Exergy Evaluation of a Water Based Heat Pump Working With Various Refrigerants

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1. INTRODUCTION

The objective of a heat pump is to maintain the temperature within a dwelling or other building above the temperature of the surroundings or to provide a heat transfer for certain industrial processes that occur at elevated temperatures [1]. It is a device which transfer heat from a low-temperature (Atmosphere, water well, geothermal source) region to a high temperature region (indoor, water well). Refrigerants are substances or mixtures, usually a fluid, used in a heat pumps and refrigeration cycles. In most cycles it undergoes phase transitions from a liquid to a gas and back again, many working fluids R134-a, R404, and R600-a have been used in the study. R134-a which known as Tetrafluoroethane (CF3CH2F) Currently widely in use in the heat pump systems.

The refrigerant R 404-a is a Medium and low temperature commercial and industrial direct expansion refrigeration and ice machines and is contains from a mixture of R125, R143-a, and R134-a. The refrigerant R 600-a, or isobutane, is a possible replacement for other refrigerants, which have high impact on the environment, in domestic refrigerators. It has zero ozone depletion potential ODP and a negligible global warming potential GWP.

Exergy (availability or available energy) is property used to determine the useful work potential of a given amount of energy at some specified state. It is important to realize that....
exergy does not represent the amount of work that a work-producing device will actually deliver upon installation. Rather, it represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws.

M. Chandrasekharan [2] studied the comparative analysis of the influence of refrigerant on the performance of a simple vapor compression refrigeration system. The study was based on the refrigerants R12 and R134a and further more energy and exergy analysis is presented for investigation of the effects of evaporating temperature and degree of sub-cooling on the coefficient of performance and exergetic efficiency of the refrigerator. The exergy destruction rates were estimated for each component of the system in a comparative manner for two refrigerants (R12, R134a).

Gaurav, and R. Kumar [3] are presented comparison of energy and exergy analysis for R134a, R152a, R290, R600 and R600a in refrigerator. The paper analyzed the domestic refrigerator with alternative refrigerants for computing coefficient of performance, exergy destruction ratio, exergy efficiency and efficiency defect. It is established that efficiency defect is maximum in condenser and lowest in evaporator. Comparison of various properties for alternative refrigerants has been done for a domestic refrigerator. Their study concluded that R152a has the highest value of coefficient of performance and exergetic efficiency among the refrigerants and R600a has the highest value of EDR and Efficiency defect in compressor.

L. Jerald, and a. Senthil [4] are investigate performance of vapor compression system used with zeotropic refrigerant R404a. The experiment was carried out to compare the performance and effectiveness of the system using five different capillaries. The result obtained from the observation will help to identify the optimum diameter of capillary which could be used in the system to give the best performance. The system concluded that the system that operates with R404a provided better cooling capacity than R 134a and the energy consumed was 20% less.

R. S. Mishra [5] presented Irreversibility analysis of multi-evaporators vapor compression refrigeration systems using refrigerants: R134a, R290, R600, R600a, R1234yf, R502, R404a and R152a and R12, and R502. They considered improving first law, second law efficiency, energy and exergy analysis of multi-evaporators at different temperatures with multiple compressors and multiple expansion valves in parallel and series with intercooler and flash chambers in the six type vapor compression refrigeration systems. It concluded that COP and exergetic efficiency for R152a and R600 are matching the same values are better than that for R404A at 313K condenser temperature and showing 12–23% higher value of COP and exergetic efficiency in comparison to R404a. Also for practical applications R-134a is recommended because it is easily available and has second law efficiency slightly lesser than R-152a which was not applicable for commercial applications.

J. Soni and R.C. Gupta [6] presented exergy analysis of vapour compression refrigeration system with using R-407C and R-410A. They present a theoretical performance study of a vapor compression refrigeration system with refrigerants R-407C and R-410A. A computational model based on energy and exergy analysis is presented for the investigation of the effects of evaporating temperatures, degree of sub-cooling, dead state temperatures and effectiveness of the liquid vapor heat exchanger on the coefficient of performance, second law efficiency and exergy
destruction ratio of the vapor compression refrigeration cycle. A theoretical investigation showed that better performances of R-407C in comparisons with R-410A.

T. H. Prasad and others [7] presented a computational model based on the exergy analysis for the investigation of exergy losses, the second law efficiency and the second law efficiency and the coefficient of performance (COP) of a vapor compression refrigeration cycle. It is found that the evaporating and condensing temperatures having strong effects on the exergy losses in the evaporator and condenser, on the second law efficiency and COP of the cycle but little effects on the exergy losses in the compressor and the expansion valve. It is also found that degree of sub cooling and degree of super heating have strong effects on exergy losses, second law efficiency and COP of the cycle.

