

Study concerning the influence of refrigerant injection on the efficiency of a heat pump

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Abstract. Heat pumps are today a viable alternative to conventional heating systems. Their main disadvantage is the strong dependence on ambient temperature. For high performance operation in the case of temperature lift increase, it is necessary to use a two-stage compression system. There is the possibility of using an alternative solution, namely refrigerant injection technology. Instead of using a two-stage compressor where two-phase refrigerant can be injected between the two stages in order to cool the suction gas before it enters the high pressure stage, it is also possible to inject refrigerant at an intermediate pressure during a single-stage compression process. This measure is only possible for a few special compressor types. Examples for such compressors are screw or scroll compressors. This paper presents a study on the possibilities of improving the performance of a pump by using refrigerant injection. Comparative analyses of different solutions (flash tank, economizer and liquid injection) are analysed.

1. Introduction

Air source heat pumps represent a very promising technology to contribute to the building sector decarbonisation and to decrease the primary energy consumption for the heat demand in the EU countries. Building heating systems can be classified into two categories.

The first one includes systems whose performance is virtually independent of ambient temperature and can be sized to meet the required highest thermal loads of the building. This category includes gas furnaces, boilers and systems operating inside the building; therefore their operation depends only on the internal temperature of the building.

The second category includes systems whose performance and heating capacity are adversely affected by ambient temperature; this includes air source heat pumps.

For this type of system there is a more complicated solution to ensure the appropriate heating load of the building during extremely low ambient temperatures.

Until a few years ago, the heat pumps (in the classical configuration of the cycle with one-stage mechanical compression cycle) were dimensioned to allow the thermal load of the building up to a certain outside temperature; below this temperature value an additional backup system was used.

This is because for conventional air/water heat pumps with on/off control, the generated heating capacity paradoxically increases with increasing ambient temperature and the associated decrease in required heating capacity.

The four main problems at very low ambient temperatures for air source heat pumps are:



- Insufficient heat output as the required heat is the largest whereas the heat pump capacity is reduced due to lower mass flow rates of the refrigerant;
- High compressor discharge temperature caused by the low suction pressure and high pressure ratio across the compressor. This leads to bivalent heat pump systems which use the heat pump at medium ambient temperatures. At very low ambient temperatures the compressor is turned off to protect it from overheating and electric resistance heating is used instead. The combined efficiency of such systems is quite low;
- The coefficient of performance (COP) decreases rapidly for high pressure ratios which can be found at low ambient temperature conditions;
- If the heat pump is designed for low ambient temperature conditions it will have a capacity that is far too large at medium ambient temperatures. Therefore, the heat pump needs to cycle on and off at higher ambient temperatures in order to reduce its capacity, which leads to a lower efficiency of the system compared to steady-state performance and also a lower comfort level of the inhabitants.

Increasing the efficiency of heat pumps can be achieved either by reducing the temperature lift between the heat source and the sink or by improving the performance of the thermodynamic cycle. In order to determine the possibilities for improving the performance of a heat pump thermodynamic cycle, an exergy analysis is very useful in addition to energy analysis. In the case of a mechanical drive heat pump, the energy efficiency is greater than 1, while the exergetic efficiency is always less than 1. For an on/off controlled single stage heat pump working at low ambient temperature, the exergy loss in compressor is even four to eight times as high as the other three sub-processes, [1].

Therefore, improving the compressor operation results in a significant increase in the efficiency of the heat pump.

A way to improve is the injection of refrigerant at intermediate pressure. This became possible due to compressor technology development.

A comparative analysis for an air source heat pump with 116 kW heating capacity and R410a refrigerant is presented.

2. Refrigerant injection technics

From thermodynamic point of view, the factors effecting refrigerant injection system include injected refrigerant states, namely injection pressure (intermediate pressure) and injection enthalpy.

Depending on the state of the working fluid at the entrance of the compressor, refrigerant injection can be classified in:

- Liquid injection;
- Vapour injection.

