Increasing the air source heat pump efficiency at low ambient temperature by using a two-phase ejector

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Abstract. The use of an ejector as expansion device is one of the alternative ways to improve the performances of an air source heat pump at low ambient temperature. This article presents a theoretical energetic and exergetic analysis of an ejector expansion vapor compression heat pump with on/off control. By using the ejector, the expansion throttling process is replaced by an adiabatic expansion. Furthermore, compressor operation is much improved due to lower compression ratio and reduces the temperature of the working medium at the end of the compression process. It also enables to reduce size of the evaporator, It also enables to reduce size of the evaporator, by using a phase separator. The results show that, by using an ejector instead a throttle vane in basic vapour compression cycle, both the energy efficiency and the exergetic efficiency of the cycle increase. The phase separator placed after the ejector has a significant influence on the cycle performance too. The exergy loss in every heat pump components is calculated. Thus, it can be seen that the process needs to be improved for better performance of the heat pump. The results highlights that the most important exergy loss at low ambient temperature have place in the compressor.

1. Introduction
Air source heat pumps (ASHP) have become a competitive alternative for building heating systems. Due to the existence of alternative heating systems (mainly those that work by using chemical or electrical energy), it is necessary to improve their efficiency. For not very low temperatures in the winter, the heat pump can operate on the basis of a single stage refrigeration cycle. But when the temperature lift is increasing, the heat pump efficiency is badly affected. In this situation, the coefficient of performance (COP) is dramatically affected.

To improve the efficiency of a heat pump, an energy analysis is required, but this is not enough. An exergy analysis is very useful to identify the location, magnitude, and sources of exergy destruction and exergy loss, to determine the possibilities of system performance improvement.

In the basic single stage mechanical vapor compression thermodynamic cycle, there are five thermodynamic losses that significantly reduce the value below that of the Carnot cycle. These include compressor inefficiency and throttling process in expansion valve. The first one is function of the compressor used, while the second is an intrinsic loss of the cycle. By replacing the throttle valve with an ejector, instead of extracting mechanical work from the expanding refrigerant, its kinetic energy is used to partially compress the saturated vapor leaving the evaporator, increasing the enthalpy change in the evaporator and reducing the load on the compressor.
For the first time, the use of the ejector as expending device in a vapour compression cycle was proposed by Kornhauser in 1990, [1]. Most studies published in the last years are concerned in ejector application in refrigeration area, [2-6]. There are a few papers concerning expansion ejector heat pumps, [7-12]. The main objective of this paper is to highlight the influence of the ambient temperature on the air source heat pump performance. It also analyses the environmental temperature dependence of exergy losses in each component of the heat pump.

2. Heat pump system description

The study was carried out on basic conventional vapor compression cycle (BC) and expansion ejector vapor compression cycle (EC) in order to compare the performance of each air-conditioning system.

The conventional cycle (BC) was conducted by using a throttling valve as an expansion device while the other cycle (EC) was conducted by using ejector as an expansion device and a phase separator.

![Figure 1. Schematic drawing of expansion ejector vapour compression system (a) and p-h diagram for the heat pump cycle (b).](image)

In figure 1a the schematic diagram of the ejector-expansion heat pump cycle is presented. High-pressure working fluid out of the condenser is expanded in the primary nozzle of the ejector. The resulting expanded two-phase flow entrains and raises the vapor pressure at the outlet of the evaporator. The mixture resulting from the two fluids in the mixing chamber enters in diffusion nozzle, where its speed is reduced and its pressure is increased. Then, it is introduced in the phase separator, the vapor resulting enters the compressor and the liquid is introduced through a throttle valve in the evaporator. As against to the basic cycle, the compression work consumed decreases due to increased suction pressure.

Figure 1b presents the p-h diagram for ejector vapor compression cycle and for conventional vapor compression cycle. From this figure it is very clear that the compressor work required ejector vapor compression cycle is smaller than in conventional vapor compression cycle.

