INCREASE COP OF HEAT PUMP SYSTEM USING VAPOUR INJECTION AND PERMANENT MAGNET MOTOR

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ABSTRACT

This study analyzes the performance of variable capacity heat pump scroll compressor which is equipped with vapour injection and permanent magnet motor. Refrigerant used in the system is R410A. The study is divided in two phases. In first phase, tests are carried out for heat pump without vapour injection. Heat pump's performance including COPs, heating/cooling capacities, inverter losses, heat transfer behaviour in condenser/evaporator are analyzed. Inverter losses increase but the ratio of inverter losses to the total compressor power decreases with increase in compressor speed. Electromechanical losses of compressor are much higher than the inverter losses and so make most part of the total compressor losses (summation of inverter and electromechanical losses). In second phase benefits of vapour injection are analyzed. For vapour injection, heat pump's performance is evaluated for two different refrigerant charges: 1.15kg and 1.28kg. It is noted that heat pump performs better for refrigerant charge 1.15kg even at lower compressor speeds as compared to refrigerant charge 1.28kg. For refrigerant charge 1.15kg, heat pump COP cool with vapour injection increases by an average of 10.66%, while COP heat increases by an average of 9.4%, at each compressor speed except for 30Hz, as compared to conventional heat pump cycle with no vapour injection. Similarly refrigerant temperature at outlet of compressor also reduces with vapour injection which leads to the better performance of heat pump.

1. INTRODUCTION

Ground source heat pumps, exchange heat to and/or from ground source to provide heating or cooling. GSHPs make use of the relatively constant temperature of ground throughout the year as compared to ambient air and a circulating fluid (refrigerant, water, brine etc.) to exchange heat. Temperature gradients in ground at about 3-ft depth or lower are less variable than ambient air . Like a cave, the ground temperature is warmer than the air above it in winters and cooler than air in summers. The earth acts as a heat source in winters and heat sink in summers. As with any other heat pumps, GSHPs are able to heat, cool and supply hot water when needed. Compared to air-source heat pumps, they do not depend on the outside air temperature. with the refrigerant in a heat exchanger and once it has circulated through the system it is important that consideration be given to their efficiency improvement to save energy and reduce greenhouse gases.

1.1 Objectives

The objective of this study is to analyze the performance of variable capacity heat pump scroll compressor with and without vapour injection compressors with permanent magnet motors can reduce the electromechanical1 losses incurred during the operation of heat pump.
This study also aims to determine the impact of the vapour injection on the overall performance of heat pump unit. For this purpose an economizer, expansion valve and a sight glass are added in the system.

2. Working principle of the heat pump system used in experimentation

In this study a vapour-injected scroll compressor equipped with permanent magnet motor is being used. The general working principle of heat pump with this arrangement is the same as any other heat pump except that an additional economizer is added into the system.
In this section a general working principle of a heat pump system is described. Some explanation about the vapour injection configuration into the heat pump and its possible advantages is also given.

How heat pump works:
Heat pump is a device that transfers energy from a heat source at low temperature to the heat sink that is relatively at a higher temperature than the heat source. It works on the principle of refrigeration cycle (also called vapour compression cycle). It can be used for both heating and cooling depending on the application.

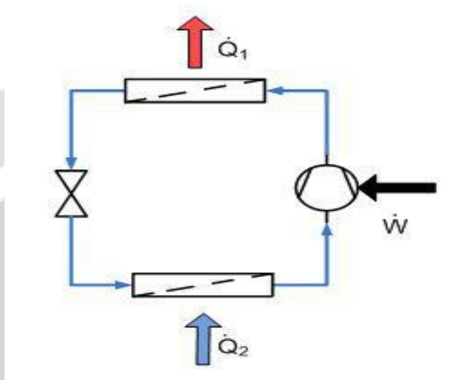


Figure 2.1: Schematic diagram of a heat pump system

For adiabatic system the heat balance can be written as

$$Q1=Q2+W \qquad \ldots\ldots\ldots\ldots..1$$

The cooling COP is defined as

$$COP_{cool} = Q2/W \ldots\ldots\ldots\ldots..2$$

Where Q2 is the evaporating capacity, also called the refrigerating capacity.