A simple thermodynamic model for each cycle was developed using the software package Engineering Equation Solver (EES).

The mathematical model was obtained using the mass and energy conservation laws.

2.1. Liquid injection

Liquid refrigerant injection refers injecting liquid-state refrigerant into the compressor. Injecting liquid refrigerant in reciprocating compressor suction has been applied for time ago.

This technique was mainly applied for refrigeration applications. With the development of dynamic compressor technology, it began to be used to an intermediate pressure.

Due to the increasing use of heat pumps as home heating systems, this liquid injection technique has been increasingly used to improve the operation of heat pumps at low ambient air temperatures.

The liquid injection technique can effectively reduce the compressor discharge temperature, which leads to improved compressor reliability when operating at a high pressure ratio.

The heat pump diagram and ln p-h chart for its thermodynamic cycle are shown in the figure 1.

A small fraction of the liquid flow resulting from the offset of the condenser installation is extracted from the main circuit and passes through an expansion valve, where the liquid is laminated to the injection pressure and introduced into the intermediate compression chamber of the compressor.

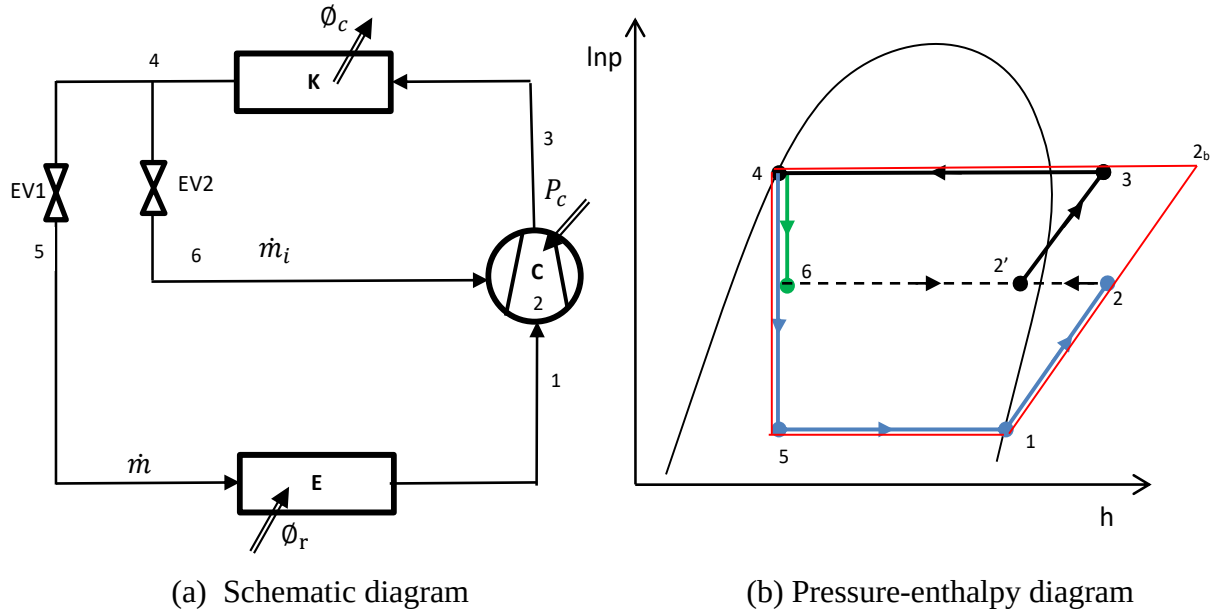


Figure 1. Two stage liquid injection cycle.

