Recent developments in ejector refrigeration system

P J Manoj1 and V Lijo

Department of Mechanical engineering, Government Engineering college Thrissur, Affiliated to APJ Abdul kalam technological university, Kerala, India – 680009.

1Email:manojpjose@gectcr.ac.in

Abstract. Ejector refrigeration system (ERS) is one of the major methods of refrigeration. It finds its maximum application in industries because it makes use of heat energy as input for refrigeration. ERS is also known as steam jet refrigeration because earlier only steam was used as working fluid. But latest developments offers make use of a variety of working fluids. Recent research results show that there is a large scope for improving efficiency and utility of the system with different working fluids. If suitable working fluid is selected, the ERS can make use of low temperature source like solar energy as input source. A large number of numerical and experimental works are actively going on in the field of ERS. The utilisation of computational fluid dynamics (CFD) software like ANSYS FLUENT has very much simplified the research activities of ERS. The effect of geometric design modifications of major components like nozzle or throat can be easily studied with the help of CFD software. This paper reviews the recent research and development in the area of ERS.

1. Introduction

Ejector refrigeration system (ERS) is one of the important methods of refrigeration. It utilises heat energy as input for making refrigeration effect. Usually, industries are very much interested in ERS because they may have a lot of waste heat which can be efficiently utilised for making refrigeration. Ejector refrigeration is also known as steam jet refrigeration because high pressure and high temperature steam is commonly used in industries as working fluid. Household applications of ERS are limited due to the following reasons-the ERS is bulky, on-availability of heat energy and very lower value of coefficient of performance (COP).

The researches going in ERS can be classified in different ways.

• Improving the performance of ERS by varying the working fluids.
• Improving the performance by geometrical modification of different components of ERS.
• Make the ERS environmentally friendly by utilising green energy source and environmentally friendly refrigerants.
• Design modification of ESR to eliminate moving components like pump.
• Numerical and experimental research.

2. Basics of ejector refrigeration system and its performance characterization.

The standard configuration of an ERS consists of an ejector, generator, condenser, evaporator, throttle valve and a pump as shown in Figure1. The generator produces high pressure vapour utilising the heat energy.
This high-pressure vapour is expanded through a nozzle inside an ejector creating a low pressure as shown in Figure 2. This will lead to the evaporation of a secondary fluid supplied from the evaporator. The evaporation of secondary fluid causes lowering of the temperature of secondary fluid inside the evaporator. This cold secondary fluid can be used further for refrigeration purpose using secondary circuit. The throttle valve supply makeup fluid from condenser to evaporator by reducing the pressure. The pump supply condensed fluid from condenser to generator.

The main component ERS is an ejector. A schematic view of a typical supersonic ejector is shown in Figure 2. Ejector consists of a nozzle and a mixing chamber. The mixing chamber has three sections; a converging section, a constant area section and a diverging section or a diffuser. High pressure primary fluid expands and accelerates through the nozzle. It fans out with supersonic speed to create a very low-pressure region at the nozzle exit plane. The high-velocity primary flow stream draws or entrains the secondary fluid into the mixing chamber. The combined streams are assumed to be completely mixed inside the constant area section of the mixing chamber. That is from section y-y to m-m as shown in Figure 2. A normal shock wave is then produced at section s-s within the constant-
area section, creating a compression effect, and the flow speed is reduced to subsonic value. Further compression of the fluid is achieved as the combined streams flow through the subsonic diffuser section.

The primary fluid flow creates a flow profile after expansion through nozzle as shown in Figure 2. This will create a congested flow path for secondary fluid before mixing of two fluid streams. That is a fictitious throat is created in the flow path of secondary fluid near the section y-y in the Figure 2. By properly selecting the flow velocity of primary fluid and geometrical parameters, it is possible to create sonic velocity for secondary fluid at this fictitious throat. That is known as choking of secondary fluid. The refrigeration effect is due to the evaporation of secondary fluid due to the entrainment by the primary fluid. Usually, the primary flow will be made to choke at the nozzle throat. It is known as double choking. That means primary fluid is choked at the nozzle throat and secondary fluid is choked at the fictitious throat inside the mixing chamber.

