suction, discharge and condenser inlet temperatures by 29.8%, 17.42% and 24.7% respectively. While hybrid injection improved the cycle PF by 33% and exergy efficiency by 21.45%. From above, it was found that hybrid injection gave optimum results when the volume ratios of injected vapour and liquid were 2% and 3% respectively in comparison to other cases.

Keywords: Refrigeration, Refrigerant injection, Exergy analysis, Heat pump.

1. Introduction

Vapour compression refrigeration (VCR) unit work satisfactorily in moderate ambient temperatures. However, system performance degradation becomes quite significant when ambient temperature decreases much lower than -8°C for heating applications, or higher than 35°C for the cooling applications (Anmar, 2013). For low temperature heat pump system and high condensing temperature refrigeration system, refrigerant injection would not increase capacity and COP of the system only but also decrease the discharge temperature. Refrigerant injection was investigated by many works, (Wang, 2008) has injected vapour refrigerant into intermediate compressor pressure port. (Hwang *et al*, 2010) proved that injected refrigerant could be optimized to improve system capacity and COP. Hwang, also tested a liquid injection instead of vapour into compressor's port in an effort to further improve in the performance. (Vakiloroaya *et al*, 2014, Hadawey and Tassou, 2008) used an LPA pump technique to improve the system performance, they showed that the liquid refrigerant entering the liquid

line was pressurized by a centrifugal pump in an amount that sufficient to overcome the pressure loss between the receiver and condenser inlet. (Cho and Kim, 2000) described the effects of vapor injection system on the performance of heat pump using variable speed compressor of 3.5 kW with a back pressure chamber. A theoretical and experimental study on the fundamental and practical influences of liquid injection on scroll compressors was conducted by (Dutta *et al*, 2001). In 2002 (Winandy and Lebrun, 2002); conducted tests of injected R22 vapour into the sealed suction pocket of a scroll compressor in a heat pump system.

The division of scroll compressor process for vapour injection into two stages was studied by (Siddharth *et al*, 2004). A new design of injection ports was simulated by (Lifson, 2005) the simulation results showed that the new design could improve the capacity and efficiency at high ambient temperatures. A heat pump system charged by R-22 with twin rotary type compressor and vapour injection was studied experimentally by (Heo *et al*, 2007). A comparison between flash tank-capillary tube cycle and economizer-thermostatic expansion valves was studied by (Nguyen *et al*, 2007). They used R407C heat pump

*Corresponding author: Abdul Hadi N. Khalifa

system with an economized vapour injection compressor. In the Early of 2008 (Wang *et al*, 2008) developed and tested an 11 kW heat pump cycle with injected scroll compressor. The effects of vapor injection by flash tank on the heating performance of a two-stage heat pump with an inverter-driven twin rotary compressor was studied by (Heo *et al*, 2010) under compressor frequency ranging from 50 to 100 Hz and ambient temperatures of (-15, -5, and 5 °C). In 2013 (Anmar, 2013) studied the performance of a heat pump system of 3 ton capacity with a scroll compressor with a liquid heat exchanger.

In this work the effect of injected refrigerant, in the form vapour, liquid and hybrid injection, on the performance of heat pump system, of 5 ton capacity, were studied experimentally.

2. Experimental works

A split air conditioner unit of 5 TR nominal capacity, charged with R-22, was build. The split unit heat pump consist of, hermetic scroll compressor manufactured by Copeland Company of a model (ZR61K3-FTD-230). The coiled air cooled condenser was of two depth rows made of copper tubes; the aluminum plate fins were of 0.105 mm thickness, 1200 mm width, 45mm depth and 1.39 mm fin pitch. The

evaporator consists of nine circuits two rows plate-finned-tube forced convection evaporator. The capillary tube has 2.6 mm inner diameter and 1200 mm length. Liquid refrigerant pump (LPA) manufactured by HY@SAVE Company of model 809 SS, was used in the current study, inlet and outlet connection diameters of the LPA pump are 5/8" and 1/2" respectively. The flow rate range of LPA pump was 1 to 5 GPM. The performance of the heat pump was studied under three approaches. The first approach was injected refrigerant vapour into the accumulator to mix with superheated vapour leaving evaporator. The volume ratio of injected vapour was varied from 1 to 4%. The second approach was achieved by pumping liquid refrigerant by an LPA pump. The pumped refrigerant was injected into the discharge line in volume ratios of 1 to 5%. A hybrid injection was the third approach, in which both vapour and liquid injection were used simultaneously. The volume ratio of injected vapour was 1 to 2% while the volume ratio of injected liquid was as mentioned above. The performance of the split unit was studied within a test zone consist of two rooms; the inner one is the conditioned room with dimensions of 7.4m x 4.8m x 2.4m. The dimensions of the outside room are 7.4m x 15m x 3m. The layout of heat pump system and test zone is shown in Fig. (1).