The mathematical model is obtained by using the mass and energy balance.
Heat flux extracted from ambient:

$$\dot{\Phi}_r = \dot{m} \cdot (h_1 - h_5). \quad (1)$$

Power consumed in compressor:

$$P_c = \dot{m} \cdot (h_2 - h_1) + (\dot{m} + \dot{m}_{inj}) \cdot (h_3 - h_{2'}). \quad (2)$$

Heat flux evacuated in condenser:

$$\Phi_c = (\dot{m} + \dot{m}_{inj}) \cdot (h_3 - h_4). \quad (3)$$

Thermal balance in compressor injection area:

$$\dot{m} \cdot h_2 + \dot{m}_{inj} \cdot h_6 = (\dot{m} + \dot{m}_{inj}) \cdot h_{2'}. \quad (4)$$

The injection liquid rate is:

$$\mu = \frac{\dot{m}_{inj}}{\dot{m}}. \quad (5)$$

The coefficient of performance COP of the heat pump with liquid injection:

$$COP_{Lij} = \frac{\Phi_c}{P_c}. \quad (6)$$

2.2. Vapor injection

There are two different operations of the vapor-injection cycle. One is called flash tank cycle (FTC), and the other is called internal heat exchanger or economizer cycle (IHXC).

Unlike the conventional and liquid-injected cycle, in the vapor injection cycle with a flash tank there are two expansion processes at different pressure levels. The liquid refrigerant from the condenser turns to two-phase flow in the first expansion process. The two-phase refrigerant at an intermediate pressure is then separated in a flash tank. The saturated vapor leaving from the top is injected to the intermediate compression chamber through an injection port. The saturated liquid leaving from the bottom is expanded to a two-phase mixture by the second expansion device, and then enters the evaporator. The FTC heat pump diagram and ln p-h chart for its thermodynamic cycle are shown in the figure 2.

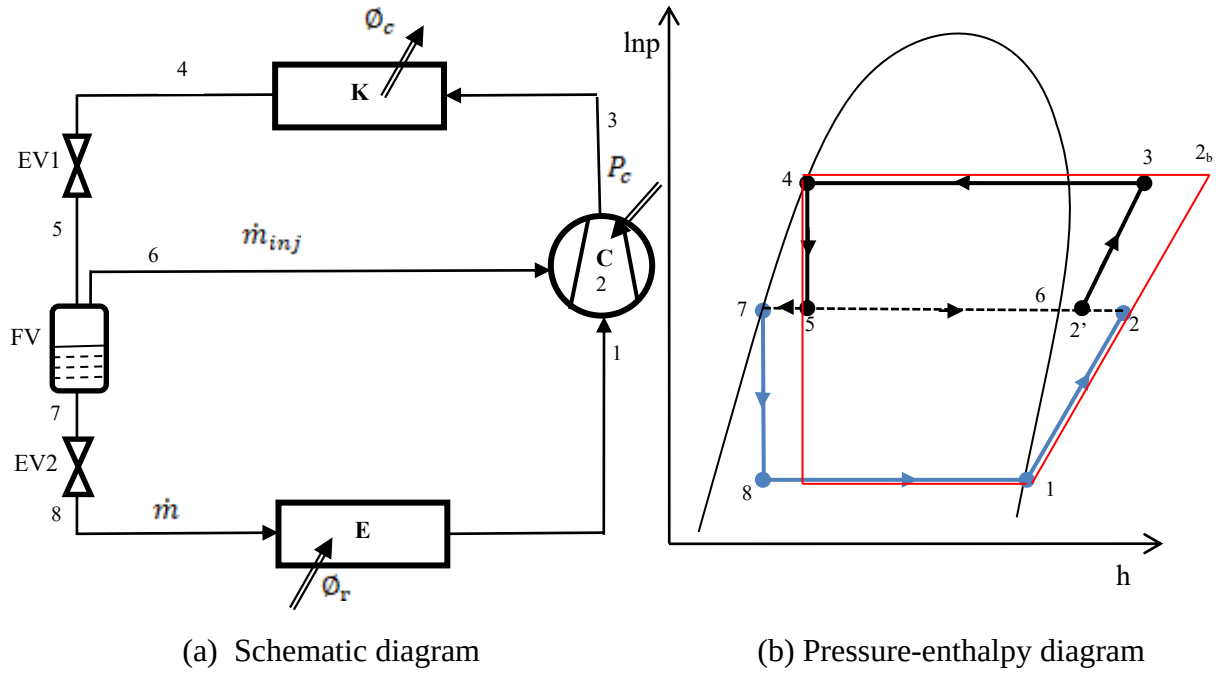


Figure 2. Two stage flash tank vapor injection cycle.