Whereas heating COP is given by the following correlation

$$COP\ heat = Q1/W$$

Q1 is the condensing capacity.

In case of vapour injection a portion of the condensed liquid is expanded through an expansion valve into the economizer (brazed plate counter flow heat exchanger) which acts as a subcooler for the condensed liquid. The expanded refrigerant is superheated in this section and is injected in the intermediate vapour injection port in scroll compressor. The additional subcooling increases the evaporating capacity by reducing the enthalpy of refrigerant entering the evaporator. Heating capacity also increases due to the additional mass flow through the condenser. The vapour injected in the intermediate port is compressed from higher inter stage pressure than the suction pressure. The COPs are also higher with vapour injection scroll compressors than conventional scroll compressors delivering the same capacity because the added capacity is achieved with less power.

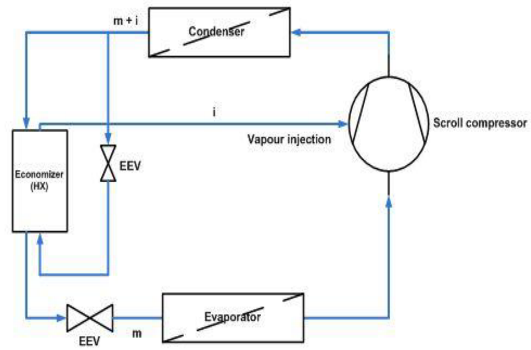


Figure 2-2: Vapour injection with upstream liquid extraction

Liquid is usually extracted upstream for the economizer expansion device as shown in Fig.2-3. Downstream extraction refers to taking the liquid for heat exchanger expansion device from HX liquid exit below. The overall heat gain or loss for downstream extraction is negligible compared to upstream extraction. The injected mass flow, i, passes through HX twice and causes additional pressure drop on liquid cooling side, which may result in need for a larger HX. For these reasons upstream liquid extraction is usually preferred.

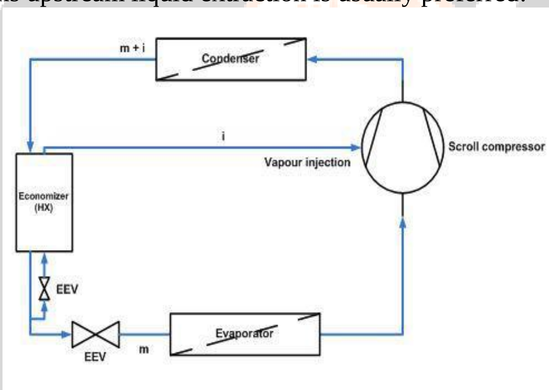


Figure 2-3: Vapour injection with downstream liquid extraction

Chapter 3

Experimental setup

An experimental test rig used to analyze the variable capacity compressor, as shown in Fig.3-1. To carry out experiments without vapour injection, test rig is equipped with heat pump unit with brazed plate evaporator and condenser, inverter-driven variable speed compressor, water tank, brine pump, water pump, two external plate heat exchangers, valves, power meter and data acquisition system. Electronic expansion valve is used to maintain the degree of superheat at 5^{o}C before the compressor inlet. To carry out experiments with vapour injection, additional heat exchanger, called economizer and an electronic expansion valve are added in the test rig. Refrigerant R410A is used in the heat pump unit. Power is measured before and after the inverter using the power meter.

3.1 Test facility

The experimental facility consists of four separate loops: refrigerant flow loop, brine loop and two water loops.

3.1.1 Refrigerant flow loop

The refrigerant loop contains a variable speed compressor that circulates refrigerant through condenser, economizer (in case of vapour injection), expansion valve and evaporator at variable flow rate. In case of heat pump system without VI, refrigerant is pumped into the condenser by the inverter-driven variable capacity compressor where it exchanges its heat with water in the secondary circuit. Refrigerant is then expanded through an electronic expansion valve into the evaporator, it is superheated here and pumped again through compressor.