2. THEORY

Heat pumps and air conditioners have the same mechanical components (compressor, condenser, expansion valve, and evaporator) The most common energy source for heat pumps is atmospheric air (air to-air systems), although water and soil are also used. The major problem with air-source systems is frosting, which occurs in humid climates when the temperature falls below 2 °C to 5 °C [8]. The exergy destruction is the exergy that is lost to the environment and cannot be used anywhere, e.g. due to system irreversibilities. The exergy loss represents the amount of exergy that is transferred from the analyzed system to some other system. Overall, in a control volume the steady-state exergy balance can be expressed as [6]:

\[ \sum \dot{E}_{in} - \sum \dot{E}_{out} + \left[ \sum \dot{Q} \left( 1 - \frac{T_{in}}{T} \right) \right]_{in} + \left[ \sum \dot{Q} \left( 1 - \frac{T_{out}}{T} \right) \right]_{out} \right] \dot{W} + \dot{E}_d = 0 \]  

(1)

where \( \dot{E}_{in} \), \( \dot{E}_{out} \), \( \dot{Q} \), \( \dot{W} \), and \( \dot{E}_d \) denote, respectively the exergy flow rate of stream entering a component or system, exergy flow rate of stream leaving a component or system, heat flow rate, mechanical work transfer to or from the control volume and rate of exergy destruction, subscript “o” denotes the extensive property of the system brought in the restrictive dead state. Total exergy destruction in the system is the sum of the exergy destruction in different components of the system and is given by[6]:

\[ \dot{E}_{d_{total}} = \dot{E}_{d_e} + \dot{E}_{d_{comp}} + \dot{E}_{d_c} + \dot{E}_{d_t} \]  

(2)

Exergy destruction in each component of the cycle is calculated as:

2.1. Exergy destruction in Evaporator

\[ \dot{E}_{d_e} = \dot{E} X_e + \dot{Q}_e \left( 1 - \frac{T_e}{T} \right) - \dot{E} X_1 \]  

(3)

2.2. Exergy destruction in Compressor

\[ \dot{E}_{d_{comp}} = \dot{E} X_1 + W - \dot{E} X_2 \]  

(5)

2.3. Exergy destruction in Condenser

\[ \dot{E}_{d_c} = \dot{E} X_2 - \dot{E} X_3 - \dot{Q}_e \left( 1 - \frac{T_e}{T_r} \right) \]  

(7)

\[ \dot{E}_{d_c} = \dot{m}_r (h_2 - T_o S_2) - \dot{m}_r (h_3 - T_o S_3) \]  

(8)

2.4. Exergy destruction in Throttle Valve

\[ \dot{E}_{d_t} = \dot{E} X_3 - \dot{E} X_4 \]  

(9)

\[ \dot{E}_{d_t} = \dot{m}_r (h_3 - T_o S_3) - \dot{m}_r (h_4 - T_o S_4) \]  

(10)

2.5. Product Exergy Rate

\[ \dot{E}_p = \dot{Q}_{cond} \left( 1 - \frac{T_o}{T_{cond}} \right) \]  

(11)

2.6. Fuel Exergy Rate

\[ \dot{E}_F = \dot{W}_{comp} \]  

(12)

2.7. Exergy Efficiency

Exergy efficiency measures the irreversibility of real operation with respect to theoretical possible operation. Exergy
efficiency is the most common parameter for evaluating the performance of an energy system from thermodynamic point of view. It indicates the share of exergy fuel that is converted to exergy product.

\[ Ex_{eff} = \frac{\dot{E}_p}{E_p} \]  \hspace{1cm} (13)

### 2.8. Coefficient of performance COP

Coefficient of performance COP is the measure of performance of refrigerators and heat pumps. It is expressed in terms of the desired result for each device (heat absorbed from the refrigerated space for the refrigerator or heat added to the hot space by the heat pump) divided by the input, the energy expended to accomplish the energy transfer (usually work input). Heat pump coefficient of performance is the efficiency of a heat pump, denoted by \( COP_{HP} \), and expressed as [8]:

\[ COP_{HP} = \frac{Q_H}{W_{net.in}} \]  \hspace{1cm} (13)

### 3. Experimental Work

The paper studies the water based heat pump using different refrigerants. The Schematic diagram of the used device is shown in figure (1); two helical heat exchangers placed in water baths and operates as condenser and evaporator, they reject and absorb heat to the water. Various calibrated K-type thermocouples placed in different points in the cycle to record the refrigerant and the water temperatures; pressure gauges used in measuring the high and low pressures of the system. The software (Computer-Aided Thermodynamic Tables) used to find the values of enthalpy and entropy in each point by the two thermodynamic properties (pressure and temperature). For each refrigerant types the data was taken every five minutes.

### 4. Data and Results

The experiment done in a water to water heat pump on the refrigerants R134-a, R404, and R600-a, calibrated temperature and pressure gauges used to read the required data. Computer Aided Thermodynamic Tables and thermodynamic tables are used to find the thermodynamic properties that are needed in the thermodynamic equations. The obtained data and the results are shown in the figures.

### 5. DISCUSSION

The first curve (figure 2) shows the deviation of total exergy destruction with time. Total exergy destruction values increases with the time. R600-a has maximum total exergy destruction differs from the other refrigerants, but R-404a and R134a are closer to each other. Figure 3, shows the relation of total exergy destruction with the evaporator water temperature, the destruction value the increases as the water temperature decreases. Figure 4 represents the deviation of COP with the time. R134a has the maximum COP value, COP of the refrigerants decreases with the time due to increasing of the evaporator temperature and decreasing amount of rejected heat in the condenser (Figure 5). Figure 6 shows deviation of exergy efficiency with time, and figure 7 is deviation of second efficiency with evaporator temperature. These two values are in low values in the beginning, and they increased later.

