Exergy analysis of heat assisted ejector refrigeration system using R1234yf

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Abstract. An ejector refrigeration system (ERS) is introduced which operates on low-grade energy like solar energy, industrial waste heat etc. In this paper, the performance parameters and the conventional exergy analysis of ejector refrigeration system is measure with reference to ambient conditions. Exergy analysis was applied independently to each component of the system. The refrigerant R1234yf which has low Ozone depletion potential (ODP) and Global depletion potential (GWP) has been used to analyzed the exergy analysis with the help of Engineering Equation solver software. The results shows that maximum exergy destruction in generator followed by ejector and other components.

Keywords: Ejector, Exergy analysis, refrigeration.

1. Introduction

As the economy of the world grows at fast rate, the living standard of the peoples also change which results in increase the demand of cool-fresh air used for refrigeration. Refrigerator-freezers are used for food and milk storage applications which uses the large amount of electricity. In this Ejector refrigeration system (ERS) single phase (vapor) ejector is mostly used [1] and works by using the low-grade waste energy for refrigeration. Earlier ejector is used as jet refrigeration system [2] but now it is most focus topic for research. Abdulateef et al. [3] explained the different technology used in solar-driven ejector refrigeration system and provided the summary of the various option for solar-driven cooling systems with corresponding refrigerants. Yan et. al. [4] works on hot pumped water which was driven by solar ejector compression heat pump system and concluded that ejector generate maximum exergy destruction by amount of 25.7% of the system. Performance parameter of the ERS with different refrigerants like R600a, R245fa and R141b are evaluated by Chen. Et. al. [5].

The researchers have focused their attention on ERS to enhance the performance of the system and by using environment friendly refrigerants. Many researchers have analysed the behaviour of the ejector using ideal and real gas equations for wide range of operating conditions and using R113, R141b, R134a, R142b, R600a, steam, air, propane etc. [6, 7, 8, 9, 10,11,12,13,14,15]. Huang et al. [7] proposed and developed a one-dimensional gas dynamic equation based mathematical model for evaluating and analysing the performance of a single-phase ejector working under double choking mode for wide range of operating conditions using R141b as a refrigerant. They found the area-ratio is the most critical dimension of an ejector for obtaining desired condenser pressure. Kumar and Sachdeva [16] proposed a mathematical model for calculating complete geometry of a single-phase ejector working under double choking conditions. The desired operating conditions and performance are the input parameters to the
proposed model and the complete geometry of the ejector is the output. Arbel et al [17] considered mainly three factors mixing, kinetic and shock wave to showed the exergy irreversibility. Exergy loss in each component of solar-driven ERS by Alexis [18].

2. System description and assumptions

The schematic diagram of the ERS is shown by fig. 1 which comprises of evaporator, condenser, generator, ejector, refrigerant pump and an expansion valve. The generator, condenser, evaporator use as a heat exchanger and water use as external fluid for heat transfer. This system is as similar as the vapor compression refrigeration system, the only difference is the ejector and pump which replaces the compressor that consumes lot of power as compared to the pumps.

Figure 1. Schematic diagram of heat assisted ERS

An ejector in the ERS is the heart of system that works in place of compressor [19]. An ejector is comprising of four parts i.e., nozzle, suction section, mixing chamber and diffuser. The high-pressure motive flow refrigerant moves to the generator in liquid phase, where it takes heat from the waste heat and change into vapor. A high-pressure refrigerant expands through the primary nozzle at supersonic velocity and exits at high velocity and low pressure. Thus, creates suction effect for the low-pressure secondary refrigerant coming from the evaporator. Both refrigerant starts mixing according to constant pressure mixing in the constant area section and a normal shock develops at the end of mixing section because of the sudden back pressure developed by the condenser. Mixed refrigerants exit from diffuser section at subsonic velocity where it recovers the pressure, and discharge into condenser. The details related to the information of the system is available in Yapici et al [20]. Mixed refrigerant after leaving from condenser in condensed form where it separates into two different flows, one fluid flow goes through the pump and moves into generator and another part goes to the evaporator through expansion valve. Based on some assumptions, the p-h diagram is shown in Fig. 2.
Figure 2. P-h diagram of an Ejector Refrigeration System