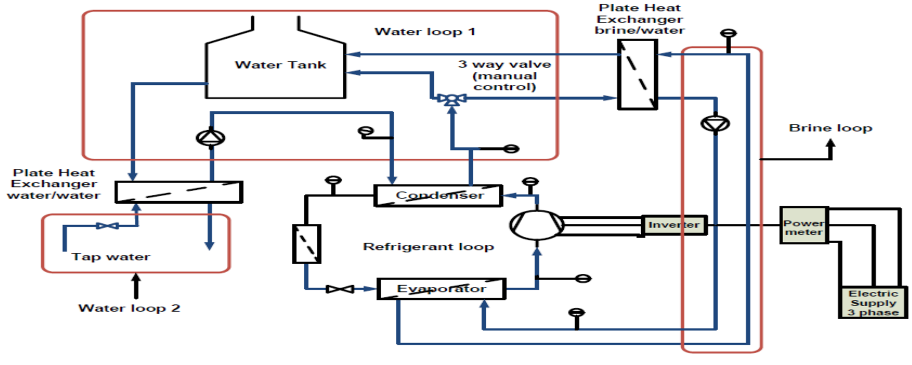


Figure 3-1: Schematic showing the heat pump system without vapour injection of test rig

For vapour injection system, some of the condensed liquid is extracted from the main liquid line and expanded into an economizer where it exchanges heat with the condensed liquid flowing in the pure liquid line. Economizer acts a subcooler for the already condensed liquid. The extracted vapour is superheated in the economizer and injected into the compressor at intermediate pressure through a vapour injection port.

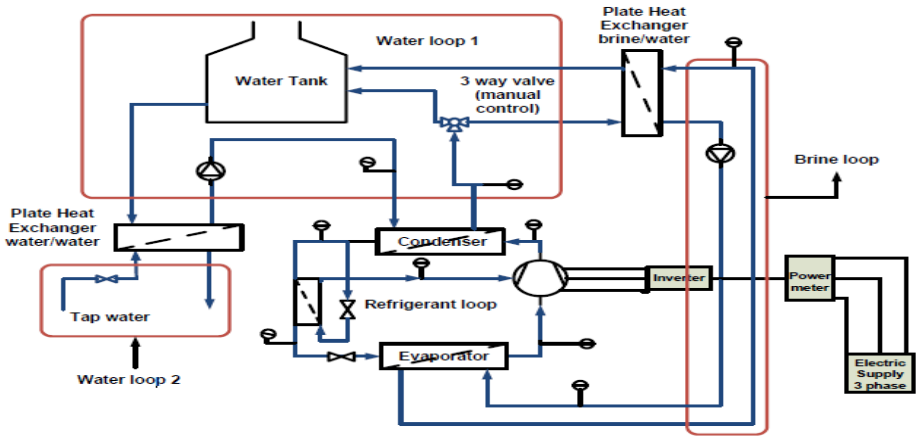


Figure 3-2: Schematic showing the heat pump system with vapour injection and other components of test rig

3.1.2 Brine and water loops

As shown in Fig. 3-2, secondary circuits to the evaporator and condenser side are: brine loop and water loop 1 respectively. A fixed speed pump in water loop 1 circulates water through the secondary circuit on condenser side. Water takes away heat from the refrigerant in condenser through water loop 1 and exchanges some of the heat with brine in an external plate heat exchanger (plate heat exchanger, brinr/water) to maintain brine's temperature entering the evaporator. Heating load to the brine is provided by water loop 1. Brine is circulated in a secondary loop through the evaporator where it gives off its heat to vaporize the refrigerant in evaporator. Temperature at the inlet of brine is controlled by a three-way manual valve, which is positioned at different incremental points from time-to-time. Water temperature at inlet or outlet of condenser is controlled via a tap water valve in water loop 2. Tap water circulates through water loop 2 to maintain temperature of the water in water loop 1 at inlet or outlet of condenser.

Chapter 4

Methodology

This study is carried out in two phases:
I. In the first phase experiments are run without vapour injection II. In the second phase vapour injection components are added and experiments are run again for different refrigerant charges.

Loss behaviour of variable speed compressor, frequency inverter and total isentropic efficiency are analyzed only in the first phase of study. While the overall heat pump performance, heat transfer behaviour in condenser and evaporator is analyzed in both the first and second phase.