The performance of ejector depends on so many factors like velocity of the fluids, properties of the fluids, dimensions of the ejector, like area of cross sections at different locations, nozzle exit position inside the mixing chamber etc. The nozzle opening may be located inside the constant area section or in converging section of mixing chamber. Then it is known as constant pressure mixing and constant area mixing respectively.

There are several parameters used to describe the performance of an ejector. One of the performance parameters is the coefficient of performance (COP). It is defined as the ratio of the cooling capacity at the evaporator and energy input at the boiler and pump. The second performance parameter is the entrainment ratio. It is the ratio of mass rate of evaporation of secondary fluid to mass flow rate of primary fluid. The third one is the compression ratio. It is the ratio of the condenser pressure to the evaporator pressure.

3. Performance analysis of ERS with varying the operating modes of ejector.

Ejector can work in three different modes. Critical mode, sub-critical mode and back flow mode as shown in Figure 3. Performance of ejector is affected by the modes of operation. In a critical mode of operation, there will be double choking as mentioned earlier.

![Figure 3. Modes of operation of an ejector](image-url)
The experimental studies carried out on the ejectors refrigerator [10] showed that, when the ejector is operated under the “critical condenser pressure” (Pc), entrainment ratio & cooling capacity is maximum and it remains constant. Further increase in condenser pressure above the critical condenser pressure moves the thermo-dynamic shock wave into the mixing chamber and prevents secondary flow from reaching sonic velocity. Upstream conditions can now be transmitted downstream, which results in a reduction in secondary flow, entrainment ratio and COP. Eventually, secondary flow drops to zero, the ejector loses its function and primary flow will reverse its direction or back flow into the evaporator.

4. Effect of compression ratio and expansion ratio on the performance ERS.
Effects of non-dimensional parameters like compression ratio (pressure ratio of condenser to evaporator) and expansion ratio (pressure ratio of generator to evaporator) on the system performance were studied by Sankarlal and Mani L [2]. The results showed that COP increased with increase in expansion ratio and decreased with compression ratio.

In order to analyse the pressure change along ejector profile, Chunnanond and Aphornratana [3] carried out an experimental investigation of a steam ejector refrigerator. They concluded that there were two parameters which dominated the performance of an ejector refrigerator, the amount of secondary fluid passing through the mixing chamber and the momentum of the mixed stream. They observed that an increase in evaporator pressure, which was the ejector’s upstream pressure, increased the critical condenser pressure. This will increase the mass flow through the mixing chamber and consequently increasing cooling capacity and COP of ERS.

5. Performance analysis of ERS by varying geometrical parameters.
The nozzle exit position (NXP), marked as distance ‘x’ in figure 2, inwards or outwards the mixing chamber will affect both the entrainment and pressure ratio performance of ejectors. In the experimental studies [4] and simulations [5] it was demonstrated that moving the nozzle exit into the mixing chamber that is nearer to the constant area section, reduced COP and cooling capacity of ERS.

6. Performance analysis of modified ERS without pump.
A numerical analysis on a two-phase (gas-liquid) ejector in a refrigeration system was carried out by Senoo and White [6]. The pump is eliminated by using a secondary gas-liquid ejector as shown in Figure 4. The secondary gas-liquid ejector will work as a pump and it will pump liquefied fluid from condenser to generator. Strong shockwaves reported in the secondary two-phase ejector and there by huge increase in pressure rise.

![Figure 4. ERS without mechanical pump](image)
Another study of gravitational simulation conducted by Kasperski J [8] eliminated the pump and throttle valve by placing the evaporator, generator and ejector at different heights as shown in Figure 5. The pumping work and expansion will be carried out by gravitational force. The main drawback of such a system is that, it requires more length of pipe and more space.

![Figure 5. Eliminating the throttle and pump by placing the evaporator, condenser and generator at different heights](image)

7. **Performance analysis of ERS with solar energy input.**

Besagni [8] developed a solar-driven ERS with thermal energy storage (TES) with a refrigerant having low boiling point. This will make the ERS system working completely on green energy. TES provided in the generator side will store the solar energy and that can be used when solar energy is not available as shown in Figure 6. An additional storage tank in the evaporator side is also suggested for the continuous use of ERS.

![Figure 6. ERS with solar energy input.](image)
8. Performance analysis of ERS with different working fluids.

