Performance Investigation of Vapor Compression Cycle with a Variable Speed Compressor and Refrigerant Injection

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ABSTRACT

The performance of vapor compression refrigeration system with controllable speed compressor and vapor and liquid refrigerant injection techniques is experimentally investigated. For this purpose, a 5-tons (17.6 kW) split air conditioner unit charged with R-22 refrigerant was modified and equipped with, frequency inverter, secondary capillary tube, and liquid pressure amplification pump (LPA). Vapor refrigerant was injected into the accumulator with three injection mass ratios 2, 3, and 4%. LPA pump was used to inject liquid refrigerant from the condenser outlet to the discharge line with injection mass ratios 0.5%, 1.5%, and 2%. The compressor speed was controlled by frequency inverter, where the range of the frequency used was from 35 to 60 Hz with 5 Hz step. The results showed that the coefficient of performance (COP) of the modified system using vapor injection technique was improved by 11.26% compared to the conventional system, and the suction temperature reduced from 10.3 to -0.1°C with 3% vapor injection ratio. The best enhancement in COP was 9.9% for the 0.5% liquid injection ratio. Reduction of the compressor speed leads to improve the COP by 18% and reduces the compressor power by 36.4% at frequency 35Hz. Using the vapor injection with variable speed compressor improved the COP of the modified system by 75% at 35 Hz and 2% injection mass ratio.

Keywords: *Frequency Inverter, Liquid Injection, Vapor Injection, Variable Speed*

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Introduction

Nowadays, people are looking forward to improving the quality of life in accordance with the higher economic and cultural level. In this situation, the demand of the air-conditioning and refrigeration systems has been increased in the tropical region with annual high ambient temperature such as the Middle East. However, as ambient temperature increases, the condensing pressure in the air-conditioning system is correspondingly increases to raise the refrigerant saturation temperature for a value greater than the ambient air temperature for the sake of heat exchange. Thus, the refrigeration system operates at a high compression ratio for efficient condensation in the tropical region. Since the compressor discharge temperature is very high, it may result in the breakdown of the lubricating oil causing excessive wear and reduced life of the compressor valves [1]. Therefore, it is highly important to overcome constraints such as excessive compressor discharge temperature and performance degradation for stable operation on a refrigeration system in the tropical region. Recently, development of injection type compressor with supplementary injection port has raised the potential of the operating range extension and performance improvement for the refrigeration system.

In present work, both variable speed compressor (variable cycle capacity) and refrigerant injection are used to investigate their effects on, cooling capacity. COP, discharge temperature and power consumption for split air conditioner unit. The experimental analysis of injected refrigerant in a scroll compressor of a heat pump system was introduced by Winandy *et al*. [2]. In this work, the injection ratio of R-22 was varied from 0 to 45%. The performance of a variable speed scroll compressor with liquid injection was performed by Cho *et al*. [3]. The effect of the liquid injection on the performance was a function of operating parameters and the location of injection. The capacity control of a variable speed vapor compression system using superheat information at the compressor discharge was investigated by Yang *et al*. [4]. They devised the physical relationship between the superheat at the discharge line and the system variables such as inverter frequency, expansion valve opening, and temperatures.

The performance of an R-410A vapor compression refrigeration of 11 kW capacity with refrigerant injection in scroll compressor was studied by Wang *et al*. [5]. They found that the vapor-injection technique increased the system performance effectively. Lee *et al*. [6] developed a model for a ground-source heat pump fitted with a variable-speed compressor for a general office based on the weather conditions in different locations. He concluded, the adoption of a variable-speed part-load control of the heat pump, in both the cooling and heating mode operations was better.

Three different control algorithms, proportional, integral and differential fuzzy logic and artificial neural network were experimentally investigated by

Ekren *et al*. [7]. The effects of different control methods on a scroll-type variable speed compressor and electronic expansion valve in a chiller system were studied. The annual performance of the on/off controlled and inverter-driven variable capacity heat pump systems was investigated by Madani *et al*. [8]. The results of annual performance of the on/off controlled system were compared with that of the inverter-driven variable capacity heat pump system. The analyzing of the performance of variable capacity heat pump with refrigerant R410A using scroll compressor equipped with vapor injection and permanent magnet motor was introduced by Awan [9]. In his study, the tests were carried out for heat pump without vapor injection and then the benefits of vapor injection were analyzed. Colmek and Laurent [10] studied the performance of a vapor compression refrigeration system with and without vapor injection. They found out that, the vapor-injection technique could increase the system performance effectively. Bell et al. [11] investigated the performance of heat pumps in cold climate using one and two vapor injection lines in the scroll compressor. The heating-mode efficiency improved by 10% with one injection line and 16% with two injection lines. Bach et al. [12] studied experimentally the benefits in capacity and performance of a hybrid control of expansion valves for two domestic heat pumps. The first one was equipped with an electronic expansion valve, while the second was equipped with a vapor injected compressor. The COP was improved by 26% and 13% for the first and second heat pumps respectively.