1. To analyze the loss behaviour of variable speed compressor, frequency inverter, total isentropic efficiency, following parameters are kept constant:
Brine temperature to the inlet of evaporator (called the source temperature) = T br, in and water temperature to the outlet of condenser (called the sink temperature) = T wt, out
The following set points are used:
a. 2C/40C as the source/load side temperature respectively
b. 2C/45C as the source/load side temperature respectively
c. 5C/45C as the source/load side temperature respectively
Where 2C, 5C are the brine inlet temperatures to the evaporator and 40C, 45C are the water outlet temperatures of the condenser.

2. To analyze the overall heat pump performance, heat transfer behaviour in condenser and evaporator, the following parameters are kept constant
Brine temperature to the inlet of evaporator (called the source temperature) = T_br,in, water temperature to the inlet of condenser (called the sink temperature) = T_wt,in
The following set points are used:
a. 2C/25C as the source/load side temperature respectively
b. 5C/25C as the source/load side temperature respectively
c. 5C/30C as the source/load side temperature respectively
d. 5C/35C as the source/load side temperature respectively
Where 2C, 5C are the brine inlet temperatures to the evaporator and 25C, 30C, 35C are the water inlet temperatures to the condenser.

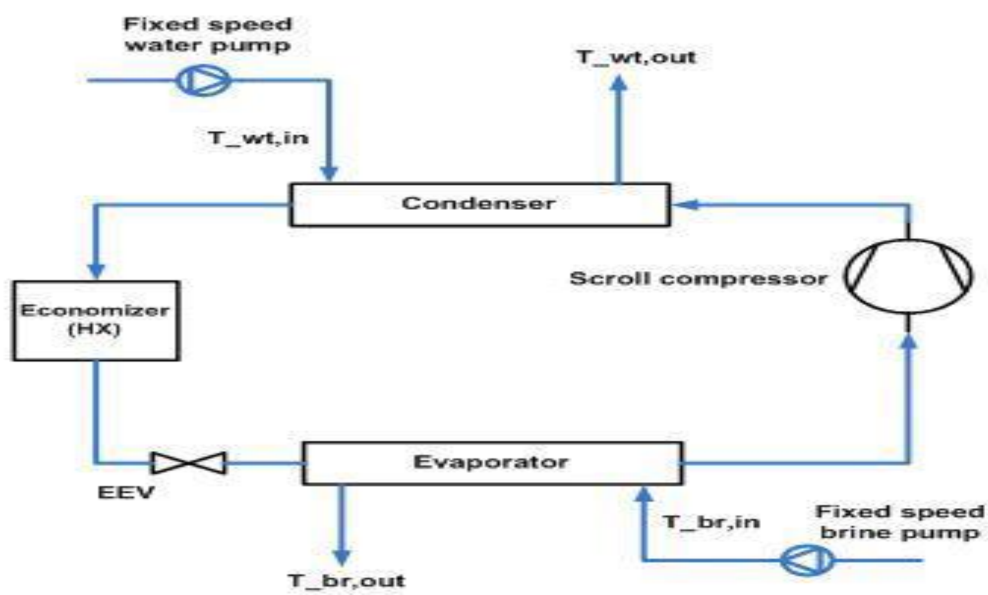


Figure 4-1: Schematic showing brine and water temperature controls in heat pump

The source and sink temperatures (set points) are chosen because of the stability of system within these temperature lifts. The source side temperature is not allowed to go below 2oC because of the sudden drop in temperature owing to the speed change of compressor. It causes the brine temperatures to drop suddenly especially at higher speeds and the system may have to shut down before proceeding further.

The brine temperature to the inlet of evaporator is controlled using three-way valve. The tap water valve controls the water temperature to the inlet and outlet of condenser. It is difficult to maintain temperatures at the set points for a long period. The measurements are, therefore, recorded for the time period of ten minutes approximately at each compressor speed for each set point.

Due to the manual control of temperatures on brine and water side using three-way valve and tap water valve respectively, it is very difficult to maintain the exact temperatures of T_br,in, T_wt,in and T wt,out. Therefore, the variation of ±0.4oC is allowed in the measurement of these temperature. With and without the vapour injection, compressor is run from 30Hz to 90Hz, because as the frequency (f) is increased beyond 90Hz compressor gets heated up and trips off.