The ejector parameters that significantly influence the performance of the heat pump are the mass entrainment ratio and the pressure lift ratio.
The entrainment ratio represents how much working fluid mass is able to entrain. The entrainment ratio is seen to be highest when the entrained fluid reaches a choked condition in the mixing region, [12]. This ejector parameter is defined by relationship:

\[ \Delta p = \frac{p_0}{p_s}. \]  

(1)

The pressure lift ratio is the defined as the ratio between the working fluid pressure at the exit from ejector and the working fluid pressure in the evaporator:

\[ \Delta p = \frac{p_0}{p_s}. \]  

(2)

3. Energy analysis

Energy analysis, or First law analysis, for a heat pump, refers to coefficient of performance analysis. Using EES (Engineering Equation Solver) program, we consider certain input data:

- Ambient temperature \( (t_a) \): -15°C;
- Heating temperature \( (t_H) \): 50°C;
- Evaporating temperature \( (t_e) \): -20°C;
- Condensing temperature \( (t_c) \): 60°C;
- Fluid refrigerant: R 410a.

The following assumptions have been used to simplify the theoretical model:

- the refrigerant will be at all times in thermodynamic quasi-equilibrium;
- steady state one-dimensional model;
- thermodynamic processes in compressor, expansion valve and ejector area assumed to be adiabatic;
- the flow across the throttle valve is isenthalpic;
- the refrigerant condition at the evaporator outlet is saturated vapour and condenser outlet is saturated liquid;
- the vapour condition from the separator is saturated vapour and the liquid coming from the separator is saturated liquid.

For the expansion ejector vapor compression heat pump EVCC, the following energy conservation equations can be written.

The energy conservation equation between the inlet and the exit of the motive nozzle:

\[ h_7 = h_4 + \frac{v_7^2}{2}. \]  

(3)

The energy conservation equation between the inlet and the exit of the suction nozzle:

\[ h_5 = h_6 + \frac{v_6^2}{2}. \]  

(4)

The energy conservation equation in the diffusion nozzle is:

\[ h_9 = h_8 + \frac{v_8^2}{2}. \]  

(5)

The overall efficiency of the ejector is given by equation:

\[ \eta\eta_2 = (1 + \mu)h_y. \]  

(6)

The entrainment ratio must satisfy the equation:
\( \mu = \frac{1-x}{x} \). \quad (7)

The specific compressor work can be found by equation:
\[ w_{\text{comp}} = h_2 - h_1. \] \quad (8)

The specific heating effect is:
\[ w_{\text{cond}} = h_2 - h_3. \] \quad (9)

The energy efficiency EVCC cycle, which is defined by coefficient of performance:
\[ COP_{\text{EVCC}} = \frac{q_{\text{cond}}}{w_{\text{comp}}} = \frac{h_2 - h_3}{h_2 - h_1}. \] \quad (10)

The energy efficiency of the classic vapor compression cycle (VCC):
\[ COP_{\text{VCC}} = \frac{q_{\text{cond}}}{w_{\text{comp}}} = \frac{h_1 - h_3}{h_1 - h_5}. \] \quad (11)

The energy efficiency improvement of the EVCC over basic cycle:
\[ COP_{\text{im}} = \frac{COP_{\text{EVCC}} - COP_{\text{VCC}}}{COP_{\text{VCC}}}. \] \quad (12)

4. Exergy analysis

Exergy analysis, or Second law analysis, for a heat pump, refers to exergy efficiency \( \eta_{\text{ex}} \).

The reversible coefficient of performance of a heat pump working ideally is determined by the relationship:

\[ COP_{\text{rev}} = \frac{T_H}{T_H - T_a} = \frac{1}{\eta_C}. \] \quad (13)

where \( \eta_C \) is Carnot factor.

The exergy efficiency can be expressed as:
\[ \eta_{\text{ex}} = \frac{COP_{\text{cycle}}}{\eta_C} = 1 - \frac{\sum_{l_{\text{comp}}}^{ex_{\text{losser}}}}{l_{\text{comp}}} . \] \quad (14)

The specific exergy of the refrigerant is expressed as:
\[ ex = (h - h_e) - T_a(s - s_0). \] \quad (15)

For a specific heat transfer rate at constant temperature T, the heat exergy rate can be calculated by the relationship:
\[ ex_q = \left(1 - \frac{T_a}{T}\right)q. \] \quad (16)