Lee *et al*. [13] studied the liquid and vapor injection through a vapor compression system of a high compression ratio. The injection was achieved through the accumulator of R-22 vapor refrigeration system of 9.6 kW cooling capacity. The results were compared and discussed for better performance of the refrigeration system with respect to ratio and type of the injection. Henry *et al*. [14] studied a series of experiments on the variable speed compressor of a split AC unit in the frequencies range of 15 to 50 Hz. The heating performance of R410A vapor injection heat pump at cold regions with a twin rotary variable speed compressor was measured and analyzed by Yan *et al*. [15]. The compressor frequency was controlled in the range of 70 to 90 Hz to obtain variable compressor speed. The effect of refrigerant injection and compressor speed on the performance of a 5-ton spilt air-conditioner is studied in this work. The reciprocating compressor speed is controlled by varying the frequency of the supply power. Cho et al. [16] studied the cooling performance of R410A and R32 multi-heat pumps with variations in, outdoor temperature, compressor speed and vapor injection ratio. The results revealed an increase in the cooling capacity with vapor injection by 2.1% and 6.3% for R410A and R32 respectively. Oquendo et al. [17] presented a comparative study between the scroll compressor heat pump system with vapor injection and two-stage reciprocating compressor.

The results showed better efficiency for the system with vapor injection when working with pressure ratios below 7.5 at moderate temperature conditions. Hamad et al. [18] presented an experimental investigation of the performance for a single zone building that conditioned by a spilt air conditioner with variable speed compressor. The annual performance of the nit was simulated using TRNSYS-16. The compressor speed was controlled using frequency inverter. The range of frequency under study was in the range of 35 to 60 Hz.

Experimental setup

Split air conditioner unit of 5 tons (17.6 kW) capacity with hermetic scroll compressor and charged with R-22 refrigerant was used in the experimental work as shown in Figure 1. The test rig has equipped with a frequency inverter, secondary capillary tube, and liquid pressure amplification (LPA) pump. The frequency inverter was used to control the compressor speed in the range of frequency from 35 to 60 Hz with 5 Hz step. A secondary capillary tube was added to the system to expand the refrigerant after condenser to be injected into the accumulator. The separated saturated refrigerant vapor from accumulator mixes with the vapor from the suction line and then injected into the compressor suction line. Three mass ratios for vapor injection are used, 2%, 3%, and 4%. The injection of liquid refrigerant from the condenser outlet to the discharge line is achieved with the aid of LPA pump with three mass ratios, 0.5%, 1.5%, and 2%. The indoor setting temperature considered in the present experimental work was 23 °C and the outdoor temperature was 45 °C. The test zone used in the experimental work was consisted of two rooms with different dimensions.

The indoor unit of the air conditioner (A/C) was used to condition the first room of dimensions (10.4×4.8×2.4) m. Two secondary window type A/C units were used to control the conditioned space load. Outdoor unit was installed in the second room of dimensions of (15×7.4×3) m. Temperature at different locations of the split A/C are measured using K-type thermocouples of range -200 to 1250°C, and the pressure was measured using Bourdon pressure gauges as shown in Figure 2. A turbine volume flow meter with reading range of 0.2 to 1.2 m^3/h was installed after the condenser to measure the refrigerant volume flow rate through the cycle. The speed of air through the condenser, evaporator and the room are measured by the anemometer.

The compressor power consumption was measured using a power meter. Table 1 present the summary of the uncertainty analysis of the measuring instruments. Figure 1(a) shows the locations of the measuring instruments. While the pressure - enthalpy diagram of the cycle is depicted in Figure 2(a). It can be seen from this figure that the zone of liquid injection is shown by the mixing process line 2 - 3 - 5, while the vapor injection is shown by the process 6 - 8 - 1 - 7. The AC split unit was connected with the modification parts that mentioned before and all the measuring devices. After checking the unit for leakage, the system was charged by 6kg of refrigerant R-22. The tests were achieved during August and September within Baghdad- Iraq ambient conditions.