Heat flux extracted from ambient:

$$\Phi_r = \dot{m} \cdot (h_1 - h_8). \quad (7)$$

Power consumed in compressor:

$$P_c = \dot{m} \cdot (h_2 - h_1) + (\dot{m} + \dot{m}_{inj}) \cdot (h_3 - h_2). \quad (8)$$

Heat flux evacuated in condenser:

$$\Phi_c = (\dot{m} + \dot{m}_{inj}) \cdot (h_3 - h_4). \quad (9)$$

Thermal balance in compressor injection area:

$$\dot{m} \cdot h_2 + \dot{m}_{inj} \cdot h_6 = (\dot{m} + \dot{m}_i) \cdot h_{2'}. \quad (10)$$

Thermal balance for flash tank:

$$(\dot{m} + \dot{m}_i) \cdot h_5 = \dot{m} \cdot h_7 + \dot{m} \cdot h_6. \quad (11)$$

Coefficient of performance COP of the heat pump with flash tank vapor injection:

$$COP_{FVI} = \frac{\Phi_c}{P_c} . \quad (12)$$

The vapour injection internal heat exchanger cycle has a supplementary heat exchanger at the condenser outlet, so called internal heat exchanger. A small portion of the liquid refrigerant at the condenser outlet is drawn, and passes through an expansion valve. Then it enters the internal heat exchanger to subcool the main stream refrigerant coming from the condenser, and turns to vapor phase. The refrigerant vapor enters the intermediate compression chamber. The subcooled main-stream refrigerant is expanded by the second expansion device, and then enters the evaporator. The IHXC heat pump diagram and In p-h chart for its thermodynamic cycle are shown in the figure 3.

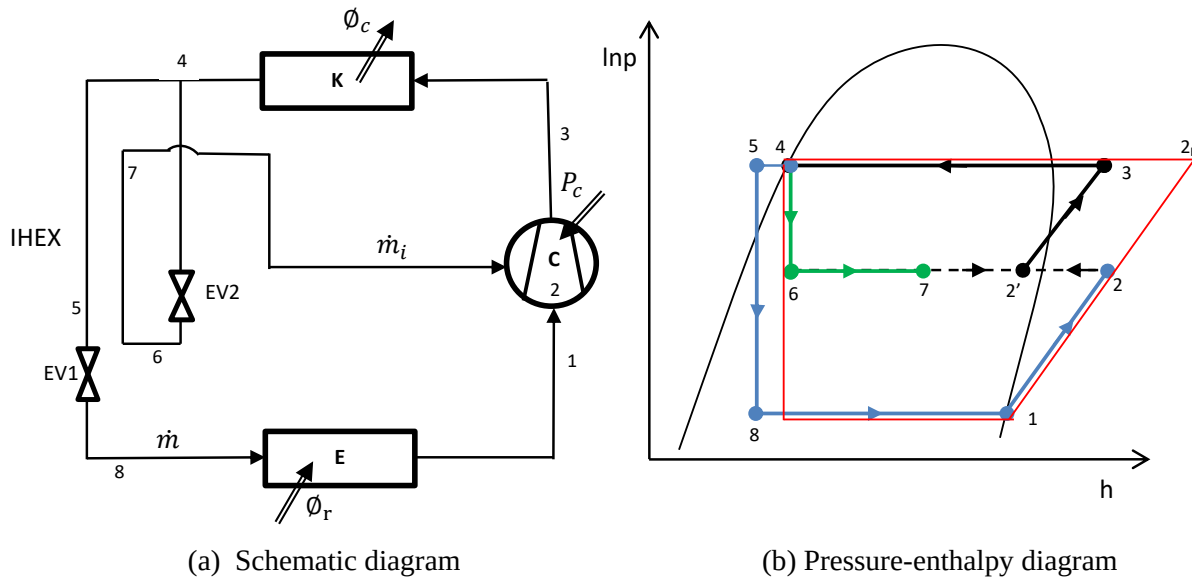


Figure 3. Two stage flash tank vapor injection cycle.