For the EVCC cycle the specific exergy losses are expressed by the following equations:
- the specific exergy loss flow in the compressor:
\[ ex_{\text{comp}} = T_a(s_2 - s_1) \] \quad (17)
- the specific exergy loss flow in the condenser:
\[ e_{x,\text{cond}} = (h_2 - h_3) - T_a (s_2 - s_3) \]  
(18)

- the specific exergy loss flow in the ejector:
\[ e_{x,\text{ej}} = T_a \left( (1 - \mu) s_y - s_y - \mu s_s \right) \]  
(19)

- the specific exergy loss flow in the evaporator:
\[ e_{x,\text{ev}} = (h_5 - h_4) \mu + T_a (s_5 - s_4) \mu \]  
(20)

- the specific exergy loss flow in the throttle valve:
\[ e_{x,\text{tv}} = T_a (s_5 - s_4) \mu \]  
(21)

- the exergy efficiency of EVCC cycle:
\[ \eta_{ex,\text{EVCC}} = 1 - \frac{e_{x,\text{comp}} + e_{x,\text{cond}} + e_{x,\text{ej}} + e_{x,\text{ev}}}{w_{\text{comp}}} \]  
(22)

For the basic vapor compression cycle VCC the specific exergy losses are expressed by following equations:

- the specific exergy loss flow in the compressor:
\[ e_{x,\text{comp}} = T_a (s_{11} - s_s) \]  
(23)

- the specific exergy loss flow in the condenser:
\[ e_{x,\text{cond}} = (h_1 - h_2) - T_a (s_{11} - s_s) \]  
(24)

- the specific exergy loss flow in the throttle valve:
\[ e_{x,\text{tv}} = T_a (s_3 - s_{3'}) \]  
(25)

- the specific exergy loss flow in the evaporator:
\[ e_{x,\text{ev}} = (h_5 - h_{3'}) + T_a (s_5 - s_{4'}) \]  
(26)

- the exergy efficiency of VCC cycle:
\[ \eta_{ex,\text{VCC}} = 1 - \frac{e_{x,\text{comp}} + e_{x,\text{cond}} + e_{x,\text{tv}} + e_{x,\text{ev}}}{w_{\text{comp}}} \]  
(27)

5. Results and discussions
In figure 2 the heat pump COP for both configurations (VCC and EVCC) are presented. It can be seen that the COP for VCC cycle is smaller than COP for EVCC cycle for all the external temperature range analyzed. This is due because the compressor work in EVCC cycle is smaller than in VCC cycle because the ejector. This observation was to be expected, due to the fact that the ejector provides a higher compressor suction pressure. COP improvement for EVCC cycle varies from 12% at -15°C to 20% at 15°C.

In figure 3 the variation of heat pump exergy efficiency for basic and improved heat pumps cycles are presented. From this figure results that by using an ejector in the basic vapour compression cycle, the exergetic efficiency will increase by about 20%. It can observed that the exergy efficiency of both cycles decrease with ambient temperature increasing. This is due by the exergy losses in condenser and evaporator, which drastically increase with ambient temperature (see figure 4).
**Figure 2.** COP variation for VCC and EVCC cycles in function of ambient temperature.

**Figure 3.** Exergy efficiency variation for VCC and EVCC cycles in function of ambient temperature.

**Figure 4.** The exergy losses ratios for air source heat pump with on/off control.
From figure 4 results that, at low ambient temperature, the exergy loss in compressor are dominant in both analysed heat pump cycles. By using an ejector as expansion device, the compressor exergy loss will slightly decrease, but it will be still high. In the same time, de exergy losses in condenser and evaporator increase drastically with ambient temperature increasing.

6. Conclusions
Using an ejector for air source heat pump with on/off control should be a solution to improve the heat pump performance. Due to no moving parts, low cost, simple structure and low maintenance requirements, the use of two-phase ejector has become a promising cycle improvement. The main advantage of an ejector is the recovery of the expansion work (COP improvement), and flash gas bypass (evaporator size reduction). The integration of ejectors allows the compressor work to be reduced by increasing the suction pressure. Implementations of the ejector expansion cycle for practical uses have not yet been worked out. this is due to the fact that the ejector has a high degree of instability in operation.

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