The following parameters are measured during the experiments:

1. Compressor speed
2. The compressor power before and after the inverter
3. Condensation and evaporation pressures
4. Water inlet and outlet temperatures to the condenser, brine inlet and outlet temperatures to the evaporator, refrigerant temperature in and out of compressor, refrigerant temperature inlet of expansion valve.

Compressor speed is changed using the computer interface. Compressor power is measured using the power meter. All pressures and temperatures are measured using the respective sensors and data acquisition system.Compressor power is measured before and after the inverter.

4.1 Limitations

The limitations which were faced during experimentations are summarized below.

1. Compressor speed cannot be increased beyond 90Hz because of protective T sensors at outlet of compressor, which trip off compressor at speeds greater than 90Hz.
2. The source side temperature is not allowed to go below 2oC because of the sudden drop in temperature owing to the speed change of compressor. It causes the brine temperatures to drop suddenly especially at higher speeds and the system may have to shut down before proceeding further.
3. Manual T control valves limit the accuracy to control brine and water temperatures at inlet/outlet of evaporator and condenser.

4.2 Assumptions

Following major assumptions are made during the calculations:

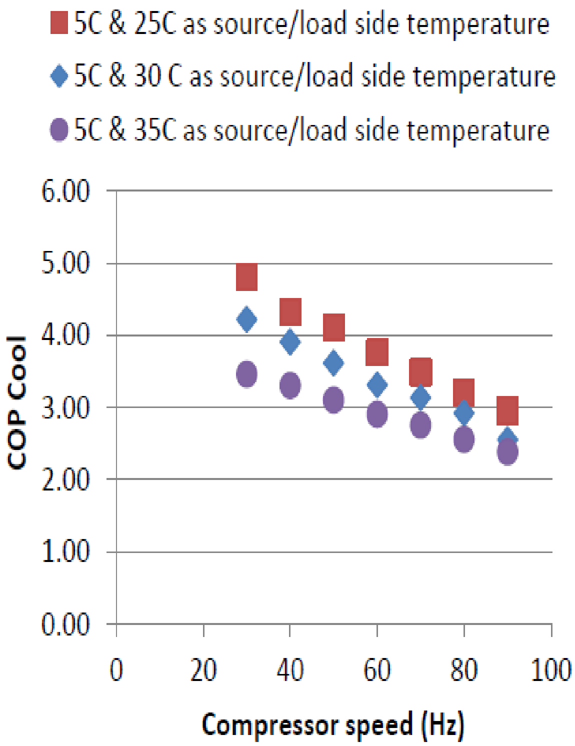
1. Heating losses in compressor are assumed to vary from 5% to 8% of total compressor power depending on compressor speed.

Chapter 5

Heat pump performance without vapour injection

As explained before, for measuring the inverter losses, the results are generated for set points (2C, 40C), (2C, 45C) and (5C, 45C). In these set points 2oC and 5oC are the brine inlet temperatures to the evaporator, whereas 40oC and 45oC are the water outlet temperatures from the condenser. For measuring the performance of heat pump unit, heat transfer behaviour in condenser and evaporator, the results are generated for set points (2C, 25C), (5C, 25C), (5C, 30C) and (5C, 35C). In these set points 2oC and 5oC are the brine inlet temperatures to the evaporator, whereas 25oC, 30oC and 35oC are the water inlet temperatures to the condenser.

Fig. 5-1 presents the heat pump COP cool for three different set points where the source side temperature is kept constant and load side temperature is allowed to vary and the compressor speed is changed from 30Hz to 90Hz. The source/load side temperatures are 5C/25C, 5C/30C and 5C/35C respectively. Fig. 5-2 presents the heat pump COP cool for two different set points for the same range of compressor speeds where the load side temperature is kept constant and source side temperature is allowed to vary. The source/load side temperatures are 2C/25C and 5C/25C respectively.



