A review on exergy analysis of ejector refrigeration system

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Abstract. Owing to the human comfort, the utilization of refrigeration system has increased nowadays. In today’s scenario, the air conditioning system has led to the innovative changes in the lifestyle of human beings. The Heat driven ejector refrigeration machine is a favorable alternative to a compression based refrigeration system for the point of view of minimizing energy utilization. As Exergy is directly related to the second law of thermodynamics and the system performance can be only evaluated on the basis of this thermodynamics law. On the basis of efficient performance, it has been concluded that good quality of ejector is more performance oriented rather than other components like condenser, generator and evaporator. This paper presents the idea of ejector refrigeration systems, its exergy analysis and working fluids used. It profoundly investigates the ejector technology and behaviour, exergy analysis, properties of refrigerant and its effect on the ejector refrigeration system.

Keywords: Ejector refrigeration system, Exergy analysis, Exergy destruction, Refrigerants

1. Introduction

The vapour compression refrigeration system (VCRS) face a few extreme difficulties in the coming tenure, the maximum recognized being a limited usage of fluorocarbon refrigerants, spiking the cost of energy and increasing environmental issue. One of the best options is to shift towards the usage of renewable energy. The waste heat can be utilized in order to enhance the system performance characteristics. The ejector does not contain any moving part pump gadget, along with no maintenance cost and lubrication. While talking about ejector system, the working of ejector is same as that of compressor. The ejector system utilizes waste energy or the heat which makes it more engrossing in this energy-conscious span. A lot of research has been done in order to understand the concepts of performance characteristics of ejector system [1-4]. They have suggested that that system
performance can be enhanced in terms of running cost, mechanical efficiency and environmental correlation. The law of entropy states that, analysis of exergy can be used to categorize the position, amount and various sources of exergy destruction. Pridasawas et.al [5] carried out his work on exergy investigation on a ejector system that runs through the utilization of solar energy. He concluded that there is a maximum destruction of exergy occurring in an ejector using butane as a refrigerant. The same conclusion were also drawn by Alexis [6] when used water as working medium. Dahmani et al concluded that maximum exergy destruction takes place in ejector working with R134a (Tetrafluoroethane) as working fluid.

Naturally, the ejector refrigeration system uses water as a working medium (refrigerant). For cooling and refrigeration purpose, steam jet system came in to existence in the mid-1900s [7]. After conducting various experiments, it was found that that the existing system has a very low co-efficient of performance (COP) values. Also, the system was unable to give desired refrigerant effect at 0°C. Consequently, the use of halocarbon refrigerants in ejector refrigeration systems because of more prominent values of COP. Primary requirements for ideal refrigerant is that it has zero ODP and GWP. Chloro-fluoro-carbons(CFCs) such as R12 and R22 etc cause destruction of ozone layer present at the stratosphere due to reaction with chlorine atoms which are present in the refrigerants.

The substitution for CFCs are hydro-chloro-fluoro-carbons(HCFCs) which also deplete ozone layer but not as much as CFCs. The replacement for HCFCs are hydro-fluoro-carbons(HFCs).HFCs have ozone depletion potential of zero unlike CFCs and HCFCs. Some examples of HFCs are R134a, R410A, R407C,etc.

2. Ejector Technology

2.1 Ejector Fundamentals

An Ejector is the critical segment in the ER system. The major important function of the ejector is that it can increase the pressure of the refrigerant without using mechanical energy. The utilisation of thermal energy in this makes it even more attractive. It can also reduce environmental problems. The ejector was first time used by Maurice Leblane in 1910 as a vapour jet refrigeration cycle. His assembly produced refrigeration effect by utilising waste heat energy. Since steam was used at that time so it is called the steam jet cooling system, later it has been replaced by a system with a mechanical compressor.

An ejector generally consists of four parts-
Figure 1: Different sections inside an ejector

**Motive Nozzle**
The primary fluid enters the motive or primary nozzle which is of convergent-divergent type. In this nozzle velocity increases in the convergent part which leads to a decrease in pressure. At the throat section of the nozzle, Mach number is unity and the velocity becomes sonic. At the divergent part of the nozzle, velocity will accelerate and pressure decreases by obeying the energy balance equation. At the outlet of the nozzle low pressure is created and the flow becomes supersonic.