Heat flux extracted from ambient:

$$\Phi_r = \dot{m} \cdot (h_1 - h_8) . \quad (13)$$

Power consumed in compressor:

$$P_c = \dot{m} \cdot (h_2 - h_1) + (\dot{m} + \dot{m}_{inj}) \cdot (h_3 - h_2) . \quad (14)$$

Heat flux evacuated in condenser:

$$\Phi_c = (\dot{m} + \dot{m}_{inj}) \cdot (h_3 - h_4) . \quad (15)$$

Thermal balance in compressor injection area:

$$\dot{m} \cdot h_2 + \dot{m}_{inj} \cdot h_6 = (\dot{m} + \dot{m}_i) \cdot h_{2'} . \quad (16)$$

Thermal balance of internal heat exchanger IHEX:

$$\dot{m} \cdot h_4 + \dot{m}_{inj} \cdot h_6 = \dot{m} \cdot h_5 + \dot{m}_{inj} \cdot h_7 . \quad (17)$$

Coefficient of performance COP of the heat pump with economizer vapor injection:

$$COP_{IHXC} = \frac{\Phi_c}{P_c} . \quad (18)$$

3. Results and discussions

3.1. Liquid injection heat pump analysis

According the diagram presented in figure 1b, the liquid injection will particularly affect the operation of the compressor as a result of lowering the discharge temperature.

The effect of the liquid refrigerant injection on the decrease of discharge gas temperature is expressed by the difference of the temperature with injection td and that without injection tdb .

The compressor power consumption P_c in the cycle with liquid injection shown in figure 5 is normalized by the power consumption in the basic cycle P_{cb} .

When the injection rate increase, the discharge gas temperature decrease but, in the same time, the power consumption slightly increases (figure 4). This is due to the excess power to compress injected refrigerant.

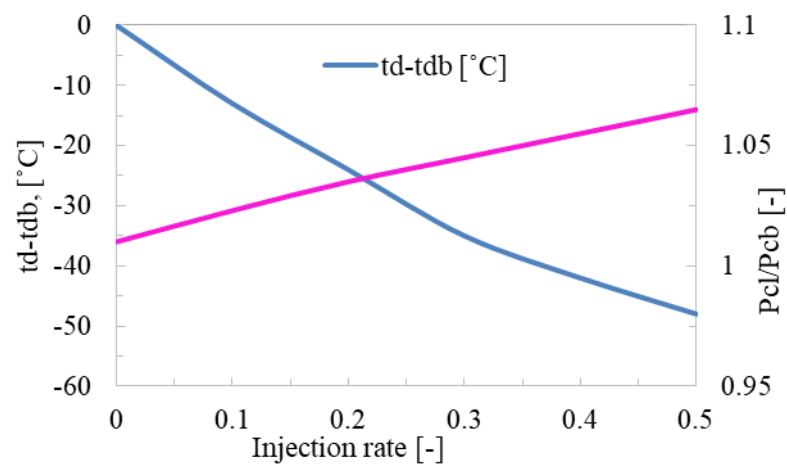


Figure 4. Discharge gas temperature decrease and power consumption versus the liquid injection rate.

3.2. Vapor injection heat pump analysis

According the diagrams presented in figures 2b and 3b, vapor injection will affect not only the discharge temperature, but also heating capacity of the system. Besides the outside temperature, the main factors that influence the performance of a vapor injection heat pump are the intermediate pressure at which the injection takes place and the injection rate. The influence of intermediate pressure injection on mass flow rate injection is very well documented in some studies [2, 3, 5, 6]. It is found that for both vapor injection schemes (IHXC and FTC) injection mass flow rate will increase with the increase in the intermediate pressure injection.