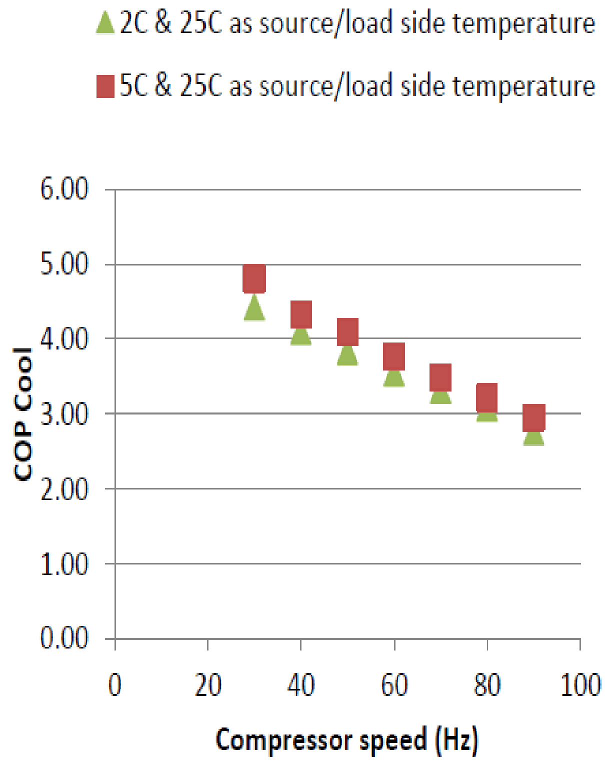


Figure 5-1: Heat pump COP cool when load side temperature is changed	**Figure 5-2: Heat pump COP cool when source side temperature is changed**

Fig.5-1 and Fig.5-2 both show the decreasing trend in COP values of heat pump as compressor speed is increased. From fig. 5-1, it can be seen that at each compressor speed COP values are the highest when load side temperature is set at the lowest point. The COP Cool values of heat pump decrease from almost 5 at 30Hz to 2.56 at 90Hz. For each set point COP values decrease as compressor speed changes from 30Hz to 90Hz because of increase in pressure ratios. In fig. 5-2, it can be seen that the COP Cool values of heat pump decrease from almost 5 at 30Hz to 3 at 90Hz. Also as the source side temperature decreases so does the COP value at each compressor speed.

Chapter 6

Heat pump performance with vapour injection (VI)

The vapour injection technique is employed in scroll compressors with the addition of an economizer in vapour compression cycle, as shown in figure 1-3. With this configuration it is possible to achieve higher COPs, heating and cooling capacities than conventional refrigeration cycles. Due to the increase in capacity, smaller displacement compressor can be used for the given heating load. The operating envelopes of compressors are also widened owing to the additional cooling provided by the intermediate vapour injection.

The compressor used in study is a scroll compressor equipped with vapour injection port. As claimed by manufacturers, it is possible to achieve the following benefits:

1. Cooling capacity improvement could be up to 40% with the same displacement compressor.

2. Cooling COP could go up by 15%.

3. Heating capacity and heating COP are improved due to higher refrigerant mass flow across condenser.

4. Cooling effect of vapour injection (lower refrigerant temperature at outlet of compressor) allows large operating envelopes.

5. Vapour injection effect is proportional to the pressure ratios, i.e. higher heating capacities and COP when needed.

To make modifications for vapour injection, system is emptied first by vacuuming refrigerant R410A into a separate bottle. When the components are installed along with piping, system is checked against any leakages. System is pressurized with nitrogen at 10Bars and left undisturbed for two days. If pressure of nitrogen does not drop, it ensures no leakages in the system. Vacuum is created inside using vacuum pump to ensure no air and refrigerant R410A is filled in the heat pump.

6.1 Results and discussions

The degree of superheat at the inlet of vapour injection port of compressor is set at 5oC. System is recharged with two different amounts of refrigerant, 1.15kg and 1.28kg, and comparison is made amongst them. Tests are carried out for set points (5C, 25C) and (5C, 30C) at compressor speed varying from 30Hz to 90Hz. As compressor speed is increased beyond 90Hz, system shuts down due to protective temperature sensors at outlet of compressor. The methodology for control of temperatures at evaporator and condenser is already explained in section 4.