**Suction chamber**
As the exit of the nozzle low pressure is created, because of which the pressure difference is caused between the evaporator and the suction chamber. Suction chamber is connected to the evaporator in the ejector. This difference in pressure leads to entry of secondary fluid in the ejector.

**Mixing Section**
The motive and entrained fluid mixed in the mixing section which is having a constant area section of the ejector. A shock wave is generated at the end of the mixing section due to supersonic flow which causes an abrupt decline in velocity. Also there is a sudden rise in pressure inside the constant area section of the ejector.

**Diffuser**
In the diffuser section, the blended fluid enters and the kinetic energy of the blended fluid is converted into pressure energy. Therefore the fluid coming out from the diffuser is at an intermediate pressure and velocity is assumed to be zero at the outlet of the diffuser.
2.2 Working principle of the ejector

Figure 2 shows the illustration of an ejector refrigeration system. The main components are generator, ejector, condenser, evaporator, circulation pump and a throttling valve. The primary or motive flow refrigerant in the vapor state enters the generator at high pressure. The low pressure vapor enters through the evaporator. Both motive flow and low pressure vapor are mixed in the mixing chamber of ejector and recovery of pressure take place. After that it enters in to the condenser, where phase changes from vapor to liquid. The phase change will occur when heat is rejected to the environment ($Q_{CO}$). The fluid coming out from the condenser is splitted in to two different passages. One section enters into the evaporator via expansion device (throttling valve) to produce refrigeration effect ($Q_{EV}$). The other segment of the fluid is reverted back to the generator where it takes heat and converts into high pressure vapor and finishes the cycle.

![Figure 2 Ejector refrigeration System](image-url)
3.1 Conventional Exergetic model

Neglecting the effects of electrical, magnetic, nuclear and surface tension in refrigeration cycle, the total Exergy (E) can be considered as the combined effect of physical, chemical, Kinetic and potential exergies (E_{PH}, E_{CH}, E_{KN} and E_{PT}) respectively.

\[ E = E_{PH} + E_{CH} + E_{KN} + E_{PT} \]

From above equation, the term E_{CH}, E_{KN}, E_{PT} can be omitted, since there is no chemical reaction occurs in the ejector refrigeration system. Thus exergy E only comprises of physical exergy E_{PH}.

\[ E_j = E_{j,PH} = \dot{m}e_{j,PH} = \dot{m}[(h_j - h_0) - T_0(s_j - s_0)] \]

here, \( e_{j,PH} \) can be divided into thermal exergy \( e^T \) because of temperature and mechanical exergy \( e^M \) because of pressure.

\[ e_j = e_{j,PH} = e_{j}^T + e_{j}^M = [(h_j - h_{j,X}) - T_0(s_j - s_{j,X})]_{p=const} + [(h_{j,X} - h_0) - T_0(s_{j,X} - s_0)]_{T_0=const} \]

The exergy destruction of the k-th component can be expressed as

\[ E_{D,k} = E_{F,k} - E_{P,k} \]

The exergy balance for the system can be represented as

\[ E_{F, tot} = E_{P, tot} + E_{D, tot} + E_L \]

where \( E_L \) represents the loss of exergy in the system. In order to investigate the exergetic performance of the component, both exergy efficiency and exergy destruction is important. The exergy efficiency ratio (\( \varepsilon_k \)) is the ratio of exergy of product to the exergy of fuel. Similarly, exergy destruction ratio (\( y_k \)) is the ratio of exergy destruction to the total exergy of fuel of overall system.

\[ (\varepsilon_k = \frac{E_{P,k}}{E_{F,k}}) \]

\[ (y_k = \frac{E_{D,k}}{E_{F, tot}}) \]
3.2 Advanced Exergetic Model

As compared to traditional exergy model, Advance exergy framework is more efficient. According to the advance model, there are two subgroups of total exergy destruction namely endogenous/exogenous and avoidable/unavoidable segments.