The choice of the appropriate working fluid plays an important role in the design of the ERS. There are research works with different environment friendly working fluids with zero ozone depletion potential (ODP) and low global warming potential (GWP) like R142b, R134a, R-1234zeE, R152a, R600a etc. This also makes the system suitable to utilise low grade thermal energy like solar energy as input source.

Y. Bartosiewicz a, Z. Aidoun a, Y et al. [9] conducted a numerical study of supersonic ejector for refrigeration application with working fluid as R142b ejector with fixed dimensions. They found very strong shock near the secondary nozzle. They predicted a condenser pressure of 0.46 Mpa condenser pressure and entrainment ratio of 0.4. An experimental investigation of ERS with working fluid as R134a with shell and tube type heat exchanger was carried out by Fenglei Li, Rongrong Li, et al. [10]. As the generator temperature increased, the entrainment ratio first increased and then decreased due to the change from subcritical mode to critical mode. They reported maximum entrainment ratio of 3.5 at generator temperature of 80°C.

Kamil Smierciew, Jerzy Gagan, et al. [11] carried out an experimental investigation of ERS with working fluid as hydro-fluoro-olefin HFO-1234zeE. They were to utilise a low temperature heat source at 70°C, thermal capacity of 90kW, maintained the motive saturation temperature of 55°C and able to produce a pressure corresponding to a temperature of -20°C in the evaporator chamber.

Jianlin Yu, Hua Chen, Yunfeng Ren, et al. [12] conducted experimental investigation ERS with two working fluid R 134a and R152a and additional jet pump. They compared the results with conventional ERS. They maintained the generator temperature at 95°C and found an increase of COP to 57.1% and 45.9% with working fluid R.134a and R152a correspondingly, compared to conventional ERS.

An experimental investigation of ERS with working fluid as R134a was carried out by A. Selvaraju A. Mani et al. [13]. They maintained the generator temperature as 338K to 363 K with different low grade heat energy and condenser temperature of 299k to 310K and cooling rate 0.5 kW. The study reported maximum entrainment ratio and COP as 0.25. Boumaraf and Lallemand [14] carried out the simulation analysis with R600a and R142b as working fluid. They maintained the evaporator temperature as 10°C, condenser temperature 36°C, and boiler temperature 120°C and obtained the COP as 0.089 with R600a and 0.126 with R142b.

9. Conclusions

Plenty of research works have been carried out in the field of ERS. Both numerical and experimental studies were conducted with a variety of working fluids and also with geometric design modifications. Numerical and experimental works have revealed that there is a large scope of improving utility of ERS with low temperature renewable heat energy input. Selection of proper working fluids, optimisation of the geometric design parameters and mode of operation are very important to make system suitable for low grade renewable heat energy input. By selecting a working fluid with zero ODP and low GWP along with renewable energy input source like solar energy will make the ERS totally environment friendly refrigeration method.

Most of the numerical studies were conducted with “ANSYS FLUENT” software. The results obtained with software are very much close to the experimental results in most of the cases. So numerical analysis can be conducted with ANSYS FLUENT software before the actual experimental works. That will simplify the design and reduce the set-up cost of experiment.

Most of studies were conducted assuming steady state conditions of generator and condenser temperatures. But in practical the generator and condenser temperature may vary depending upon availability of heat energy. For example, in the case of solar energy input, the radiation availability varies throughout the day. This requires transient boundary conditions in the analysis. Such transient analysis is found very less in the research studies.

Even though there are different studies conducted to improve COP of ERS, maximum reported COP falls below 0.4 only. Whereas the vapour compression systems give COP above 3.5. But COP
alone cannot be taken as a criterion for comparison because ERS take low grade thermal energy for refrigeration.

ERS is a very live area of research and it will emerge as a common method of refrigeration not only in the industries but also in household applications.