### 6. CONCLUSION

The following conclusions are observed from the study the three refrigerants R134-a, R404, and R600-a:

1- The refrigerant R134a was the best due to its low total energy destruction, high COP and high exergy efficiency.

2- The refrigerant R600-a was the worst Refrigerant due to its high exergy destruction and low COP.

3- Although R134-a is one of the R404-a, but this refrigerant results was not very attractive due to the small amount of R134-a (only 4%) inside R404-a.
Table (1) A sample data of R134-a

|   | T3 | T8 | T1 | T2 | T4 | T5 | T6 | T7 | T9 | T10 | P1 | P2 | P4 | P3 |
|---|----|----|----|----|----|----|----|----|----|-----|----|----|----|----|
| 1 | 300 | 14.50 | 14.15 | 15.50 | 39.20 | 39.20 | 14.86 | 0.30 | 13.40 | 14.86 | 0.30 | 9.50 | 9.30 | 0.63 | 0.70 |
| 2 | 600 | 15.70 | 13.00 | 15.60 | 40.20 | 40.20 | 15.07 | -25.75 | 10.00 | 15.07 | -25.75 | 9.70 | 9.50 | 0.73 | 0.80 |
| 3 | 900 | 16.10 | 12.80 | 15.70 | 42.80 | 42.80 | 15.38 | -26.65 | 5.50 | 15.38 | -26.65 | 9.70 | 9.50 | 0.75 | 0.80 |
| 4 | 1200 | 16.50 | 12.50 | 15.70 | 43.20 | 43.20 | 15.58 | -27.80 | 4.50 | 15.58 | -27.80 | 9.90 | 9.80 | 0.78 | 0.80 |
| 5 | 1500 | 16.80 | 12.30 | 15.90 | 43.60 | 43.60 | 16.00 | -29.80 | 4.30 | 15.99 | -29.80 | 9.90 | 9.80 | 0.79 | 0.80 |
| 6 | 1800 | 17.20 | 11.80 | 16.00 | 44.00 | 44.00 | 16.40 | -30.00 | 4.10 | 16.40 | -30.00 | 10.00 | 9.90 | 0.80 | 0.90 |
| 7 | 2100 | 18.00 | 11.44 | 16.00 | 44.40 | 44.40 | 16.71 | -30.00 | 3.90 | 16.71 | -30.00 | 10.20 | 10.00 | 0.87 | 1.00 |
| 8 | 2400 | 19.10 | 11.30 | 16.00 | 44.80 | 44.80 | 17.02 | -30.00 | 3.10 | 17.02 | -30.00 | 10.30 | 10.00 | 0.87 | 1.00 |
| 9 | 2700 | 20.80 | 11.00 | 16.40 | 45.00 | 45.00 | 17.43 | -30.00 | 2.80 | 17.43 | -30.00 | 10.30 | 10.00 | 0.87 | 1.00 |

Figure (1): Schematic diagram of the used device
Figure (2): Deviation of Total Exergy Destruction with time

Figure (3): Deviation of Total Exergy Destruction with Evaporator Water Temperature
Figure (4): Deviation of COP with time

Figure (5): Deviation of Heat Rejected in the condenser with the time
Figure (6): Deviation of Exergy efficiency with Time

Figure (7): Deviation of Second efficiency with Evaporator Temperature
7. Abbreviations

| Symbol    | Meaning                                      |
|-----------|----------------------------------------------|
| $\dot{E}_{in}$ | Exergy flow stream Entering to the system   |
| $\dot{E}_{out}$ | Exergy flow stream leaving to the system   |
| $\dot{E}_d$ | Exergy Distraction                          |
| $\dot{W}$ | Work done/supplied per unit time            |
| $\dot{Q}$ | Amount of heat transfer                     |
| $T_0$ | Ambient Temperature                         |
| $T$ | Temperature                                 |
| $T_r$ | Refrigerator Temperature                    |
| $T_{cond}$ | Condenser Temperature                        |
| $\dot{E}_d_{total}$ | Total Exergy Distraction in the heat pump |
| $\dot{E}_d_e$ | Exergy Distraction in the Evaporator        |
| $\dot{E}_d_{comp}$ | Exergy Distraction in the compressor        |
| $\dot{E}_d_c$ | Exergy Distraction in the condenser         |
| $\dot{E}_d_t$ | Exergy Distraction in the throttling device |
| $S$ | Entropy                                     |
| $\eta_{el}$ | Electric Efficiency                          |
| $\dot{Q}_e$ | Amount of heat transfer in the evaporator   |
| $\dot{Q}_c$ | Amount of heat transfer in the condenser    |
| $Ex$ | Exergy flow                                 |
| $m_r$ | Refrigerant mass flow rate                  |
| $h$ | Enthalpy                                    |
| $\eta_{ex}$ | Exergetic Efficiency                        |
| $T$ | Time                                        |

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