3.2.1 Endogenous and Exogenous exergy destruction

Endogenous exergy destruction ($E_{D,k}^{EN}$) is the total amount of exergy that is destroyed in components when the given component is working in real conditions and all other components are assumed to work ideally in the system. Exogenous exergy destruction ($E_{D,k}^{EX}$) is the loss of exergy caused by the remaining components. Therefore, it can be expressed as

$$E_{D,k} = E_{D,k}^{EN} + E_{D,k}^{EX}$$

From this information, it is easy to determine whether the focus of the study should be paid to the k-th component or the leftover component.

Unavoidable and avoidable exergy destruction

The exergy destruction can be further broken into unavoidable and avoidable segments

$$E_{D,k} = E_{D,k}^{UN} + E_{D,k}^{AV}$$
where the unavoidable exergy destruction $E_{D,k}^{UN}$ cannot be reduced due to constraints manufacturing processes, material types etc. The other part of exergy destruction i.e. avoidable exergy destruction $E_{D,k}^{AV}$ is reducable and should be more observed.

Adding the above two approaches

The two splitting approaches can be merged as

$$E_{D,k} = E_{D,k}^{UN,EN} + E_{D,k}^{UN,EX} + E_{D,k}^{AV,EN} + E_{D,k}^{AV,EX}$$

![Figure 4: Alternatives for splitting the exergy destruction within the kth component](image)

4. Selection of Working Fluid

The refrigerant is very important in the ejector refrigeration system. A suitable refrigerant can just give efficient system performance, chances of system failure are less and also good for the environment. Additional requirements for selecting working fluids are

- Global warming potential (GWP) and ozone depletion potential (ODP) from the environmental point of view.
- Toxicity, flammability for health point of view.
- Cost and availability of refrigerant.

The essential thermodynamic properties of refrigerant are given below
The higher critical temperature of the refrigerant is desirable to adjust large variation of generator temperature;

- The specific heat of vapour refrigerant should be as high as possible to limit the degree of superheat whereas that of liquid refrigerant should be low to limit the degree of irreversibility;
- It should be non-toxic and non-flammable.

The working fluids are of three types. These are namely wet, dry and isentropic fluids as shown in Figure 5.

**Figure 5: T-S diagrams of three types of refrigerant: (a) wet fluid, (b) isentropic fluid and (c) dry fluid**

Figure 5 shows a plot between temperature and entropy of the different working fluid. From figure 5 (a), it can be seen that saturation line for vapour phase is having negative slope. Due to the formation of small vapour droplets at the exit of nozzle, there is a blockage in the effective area ultimately affects the functioning of ejector. In order to avoid such problems, motive flow must be in a superheated condition before entry to the nozzle. During expansion through the nozzle, phase change do not occurs in the dry fluid. It can also be seen that the vapour saturation line is vertical in case of isentropic fluid. Owing to the environmental concern, the refrigerants having zero ozone depletion potential value is recommended. Generally, the use of ammonia and water is avoided because of high critical pressure of ammonia and also it is toxic in nature while for water its COP is low. According to Jianyong et al generally “R134a, R152a, R245fa, R290, R600 and R600a are used as working fluid in the ejector refrigeration system. From thermodynamic characteristics, there is no working fluid which is perfectly suitable for the ER system, each one has its own advantages and disadvantages.
5. Conclusion

Ejector refrigeration system is an advantageous technology for producing a desired refrigerating effect by utilising waste or low-grade heat with various working fluids. In the present paper ejector technology, exergetic models, properties of refrigerant and its impact on the ejector refrigeration system are discussed in depth. Two exergetic models are discussed i.e., conventional exergetic model and advanced exergetic model. In the conventional model fuel-product concept is discussed. In the advanced exergetic model, exergy destruction can be classified into four parts avoidable, unavoidable, endogenous and exogenous it is more accurate as compared to the conventional model. The ejector allows the use of several refrigerants but only those refrigerants are advantageous which have zero ODP and zero GWP which prevent from environment-related problems and also suitable for safety point of view along with this the refrigerants have a positive slope on T-s diagram for the proper functioning of the ejector.

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