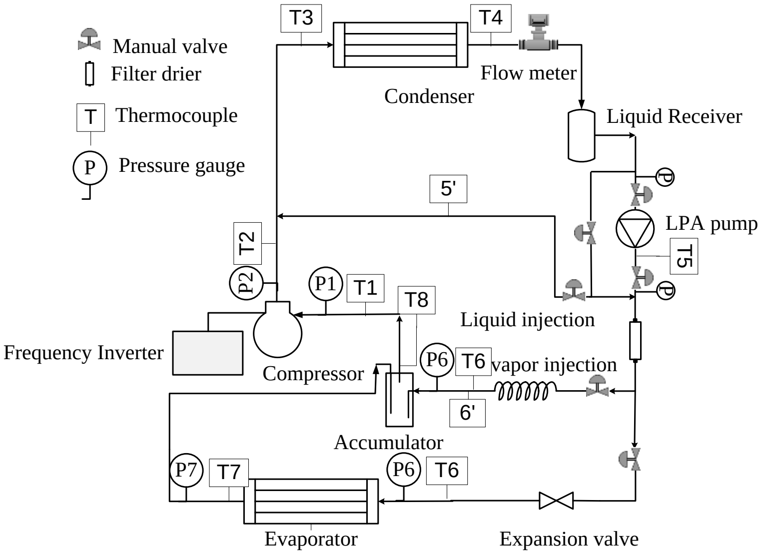

Figure 1 (a): Schematic diagram of the vapor compression cycle with locations of the refrigerant injection devices.

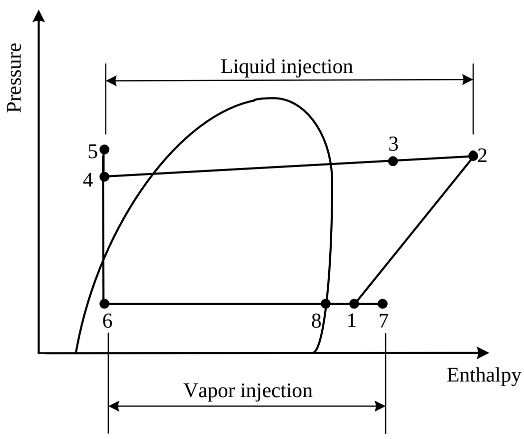

Figure 1 (b): Schematic diagram of the vapor compression cycle with liquid and vapor injection processes

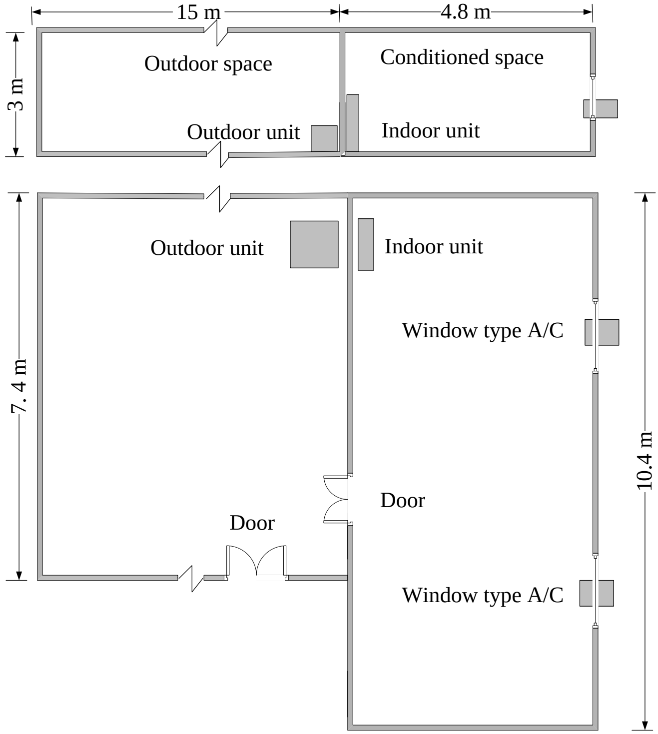

Figure 2: The test zone

Table 1 : Accuracy of the measuring instruments.