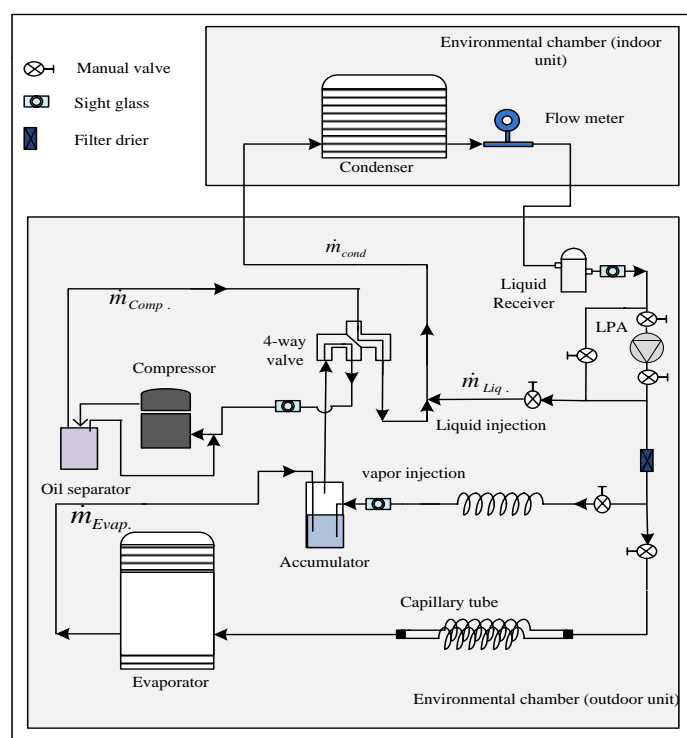


Fig. 1 A schematic for the heat pump and test zone

3. Energy and exergy analysis of heat pump system

Energy and exergy analysis of a heat pump system were conducted. The analysis includes work consumed by the compressor and LPA pump, heat flow to or from each components, exergy destruction, exergy efficiency of individual cycle components, as well as the overall

exergy efficiency of the cycle. Table (1) shows a summary of the equations used to calculate the input power to compressor and LPA pump, rate of heat exchange in condenser and evaporator, exergy destruction and exergy efficiencies for each cycle components and the overall exergy efficiency of heat pump system.

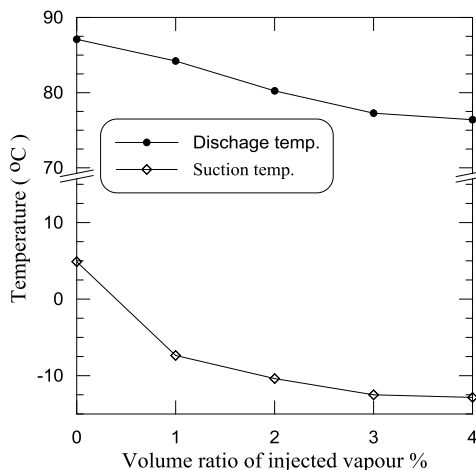
Table 1 Summary of energy and exergy equations were used in this work