References
[1] Pianthong A, Seehanam W, Behnia B, Sriveerakul A, Aphornratana S. 2007 Investigation and improvement of ejector refrigeration system using computational fluid dynamics technique. *Energy Conversion and Management* 2556–2564
[2] Zhao H, Zhang K, Wang L, and Han J. 2016 Thermodynamic investigation of a booster-assisted ejector refrigeration system. *Applied Thermal Engineering* 104: 274-281
[3] Chunnanond K, Aphornratana S.  An experimental investigation of a steam ejector refrigerator the analysis of the pressure profile along the ejector. 2004. *Applied Thermal Engineering* 24:311–22
[4] Sierra-Pallarm J, Garcia del Valle P, Garcia-Carrascal F, Castro Ruiz A. 2015 computational study about the types of entropy generation in three different R134a ejector mixing chambers. *International Journal of Refrigeration*. 63:199-213
[5] Rusly E, Aye L, Charters WWS. 2005 CFD analysis of ejector in a combined ejector cooling system. *International Journal of Refrigeration* 28: 1092–101
[6] Senoo S, White AJ. 2006 Numerical Simulations of Unsteady Wet Steam Flows. *ASME Joint U.S.-European Fluid Engineering Summer Meeting*. 1: 757-767
[7] Kasperski J. 2009 Two kinds of gravitational ejector refrigeration stimulation. *Applied Thermodynamics Engineering* 29:3380–5
[8] Besagni G, Mereu R, Inzoli F. 2016 Ejector refrigeration: a comprehensive review. *Renewable and Sustainable Energy Reviews* 53: 373-407
[9] Bartosiewicz Y, Aidoun A, Mercadier Y. 2006 Numerical assessment of ejector operation for refrigeration applications based on CFD. *Applied Thermal Engineering* 26: 604-612.
[10] Fenglei Li, Rongrong Li, Xinchang Li, Qi Tian. 2018 Experimental investigation on a R134a ejector refrigeration system under over all modes. *Applied Thermal Engineering*; 137:784-791
[11] Kamil Smierciew, Jerzy Gagan, Dariusz Butrymowicz. 2017 Experimental investigation of the first prototype ejector refrigeration system with HFO-1234ZE(E). *Applied Thermal Engineering* 110:115-125
[12] Jianlin Yu, Hua Chen, Yunfeng Ren, Yanzhong Li. 2006 A new ejector refrigeration system with an additional jet pump. *Applied Thermal Engineering* 26:312-319
[13] Selvaraju A, Mani A. 2006 Experimental investigation on R134a vapour ejector refrigeration system. *International Journal of Refrigeration* 29; 1160-1166
[14] Boumaraf L, Lallemand A. 2009 Modelling of an ejector refrigerating system operating in dimensioning and off-dimensioning conditions with the working fluids R142b and R600a. *Applied Thermal Engineering* 29:265–74
[15] Kasperski J, Gil B. 2014 Performance estimation of ejector cycles using heavier hydrocarbon refrigerants. *Applied Thermal Engineering* 71(1): 197-203.
[16] Ariafar K, Buttsworth D, Al-Doori G, Sharifi N. 2016 Mixing layer effects on the entrainment ratio in steam ejectors through ideal gas computational simulations. *International journal of Energy Research* 95: 380-392.
[17] Ariafar K, Buttsworth D, Al-Doori G, Malpress R. 2015 Effect of mixing on the performance of wet steam ejectors. *International journal of Energy Research* 93: 2030-2041.
[18] Chen X, Omer S, Worall M, and Riffat S. 2013 Recent developments in ejector refrigeration technologies. *Renewable and Sustainable Energy Reviews* 19: 629-651.
[19] Elakhdar M, Nehdi E, Kairouani L, Tounsi N. 2011 Simulation of an ejector used in refrigeration systems. *International Journal of Refrigeration* 34: 1657–67.
[20] Chen Z, Jin X, Dang C and Hihara E 2017 Ejector performance analysis under overall operating conditions considering adjustable nozzle structure International Journal of Refrigeration 84: 324-286.

[21] Wang F, Shen S 2009 A novel solar bi-ejector refrigeration system and the performance of the added injector with different structures and operation parameters International journal of Energy Research 83:2186–94.

[22] Tashtoush B, Alshare A, Al-Rifai S 2015 Performance study of ejector cooling cycle at critical mode under superheated primary flow Energy Conversation Management 94:300–10.

[23] Selvaraju A, Mani A 2006 Experimental investigation on R134a vapour ejector refrigeration system International Journal of Refrigeration 29: 1160–6.

[24] Khalil A, Fatouh M, Elgendy E 2011 Ejector design and theoretical study of R134a ejector refrigeration cycle International Journal of Refrigeration 34: 1684–98.