Two dimensionless parameters are defined:

- Relative flow injection ratio, defined as the ratio of the injected refrigerant mass flow rate to the refrigerant mass flow rate which cross through the evaporator:

$$\mu_r = \frac{\dot{m}_{inj}}{\dot{m}} \quad (19)$$

- Relative pressure injection ratio, defined as the ratio of the injection pressure to the evaporation pressure:

$$p_{ir} = \frac{p_{inj}}{p_{ev}} \quad (20)$$

In figure 5 the influence of relative injection pressure on relative injection ratio, for different ambient temperature is presented.

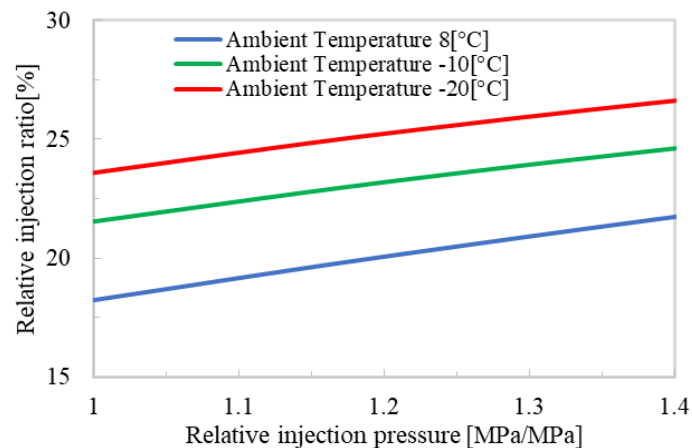


Figure 5. The variation of the relative injection ratio function of relative injection pressure for different ambient temperature.

From this figure results that the mass flow of refrigerant injected into the compressor increases as the injection pressure increases.

It also results from the this figure the ambient temperature strongly influences the injection pressure and the injection mass flow rate. This remark is valid for both vapour injection cycles analysed (FTC and IHXC).

For low ambient temperature heat pump operation, low injection pressure and small injection mass flow rate are necessary.

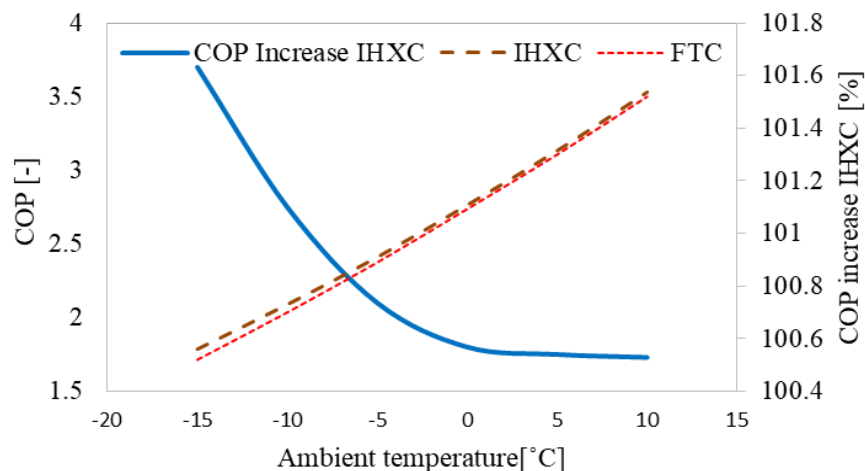


Figure 6. COP variation with ambient temperature for a vapour injection air source heat pump.

In figure 6 the influence of ambient temperature on COP of the heat pump is presented. From this figure results that, for low ambient temperature, IHXC has COP a little greater than FTC, but this difference decreases with ambient temperature increases. This is because the isentropic efficiency difference of high and low compression processes decrease when the temperature lift decrease (by increasing of the ambient temperature), what leads to equalization of COP of the two analysed cycles.