For analyzing the ERS system following assumptions are made:

- The steady state conditions are assumed in the ERS system and the heat and pressure losses in the heat exchangers is neglected.
- Steady state adiabatic one-dimensional fluid flow is assumed inside the ejector.
- Isentropic efficiencies in three section of the ejector (nozzle, diffuser and mixing) are 90%.
- Inlet and outlet temperature of external fluid are $T_7 = 100^\circ C$, $T_8 = 105^\circ C$, $T_9 = 27^\circ C$, $T_{10} = 35^\circ C$, $T_{11} = 10^\circ C$ and $T_{12} = 15^\circ C$.
- Neglect the frictional pressure loss effects.
- At inlet of the ejector, the flow is assumed to be stagnated.
- Consider the ambient temperature ($T_o = 25^\circ C$) and pressure ($P_o = 101.32 kPa$) as reference state.
- Cooling capacity is fixed at $Q_{EV} = 10 kW$.

3. Methodology

With the assumptions above, the energy analysis of ERS system is evaluated using the refrigerant R1234yf as working fluid proposed by (21).

3.1. COP and entrainment ratio of the ERS.

The capacity of the ERS is estimated by the entrainment ratio ($\mu$). Entrainment ratio is the ratio of the entrained secondary mass flow rate ($m_{eva}$) to the motive/primary mass flow rate ($m_{gen}$). The entrainment ratio ($\mu$) can be expressed as follows:

$$\mu = \frac{m_{eva}}{m_{gen}}$$

The ratio of cooling effect obtained to the heat energy supplied to the generator is known as Coefficient of performance (COP) and it can be written as follows:

$$COP = \frac{Q_{eva}}{Q_{gen}}$$
3.2. Conventional exergy analysis
During a process, when a system comes in equilibrium with its surroundings, the maximum possible useful work that brings this condition is known as exergy of the system [22]. The exergy consists of physical exergy (\(\dot{E}^{PH}\)), chemical exergy (\(\dot{E}^{CH}\)), kinetic exergy (\(\dot{E}^{KE}\)) and potential exergy (\(\dot{E}^{PE}\)) by neglecting other effects.

\[
\dot{E} = \dot{E}^{PH} + \dot{E}^{CH} + \dot{E}^{KE} + \dot{E}^{PE}
\]

Due to the absence of any chemical reaction the system, the chemical exergy is neglected. The kinetic exergy is assumed to be negligible and potential exergy is equivalent at the enter and exit of the ejector, the physical exergy (\(\dot{E}^{PH}\)) is written as:

\[
\dot{E}_n = \dot{E}_n^{PH} = \dot{m} e_n^{PH} = \dot{m} (h_i - h_o) - T_o (s_i - s_o)
\]

There is a further split of physical exergy based into thermal exergy (\(e^T\)) and mechanical exergy (\(e^M\)) due to temperature and pressure respectively.

\[
e_n = e_n^{PH} = e_n^T + e_n^M = \frac{1}{K} \left( h_n - h_{nx} - T_o (s_n - s_{nx}) \right) \left( T - T_o \right) + \frac{1}{K} \left( h_{nx} - h_{no} - T_o (s_{nx} - s_{no}) \right) \left( T - T_o \right)
\]

Where \(x\) is defined in above equation at the given pressure \(P\) and ambient temperature \(T_o\).

For evaluating destruction exergy, the concept fuel-product is to calculate in terms of exergy and the expression in form of fuel-product for each component is given by [24].

\[
\dot{E}_{F,K} = \dot{E}_{P,K} + \dot{E}_{D,K}
\]

Where \(K\) refers to the k-th components in the system. \(\dot{E}_{F,K}\) is term as fuel exergy, represents as maximum exergy to produce product exergy. \(\dot{E}_{P,K}\) term as product exergy which is the desired results attained by the components. Exergy destruction (\(\dot{E}_{D,K}\)) is the difference of the fuel and product exergy.