Components	Power/heat (kW)	Exergy	
		Destruction (kW)	Efficiency
Compressor	$\dot{W}_{comp.} = \dot{m}_{comp}(h_e - h_i)$	$\Psi_{dest.comp.} = \dot{m}_{comp}T_o(s_e - s_i)$	$\eta_{ex_{comp.}} = 1 - \frac{\Psi_{dest.comp.}}{\dot{W}_{comp.}}$
Condenser	$\dot{Q}_{cond.} = \dot{m}_{cond.}(h_e - h_i)$	$\Psi_{dest.cond.} = \dot{m}_{cond.} \cdot T_o(s_i - s_e) - \frac{\dot{Q}_{cond.}}{T_{Cond}}$	$\eta_{ex_{cond}} = 1 - \frac{\Psi_{dest.cond.}}{\dot{m}_{cond.}(\psi_i - \psi_e)}$
LPA pump	$\dot{W}_{pump} = \dot{m}_{liquid}(h_e - h_i)$	$\Psi_{dest.pump.} = \dot{m}_{liquid}T_o(s_e - s_i)$	$\eta_{ex_{pump}} = 1 - \frac{\Psi_{dest.pump.}}{\dot{W}_{pump}}$
Capillary	$h_i = h_e$	$\Psi_{dest.Ex.valve} = \dot{m}_{evap}T_o(s_e - s_i)$	$\eta_{ex_{Ex.valve}} = 0$ (Dincer and Kanoglu, 2010)
Evaporator	$\dot{Q}_{evap.} = \dot{m}_{evap.}(h_i - h_e)$	$\Psi_{dest.evap.} = \dot{m}_{evap.}T_o(s_e - s_i) - \frac{\dot{Q}_{evap.}}{T_{evap.}}$	$\eta_{ex_{evap}} = 1 - \frac{\Psi_{dest.evap.}}{\dot{m}_{evap.}(\psi_e - \psi_i)}$
The overall exergy efficiency of the cycle is: $\eta_{Overall} = \frac{COP_{cycle}}{COP_{Carnot}}$, where COP_{cycle} is the ratio of rate of heat transferred to evaporator to the summation of input work to compressor and LPA pump, while COP_{Carnot} is the ratio of condensing temperature to the difference between condensing and evaporator temperatures.			

4. Results and discussions

The basic properties such as entropy and enthalpy of the refrigerant at different state points were calculated using engineering equation solver (EES) after the measured data were collected and suitably prepared.

A specified quantity of liquid refrigerant were extracted, expanded and injected into the accumulator in saturated vapour state. This vapour then mixed with the superheated vapour from the evaporator. As a result of mixing, the suction temperature reduces significantly, as shown in Fig. (2). The reduction in suction temperature reflected on the discharge temperature. The discharge temperature was reduced by 12.74% as a result of injecting 4% of the total refrigerant volume. The reduction in suction temperature leads to minimize the entropy generation in each cycle component, which means less destruction in exergy transport due to both mass and heat transfer, this appears clearly in Fig. (3).

**Fig. 2** Variation of suction and discharge temperatures with injected vapour volume ratio

It can be seen from the figure that, the maximum exergy destruction occurs in the expansion device followed by the compressor, the evaporator and the condenser. The exergy destruction in the condenser / evaporator caused by inefficient heat exchange caused by the secondary refrigerant and the cycle refrigerant, and also due to the difference between inlet and outlet refrigerant exergy. While, the exergy destruction in the compressor is due to imperfect electrical, mechanical, and isentropic efficiencies.

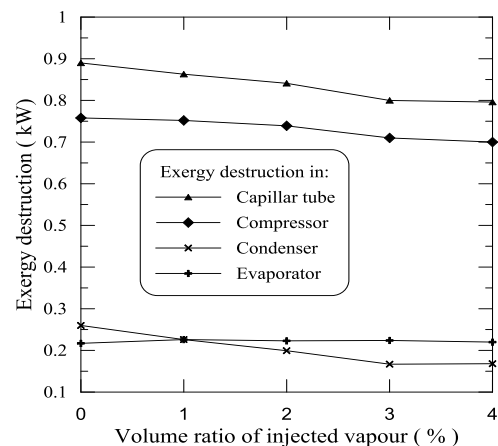
**Fig. 3** Components exergy destruction of cycle vs volume ratio of injected vapour

Fig. (4) shows the effect of the volume ratio of injected vapour on both total exergy destruction and exergy efficiency of the heat pump system. The total exergy destruction is the summation of exergy destruction in each component of the heat pump system and exergy destruction due to injection processes. The exergy destruction decreased with the increasing of the volume ratio of injected vapour. The reduction in overall exergy destruction is about 10.14% as a result of injected vapour in the ratio of 4% compared to the traditional cycle.

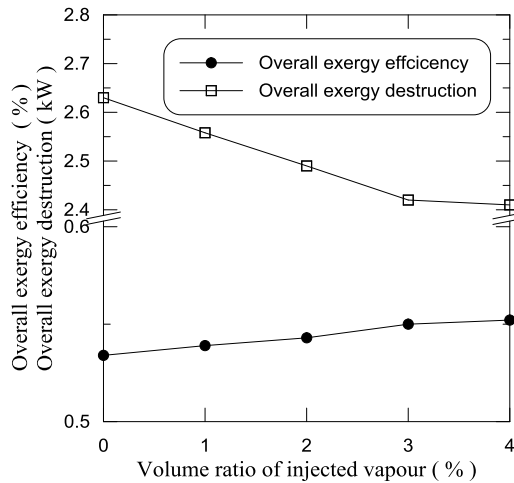


Fig. 4 Overall exergy efficiency and overall exergy destruction vs volume ratio of injected vapour

Using an LPA pump, some liquid refrigerant could be extracted and injected directly to the vapour line downstream the 4-way valve. The effect of the volume ratio of injected liquid on the suction, discharge and condenser inlet temperatures is shown in Fig. (5).