From the same figure also follows that with the decrease of the outside temperature, the COP of the vapor injection cycle increases compared to basic cycle (blue line).

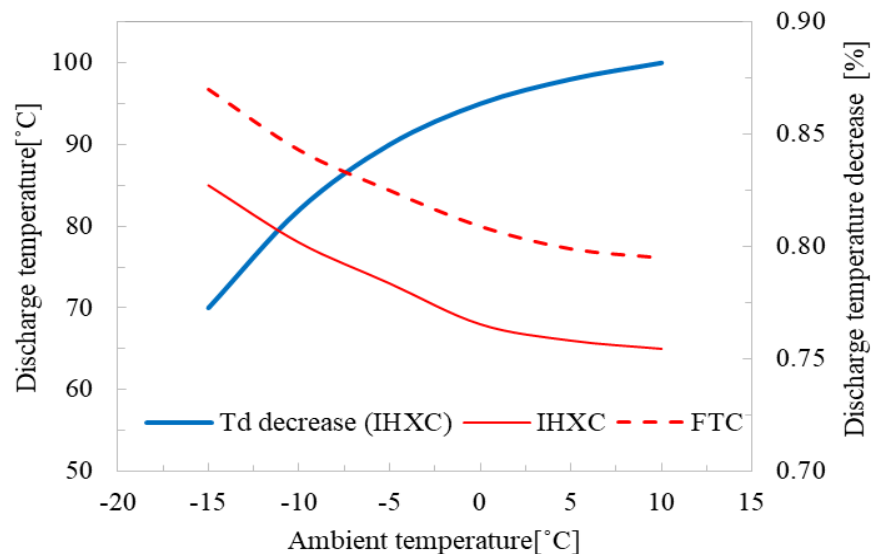


Figure 7. The influence of ambient temperature on discharge temperature of the compressor.

In figure 7 the influence of ambient temperature on discharge temperature of the refrigerant on compressor discharge. In the IHXC case, the discharge temperature decreases more than for FTC. This is because the possibility for a better control of amount and quality of injected refrigerant.

3.3. Discussions

By using liquid injection, the discharge temperature will decrease, which will produce to an extended envelope for compressor, [4]. There will be no heating and COP increase, but the compressor will have an extended envelop.

By using vapor injection technology, the heating capacity and COP oh the heat pump will increase.

This is due the decreasing of the discharge temperature and the increase of the refrigerant flow in the condenser. In the same time, but the compressor will have an extended envelop.

4. Conclusions

In order to identify the possibilities of improving the performance of an air source heat pump, a complex exergy analysis is required.

Using refrigerant injection for the air source heat pump leads to increasing performance at low ambient temperature.

Both vapour injection solutions have similar advantages and the choice of solution depends on the heat pump size and application.

Factors that affect the performance of the pump are the injection flow rate and the injection pressure.

5. References

- [1] Gasser L, Wellig B and Hilfiker K 2008 WEXA: Exergy analysis for increasing the efficiency of air/water heat pumps.
- [2] Wang X 2008 Performance investigation of two stage heat pump system with vapour injected scroll compressor *Doctoral Thesis*
- [3] Xue J, Guo X, Xue L 2017 Experimental Study on Performance of Flash-tank Vapor Injection Air-Source Heat Pump System with Refrigerant R32 *Energy Procedia* **142**, pp 950-956
- [4] Heitz J-F 2012 Optimized Heat pump with liquid injection in commercial heat pump system *Chillventa 2012*

- [5] Mackintosh T 2016 The Design and Experimental Analysis of an Air Source Heat Pump for Extreme Cold Weather Operation *Thesis* Carleton Institute for Mechanical and Aerospace Engineering
- [6] Jang Y, Lee E, Chin S and Ha S 2010 Effects of Flash and Vapor Injection on the Air-to-Air Heat Pump System *International Refrigeration and Air Conditioning Conference* paper 2477