Variables	**Accuracy error**
Thermocouple	± 1 ºC
Voltage	± 0.5 Volt
Current	± 0.5 Amp.
Pressure gauge	± 0.1 bar
Flow meter	± 0.1 % m^3/h

The coefficient of performance of the cycle can be calculated as follows:

$$COP = \frac{CC}{P_{comp} + P_{LPA}} \quad (1)$$

Where:

CC: The cycle cooling capacity (kW)

P_{comp}: Power consumption by the compressor (kW)

P_{LPA}: Power consumption by liquid pressure amplification (kW)

The cooling capacity of the cycle and the compressor power consumption can be calculated from the following equations:

$$cc = \dot{m}_{r,7}.(h_7 - h_6) \tag{2}$$

$$P_{comp} = \dot{m}_{r,1}.(h_2 - h_1) \tag{3}$$

Where:
$\dot{m}_{r,7}$: Refrigerant mass flow rate through the evaporator (kg/s)
h_7 *and* h_6: Refrigerant enthalpies at outlet and inlet of the evaporator (kJ/kg)
$\dot{m}_{r,1}$: Refrigerant mass flow rate through the compressor (kg/s)
h_2 *and* h_1: Refrigerant enthalpies at outlet and inlet of the compressor (kJ/kg)

The injected liquid refrigerant mass ratio $m_{r,L}$ is the mass of liquid injected at point (5') to the total mass flow rate of refrigerant at point (1) and can be calculated as follow

$$m_{r,L} = \frac{\dot{m}_{5'}}{\dot{m}_1} \tag{4}$$

While the injected vapor refrigerant mass ratio $m_{r,V}$ is the mass of vapor injected at point (6') to the total mass flow rate of refrigerant at point (1) and can be calculated as follow

$$m_{r,V} = \frac{\dot{m}_{6'}}{\dot{m}_1} \tag{5}$$

Results and discussion

Figure 3 show the effect of vapor injection ratio on the suction and discharge temperatures. It can be seen from the figure that, as the mass ratio of vapor injection increases, the suction and discharge temperatures decrease. The reduction in suction temperature is due to the mixing between superheated vapor leaving evaporator and saturated vapor leaving accumulator.
This reduction in suction temperature leads to reduce the discharge temperature from 96 to 80°C. The minimum percentage reduction in discharge temperature was about 5.2% when the vapor injection is 2%. While the maximum reduction in discharge temperature was 16.67% at vapor injection ratio 4% as compared with that of the conventional system (without vapor injection).

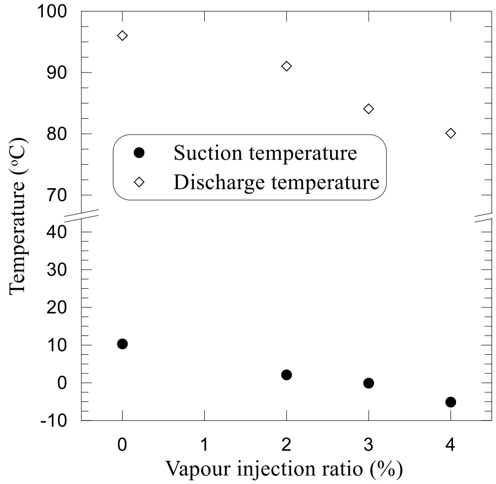

Figure 3: The variation of suction and discharge temperatures with the vapor injection ratio.

The increasing in the amount of the injected vapor in the suction line leads to raising the refrigerant mass flow rate which resulted in a slight increase in the compressor power as shown in Figure 4. The maximum value of the compressor power consumption was 6.7 kW for 4% vapor injection ratio. It can be observed that, the cycle capacity is significantly increased with the increment in the ratio of injected vapor due to the reduction in discharge temperature.

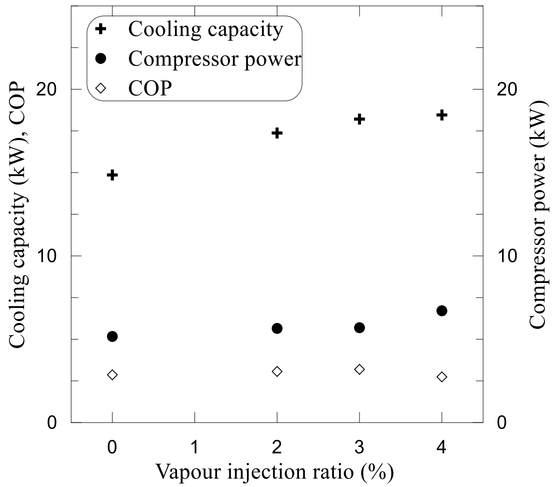

Figure 4: The effect of vapor injection ratio on the system performance.