Exegetic efficiency (\(\varepsilon\)) is the ratio of the product and fuel exergy. It is expressed for each component as follows:

\[
\varepsilon = \frac{\dot{E}_{P,K}}{\dot{E}_{F,K}}
\]

Exergy destruction ratio (\(y\)) is ratio of the exergy destruction for each component to the total exergy destruction of the system. It is expressed as follows:

\[
y = \frac{\dot{E}_{D,K}}{\dot{E}_{D,Total}}
\]

| Component          | Fuel Exergy (\(\dot{E}_{F,K}\)) | Product Exergy(\(\dot{E}_{P,K}\)) | Exergy Destruction (\(\dot{E}_{D,K}\)) |
|--------------------|---------------------------------|-----------------------------------|-------------------------------------|
| Generator (Gen)    | \(\dot{E}_{F,Gen} = \dot{m}_8 (e_8 - e_7)\) | \(\dot{E}_{P,Gen} = \dot{m}_1 (e_1 - e_4)\) | \(\dot{E}_{D,Gen} = \dot{E}_{F,Gen} - \dot{E}_{P,Gen}\) |
| Evaporator (Eva)   | \(\dot{E}_{F,Eva} = \dot{m}_6 (e_6 - e_5)\) | \(\dot{E}_{P,Eva} = \dot{m}_12 (e_12 - e_11)\) | \(\dot{E}_{D,Eva} = \dot{E}_{F,Eva} - \dot{E}_{P,Eva}\) |
| Condenser (Con)    | \(\dot{E}_{F,Con} = \dot{m}_2 (e_2 - e_3)\) | \(\dot{E}_{P,Con} = \dot{m}_9 (e_10 - e_9)\) | \(\dot{E}_{D,Con} = \dot{E}_{E,Con} - \dot{E}_{P,Con}\) |
| Ejector (Ejc)      | \(\dot{E}_{F,Ejc} = \dot{m}_2 (e_1 - e_2)\) | \(\dot{E}_{P,Ejc} = \dot{m}_6 (e_2 - e_6)\) | \(\dot{E}_{D,Ejc} = \dot{E}_{F,Ejc} - \dot{E}_{P,Ejc}\) |
| Expansion Valve (EV)| \(\dot{E}_{F,EV} = \dot{m}_5 (e_3^M + e_3^T - e_5^M)\) | \(\dot{E}_{P,EV} = \dot{m}_5 e_3^T\) | \(\dot{E}_{D,EV} = \dot{E}_{F,EV} - \dot{E}_{P,EV}\) |
| Pump (PUM)         | \(\dot{E}_{F,PUM} = W_{PUM}\) | \(\dot{E}_{P,PUM} = \dot{m}_4 (e_4 - e_3)\) | \(\dot{E}_{D,PUM} = \dot{E}_{F,PUM} - \dot{E}_{P,PUM}\) |
| System             | \(\dot{E}_{F,Total} = \dot{E}_{F,Gen} + W_{PUM}\) | \(\dot{E}_{P,Total} = \dot{E}_{P,EV}\) | \(\dot{E}_{D,Total} = \sum \dot{E}_{D,K}\) |

4. Results and Discussion
All the results are calculated by the thermodynamic equations and properties of the refrigerant and external fluid are taken from the Engineering Equation Solver (EES). Thermodynamic properties at each position are present in the given table below.
Table 2. Thermodynamic properties at each position are present in the given table below.

| Position | Refrigerant | m (kg/s) | P (kPa) | T (℃) | h (kJ/kg) | S (kJkg⁻¹k) | eᵀ (kJ/kg) | eᴹ (kJ/kg) | e (kJ/kg) |
|----------|-------------|----------|--------|-------|-----------|-------------|------------|------------|-----------|
| 1        | R1234yf     | 1.231    | 3080   | 90    | 393.6     | 1.577       | 21.16      | 40.05      | 61.21     |
| 2        | R1234yf     | 2        | 907    | 35.5  | 383.9     | 1.604       | 4.657      | 38.91      | 43.56     |
| 3        | R1234yf     | 2        | 907    | 35.5  | 247.2     | 1.163       | 38.91      | 0.607      | 38.3      |
| 4        | R1234yf     | 1.231    | 3080   | 90    | 250       | 1.165       | 0.34       | 40.05      | 40.39     |
| 5        | R1234yf     | 0.769    | 410.7  | 8     | 247.2     | 1.17        | 7.324      | 28.89      | 36.22     |
| 6        | R1234yf     | 0.769    | 410.7  | 8     | 368.4     | 1.599       | 0.4804     | 28.89      | 29.37     |
| 7        | Water       | 8.367    | 101.32 | 100   | 419.1     | 1.307       | 34.21      | 0.098      | 34.11     |
| 8        | Water       | 8.367    | 101.32 | 105   | 440.2     | 1.363       | 38.59      | 0.098      | 38.49     |
| 9        | Water       | 13.07    | 101.32 | 30    | 113.2     | 0.3949      | 0          | 0.032      | 0.032     |
| 10       | Water       | 13.07    | 101.32 | 35    | 134.1     | 0.464       | 0.353      | 0          | 0.353     |
| 11       | Water       | 4.454    | 101.32 | 10    | 42.09     | 0.151       | 1.602      | 0          | 1.602     |
| 12       | Water       | 4.454    | 101.32 | 15    | 63.01     | 0.224       | 0.6962     | 0          | 0.6962    |