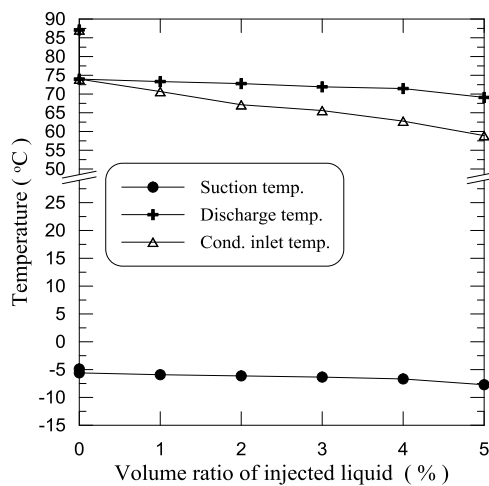


Fig. 5 effect of volume ratio of injected liquid on suction, discharge, and inlet condenser temperatures

The figure shows two discrete points on the y-axis; the upper one distinguishes the suction temperature for traditional heat pump, while the lower point is the suction temperature for the heat pump when the LPA pump operates without any refrigerant injection. The suction temperature decreases as a result of refrigerant circulation through a closed cycle. The LPA pump tends to reduce the condensing pressure, which leads to decrease in condensing temperature. As condensing temperature reduces the condenser becomes more efficient in heat transfer which means more degree of sub-cooling after condenser. Evaporation of injected liquid in hot discharge vapour cools the hot vapour. Thus, discharge temperature reduces by about 20.78% for a 5% liquid injection. While the condenser inlet temperature decreased by

about 32.4% for the same specified ratio of liquid injection as compared to conventional system.

The overall exergy destruction and overall exergy efficiency of the heat pump vs volume ratio of injected liquid are shown in Fig. (6). The overall exergy destruction reduces as a result of LPA operation in the system, further reduction in exergy destruction as liquid injected in the discharge line. The exergy efficiency was increased by about 11.22% by LPA alone due to the decrease in total exergy destruction. The exergy efficiency increased by about 15.78% for a ratio 4% injected liquid as compared to traditional cycle.

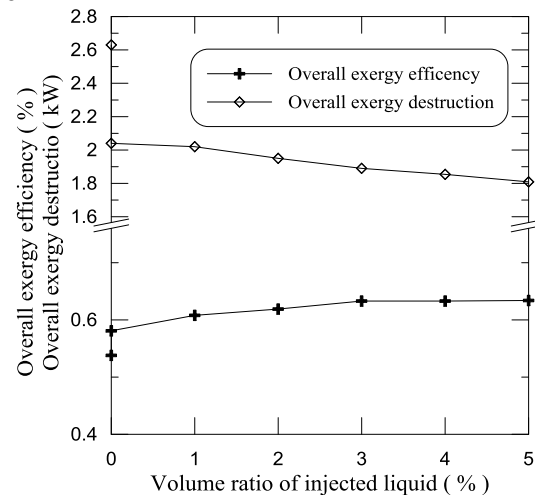


Fig. 6 Overall exergy destruction and exergy efficiency of heat pump vs volume ratio of injected liquid

When a ratio of 1 to 2% vapour is injected into the suction line simultaneously with a 1 to 5% liquid injection more improvement in system performance was shown. Both ratios of vapour injection reduce suction, discharge and condenser inlet temperatures. Fig. (7) shows that a ratio of 2% injected vapour gives better results. The effect of refrigerant injection in both vapour and liquid phases on the overall exergy efficiency is shown in Fig. (8).