The maximum enhancement in the coefficient of performance (COP) of the cycle was 11.26% and reduction in suction temperature from 10.3 to -0.1°C at 3% vapor injection ratio due to the improving in the cooling capacity. The injection of the liquid refrigerant into the discharge line of the refrigeration system leads to increase the discharge pressure which reflects inversely on the discharge and suction temperatures as shown in Figure 5.

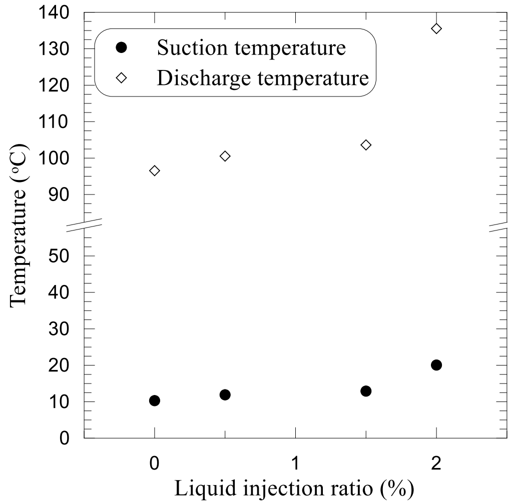

Figure 5: The variation of suction and discharge temperatures with the liquid injection ratio.

It can be seen in Figure 6 that, the increase in the coefficient of performance with increasing in the injection mass ratio is specific to a particular limit. The maximum enhancement in COP was 9.9% at injection ratio 0.5%. As the liquid injection mass ratio increases more than 1%, the COP is significantly reduced. The rise in discharge and suction temperatures leads to increase the compressor power consumption by about 38% at 0.5 injection ratio as shown in Figure 6.

Further liquid injection leads to increase the discharge temperature above the operating design temperature, thus the overload protection tends to stop the compressor operation. It can be concluded that, the injection of liquid in the discharge line of the A/C unit is not recommended in hot summer.

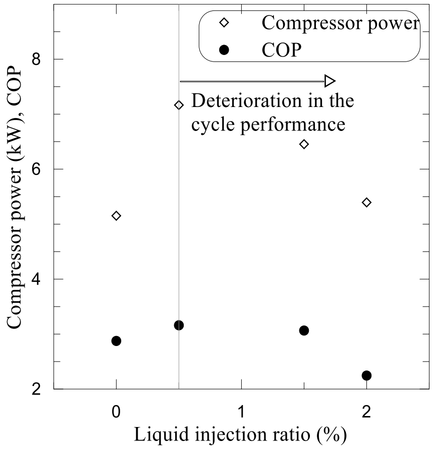

Figure 6: The effect of liquid injection on the compressor power and cycle COP.

The effect of compressor speed on the cycle performance is shown in Figure 7. It can be observed that, the increasing in frequency of compressor power supply from 35 to 40 HZ leads to increase the cycle COP. After this range of frequency, the increasing of cycle capacity with compressor speed is limited, while the compressor power shows a significant increase. The value of COP beyond frequency 45 HZ was reduced due to the rise in compressor power at relatively constant cycle capacity. The value of COP was improved by 18% and the power consumption reduced by 36.4% at frequency 35 Hz. Increasing the compressor speed to 60 Hz has reduced the COP by 29%.

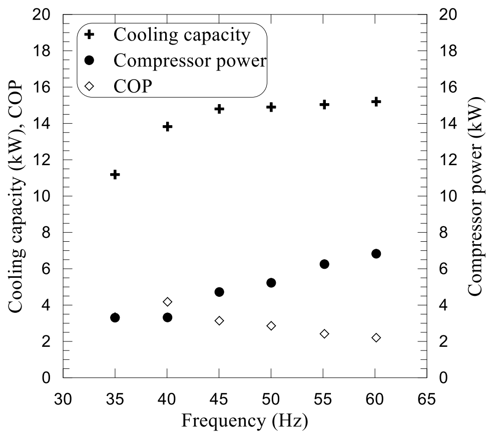

Figure 7: The effect of power supplied in frequency on the cycle performance.

The effect of different ratios of the refrigerant vapor injection and compressor speed on cooling capacity is shown in Figure 8. It can be seen obviously that the increase in both of vapor injection ratio and compressor speed have significantly improved the cooling capacity as compared with that for the conventional cycle. The average improvements in cycle capacity over different compressor speeds are about 17%, 24% and 31%, for the vapor injection ratios 2%, 3% and 4% respectively.