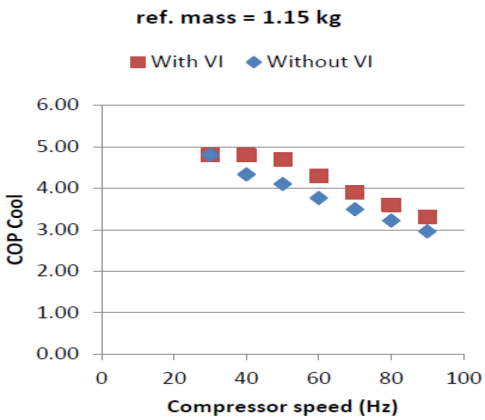


Figure 6-1: COP Cool of heat pump system with vapour injection for set point (5C, 25C) and ref. mass = 1.15kg

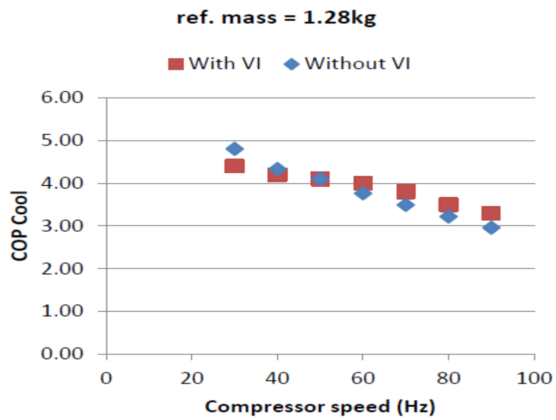


Figure 6-2: COP Cool of heat pump system with vapour injection for set point (5C, 25C) and ref. mass = 1.28kg

Fig. 6-1 and fig.6-2 present heat pump's COP cool with and without vapour injection for set point (5C, 25C) with different refrigerant charge inside system. In Fig. 6-1 with refrigerant mass = 1.15kg, it can be seen from figure that for system with VI, COP cool are higher than system without VI at all compressor speeds except for 30Hz, where COPs for VI and without VI are almost equivalent. Heat pump COP with VI increases by an average of 10.66% at each compressor speed except for 30Hz. As explained later, this is because of the same approximate refrigerant temperature at the outlet of compressor for both the configurations.

In fig. 6-2 with refrigerant mass = 1.28kg, system with VI witnesses an average increase of 8.85% in COP cool at compressor speeds beyond 50Hz. From 30Hz to 50Hz COP cool for VI is lower than heat pump without VI. This is refrigerant charge inside system which causes a higher refrigerant temperature at outlet of compressor on frequencies 30Hz to 50Hz because of high.

Chapter 7

Conclusions

The heat pump performance is evaluated in this study. A variable capacity scroll compressor is used in heat pump which has the provision for vapour injection and is also equipped with a permanent magnet motor. The study is conducted in two phases: heat pump performance without vapour injection and heat pump performance with vapour injection. The summary of results from both the phases is presented here

Phase 1: Heat pump performance without vapour injection

In this phase,

During tests it is observed that COP cool decreases by 38% while COP heat decreases by 32% with increase in compressor speed from 30Hz to 90Hz. Both heating and cooling capacities see an increase with increase in compressor speed. Carnot and total isentropic efficiency reach their maximum at compressor speed of 60Hz. It is also observed that the built-in efficiency of compressor decreases with increase in compressor speed due to increase in pressure ratios.

Phase 2: Heat pump performance with vapour injection

For vapour injection, heat pump's performance is evaluated for two different refrigerant charges, 1.15kg and 1.28kg. It is noted that heat pump performs better for refrigerant charge 1.15kg even at lower compressor speeds as compared to refrigerant charge 1.28kg. For refrigerant charge 1.15kg,

heat pump COP cool with vapour injection increases by an average of 10.66%, while COP heat increases by an average of 9.4%, at each compressor speed except for 30Hz, as compared to conventional heat pump cycle with no vapour injection. Similarly refrigerant temperature at outlet of compressor also reduces with vapour injection which

leads to the better performance of heat pump. For refrigerant mass = 1.28kg, system with VI witnesses an average increase of 8.85% in COP cool and 6.79% in COP heat at compressor speeds beyond 50Hz.
In order for this system to operate optimally for vapour injection at almost all compressor speeds, refrigerant charge inside system should be around 1.15kg.

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