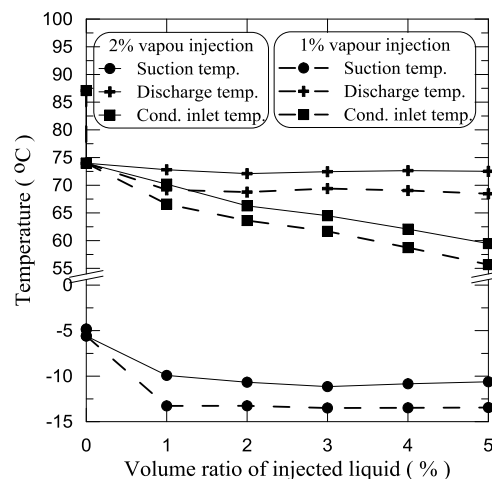


Fig. 7 Effect of hybrid injection on suction, discharge and condenser inlet temperatures

The exergy efficiency of the traditional system is about 53%, as LPA pump is activated, the exergy efficiency increases to 58%. The figure shows that the maximum exergy efficiency is for hybrid injection of 2% vapour, while the minimum exergy efficiency is for vapour injection. The improvement in exergy efficiency reflected on the cycle PF, as shown in Fig. (9), it can be seen from the figure that the maximum PF is for hybrid injection of 2% vapour. Finally, it can be concluded that the best volume ratio of injected vapour or liquid is about 3% since the increasing the ratio to 4% gives less effect on all key variables. While, for hybrid injection the best volume ratios of injected liquid and vapour are 4% and 1% respectively.

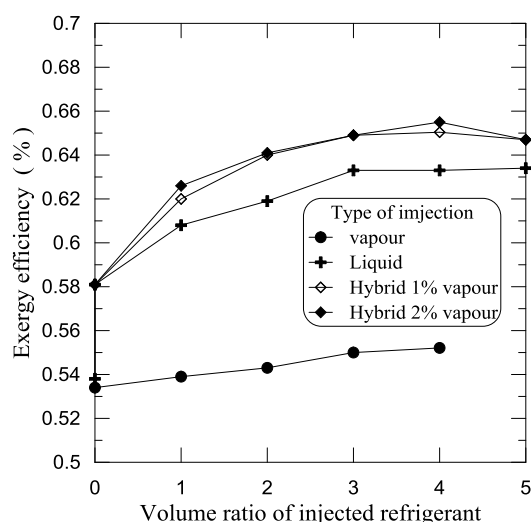


Fig. 8 Effect of refrigerant injection on overall exergy efficiency of the heat pump.

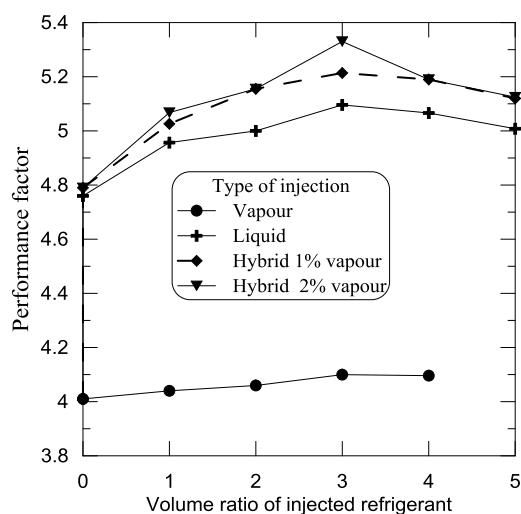


Fig. 9 Effect of refrigerant injection on cycle PF

Conclusions

1. Injected vapour in the ratio of 4% reduces the discharge temperature by about 12.7%. Best volume ratio of injected vapour is about 3%.

2. Activating LPA pump without refrigerant injection has the following impacts on the cycle: reduced suction temperature by about 14.3%, discharge temperature by about 15%, overall exergy destruction by about 22%, and increasing exergy efficiency by 8.7%
3. A 5% of liquid injection has the following remarkable effects on the cycle: Reduces condenser inlet temperature by 42%, increases exergy efficiency by 20.4%. The optimum volume ratio of injected liquid is 3%, at which the maximum improvement in cycle PF equals to 27%.
4. Using hybrid injection with 2% volume ratio of injected vapour and 3% volume ratio of injected liquid gave a maximum cycle PF, of 33%, as compared to that of traditional cycle.

Nomenclature

h	Specific enthalpy (kJ/kg)
\dot{m}	Mass flow rate (kg/s)
PF	Performance factor
Q	Heat transfer rate (kW)
S	Specific entropy (kJ/kg K)
T	Temperature (°C)
\dot{W}	Rate of work (kW)
Greek letters	
η	Efficiency
Ψ	Exergy flow rate (kW)
Subscripts	
cap.	Capillary tube
comp.	Compressor
cond.	Condenser
dest.	Destruction
e	Exit
evap.	Evaporator
exe.	Exergy
i	Inlet
LPA	Liquid Pressure Amplification
temp.	Temperature

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