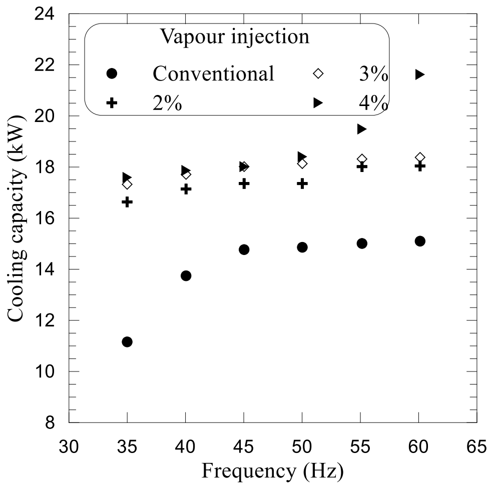

Figure 8: The variation of the cooling capacity with compressor power supply frequency.

The effect of vapor injection ratio and compressor speed on the compressor power is shown in Figure 9. It can be seen from the figure that, the minimum compressor power was for the conventional system, and the maximum compressor power was at 4% vapor injection ratio.

The variations in cooling capacity and compressor power with compressor speed for different vapor injection ratios can be well summarized using cycle COP as shown in Figure 10. It can be observed from this figure that, the cycle COP was affected strongly by both the ratio of injected vapor and power supply frequency. The injection of refrigerant vapor in the compressor suction line will reduce the degree of superheating of the vapor entering the compressor.

A low speed compressor means low load imposed on the evaporator, so a lower ratio of injected vapor will be enough to overcome the degree of superheat of the vapor. Therefore, 2% of vapor injection is effective when the frequency is in the range of 35 to 40 Hz. As the compressor speed increases, the ratio of vapor injection should be increased also to overcome the resulted degree of vapor superheating. Thus, 3% of vapor injection is compatible with the compressor speed in the range of 45 to 50 Hz. When the compressor speed is more than 50 Hz the mass ratio of injected vapor should be 4% as shown in Figure 10

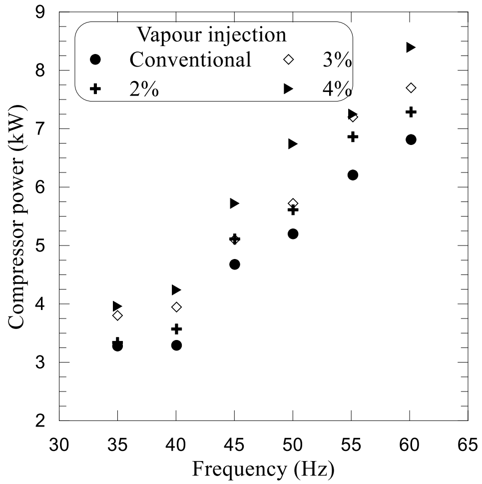

Figure 9: The variation of the compressor power with compressor power supply frequency for different vapor injection ratios.

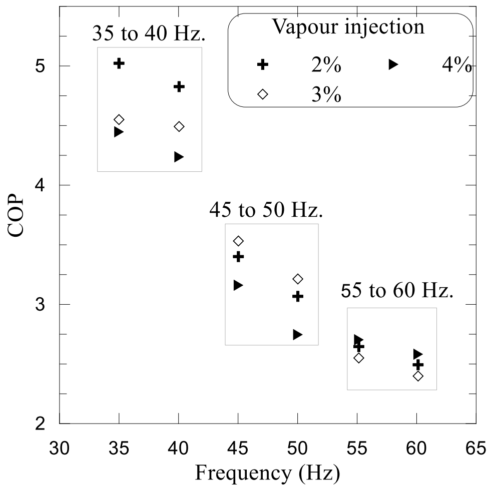

Figure 10: COP versus compressor power supply frequency for different vapor injection ratios.

Conclusions

Many conclusions can be derived from experimental results as follows: Improving of COP by 11.26%, and reduction in suction temperature from 10.3 to -0.1°C, at vapor injection ratio 3%. The best improvement with liquid injection was at 0.5% injection ratio in which the COP is improved by 9.9%. Injection of liquid has displayed insignificant effect on the vapor compression cycle and maybe leads to deterioration in cycle performance. It can be concluded that the injection of liquid can improve the cycle performance at heating mode. Using a variable speed compressor has affected the system performance as follows: improving of COP by 18% and reduction in the power consumption by 36.4% at frequency 35 Hz. Increasing the compressor speed to 60 Hz has reduced the COP by 29%. Saving in power consumption by 36% and improving of COP by 75% at speed 35 Hz when using vapor injection at ratio 2% compared to the conventional system.

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