The below table shows the calculated value of the fuel-product exergy and destruction exergy which shows that more exergy destruction in generator followed by ejector and other components.

Table 3. Result obtained from the conventional exergy analysis

| Component        | Fuel Exergy (Eᵢₚ,ᵢ) | Product Exergy (Eᵢₚ,ᵢ) | Exergy Destruction (Eᵢₚ,ᵢ) | Exegetic efficiency (ε) % | Exergy destruction ratio (y) % |
|------------------|----------------------|-------------------------|----------------------------|---------------------------|-------------------------------|
| Generator (Gen)  | 36.66                | 25.62                   | 11.03                      | 0.699                     | 27.56                         |
| Evaporator (Eva) | 5.265                | 4.032                   | 1.233                      | 0.765                     | 13.14                         |
| Condenser (Con)  | 10.53                | 4.192                   | 6.338                      | 0.398                     | 26.3                          |
| Ejector (Ejc)    | 21.71                | 10.92                   | 10.79                      | 0.5                       | 54.2                          |
| Expansion Valve  | 7.237                | 5.635                   | 1.602                      | 0.7786                    | 18.05                         |
| Pump (PUM)       | 3.38                 | 2.56                    | 0.82                       | 0.757                     | 8.44                          |
| System           | 40.04                | 4.03                    | 36.01                      | 0.1                       | 89.93                         |
Figure 3. Effects of performance parameter with the variation of generator temperature.

Figure 3 shows the variation of generator temperature keeping other temperature constant, the refrigeration effect will increase from 80-93°C but decrease further. The COP will decrease and entrainment ratio will increase with increase of generator temperature. Figure 4 shows the difference between the generator and total exergy destruction with the variation of generator temperature. Both exergy destruction will decrease with variation of generator temperature.

Figure 4. Effect of generator temperature on exergy destruction
The performance parameter of the system with the variation of condenser temperature shown in figure 5 and 6, the entrainment ratio is increases with increase in condenser temperature between 30-35 ℃ but the COP and refrigeration effect will decrease because when temperature increase it will increase secondary mass flow rate. It also increases the exergy destruction of both system and condenser in below figure.

**Figure 5.** Effects of performance parameter with the variation of condenser temperature.

**Figure 6.** Effect of condenser temperature on exergy destruction
Figure 5. Effect of evaporator temperature on exergy destruction.

Figure 6. Results of exergy destruction in each component

The above figure 6. illustrates the exergy destruction in various component of the ERS system. It shows that maximum exergy destruction in generator then ejector and minimum in pump at generator temperature 93°C, condenser temperature 35°C and evaporator temperature 5°C.

Nomenclature

- \( g \) Acceleration due to gravity
- \( h \) Enthalpy
- \( \dot{m} \) Mass flow rate
- \( Q \) Heating Effect
- \( R \) Refrigeration Effect
- \( V \) Velocity
- \( y \) Exergy destruction ratio
5. Conclusion

Conventional exergy analysis is used to analyze the ejector refrigeration system for a known operating condition. It is found from the analysis of conventional exergy that the highest exergy destruction occurs in generator followed by ejector and other components. The exergy destruction in heat exchanger like generator, evaporator and condenser can be reduced by alternate method but in ejector exergy destruction be more which cannot be decrease or eliminate by any process.

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