Journal of Basic and Applied Engineering Research
p-ISSN: 2350-0077; e-ISSN: 2350-0255; Volume 5, Issue 4; April-June, 2018, pp. 283-287

http://www.krishisanskriti.org/Publication.html

Ejector in Vapor Compression Refrigeration System: A Review

Pankaj Niranjan[1] and Gulshan Sachdeva[2]

[1,2]National Institute of Technology, Kurukshetra, Haryana-136119 (India)
E-mail: [1]panbarc@gmail.com, [2]gulshansachdeva@nitkkr.ac.in

Abstract—*Previous review on ejector for expansion work recovery have provided a detailed study about the ejectors and geometric parameters. The objective of this paper is to present a literature review on ejector assisted vapor compression system. In the past decades, study have shown that the use of ejector in vapor compression cycle improves its performance over the conventional vapor compression refrigeration cycle (VCRC). This paper also provide the various configuration in which a ejector can assist VCRC for better coefficient of performance (COP) both in terms of reduced compressor work and improved evaporative cooling capacity focusing on the past several years.. This paper also give the root understanding regarding the operating principle of ejector and its working mode. In the previous study, it has been found that ejector enhanced VCRC results in approximately 21-28% COP improvement over traditional cycle.*

1. INTRODUCTION

Refrigeration industry is one of the leading consumer of electricity produced in the world. For this purpose, vapor compression cycle is used but this cycle is nearly 100 year old, inefficient and environment unfamiliar. Now-a-days to reduce the electricity consumption leading to mitigate the problem related to the environmental pollution by utility power plant.

There are several ways in which the performance of vapor compression cycle (VCRC) can be improved which directly reflects the energy saving of the system. Using ejector as an expansion device is one of the way by which the performance of the existing VCRC can be improved and these methods are very attractive as compared to conventional VCRC.

The main aim of this paper is to update the research progress in the ejector vapor compression technology in the last decades. The paper emphasize on various combinations of ejectors used in vapor compression cycle and their performance improvement over conventional VCRC.

In refrigeration process, ejectors generally have been adopted for two kind of applications: 1) to draw low pressure secondary flow by using high pressure primary flow in ejector based refrigeration cycle, where low grade thermal energy such as exhaust from power plant gases, exhaust from vehicle engine, industrial process, solar radiation etc. can be used as a driving force. [1-4]; 2) improving the secondary flow pressure before the vapor enters the compressor, typical application involves household refrigerator, heat pump, multi-evaporator refrigeration system.[5-7].

2. HISTORY OF EJECTOR AND BACKGROUND

The ejector is the main part of refrigeration system and have been used in different applications. They are simple piece of equipment and was invented by sir Charles Parson around 1901 for removing air from the condenser of steam engine. Sokolov and Harshal [9] proposed the idea about ejector enhanced refrigeration cycle run by the pair of the pair of low grade energy and mechanical work. Gay [10] in 1931, patented 2-phased ejector to overcome with throttling losses encountered in expansion process and used ejector as an expansion valve over conventional expansion valve. A part from refrigeration use, ejector are employed in the industry in numerous, unique and even sometimes bizarre ways. They can be used singly or in stages to create a wide range of vacuum conditions or they can be used as transfer and mixing pumps.

Research have shown that using ejector as an expansion device increases coefficient of performance (COP) of vapor compression cycle [16-18]. This improvement in COP is caused by reducing mechanical work in compressor and increase in cooling capacity in the evaporator

2.1 Ejector geometry

An ejector has different name in different literature. It is also known as jet, injector or jet pump (referred for liquid-liquid ejector). Ejectors mainly classified on the state of liquid.

Table 1: Ejectors classification [11]

Type of ejector	Primary flow	Secondary flow	Exit flow	Remark
Vapor Jet Ejector	Vapor	Vapor	vapor	Two phase flow, shock wave possible
Liquid Jet Ejector	Liquid	Liquid	liquid	Single Phase flow without shock wave.

Condensing Ejector	Vapor	Liquid	liquid	Two phase flow without condensation of primary vapor, strong shock wave.
Two-Phase Ejector	Liquid	Vapor	Two phase	Two phase, shock wave possible.

The main component of ejectors includes a primary nozzle (motive nozzle), suction chamber, the mixing chamber (including convergent chamber if there is any and a constant area throat tube), and diffuser.

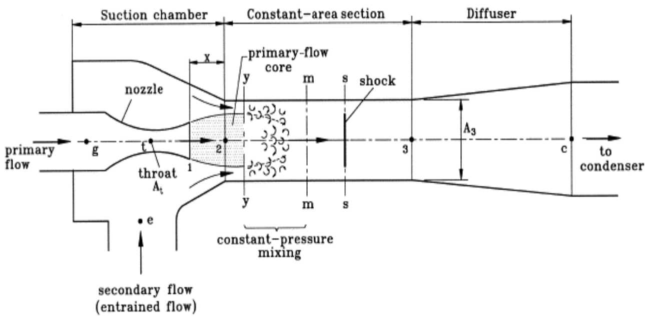

Fig. 1: Schematic diagram of two-phase ejector [8]

The shape of primary nozzle either convergent type or convergent-divergent type both. The primary fluid or motive fluid or driving fluid past and accelerates through the primary nozzle, it fans out with high speed to create a very low pressure region at the exit plane of the primary nozzle and secondary fluid or entrained fluid begins to proceed due to this pressure difference. The both fluid, primary as well as secondary fluid start to mix in the mixing chamber and flows through the diffuser to convert the kinetic energy of mixture into pressure energy.

Although the mathematical analysis of the flow inside the ejector is very vigorous but with help of conservation mass, momentum and energy, state of equation, phase change principle, isentropic relation as well as certain assumption made the analysis of flow and mixing easy in two-phase ejector.

It is difficult to classify the ejector due to their complex design and geometry. Keenan & Neumann [9-10], developed a numerical method using 1-D continuity, momentum, and energy equation to figure out the working and mixing inside the ejector. Therefore it has been concluded by Keenan et al. [9-10], that are two type of ejector based on the design and location of mixing between primary and secondary fluid.

(1) Constant-area mixing ejector-

Nozzle with its exit plane located within the constant area section of ejector, the mixing of primary (motive) and secondary (entrained) flow occurs inside the constant area section. This type of ejector is known as constant area ejector.

(2) Constant pressure mixing ejector-

When nozzle exit plane located within the suction chamber which is in front of constant area section, the ejector known as constant pressure mixing ejector. For this kind of ejector the mixing phenomenon takes place inside the suction chamber and this results in uniform mixing. This is the biggest advantage over constant area mixing ejector. Thus it is widely used by most of the researchers for numerically as well as experimentally study purpose.

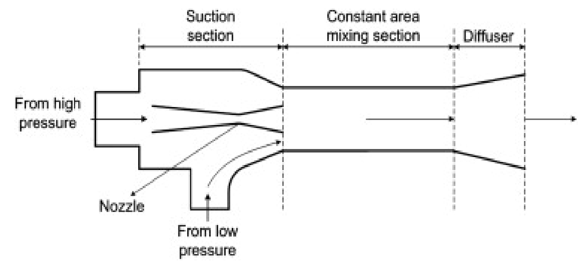

Fig. 2 (1) Constant area mixing ejector

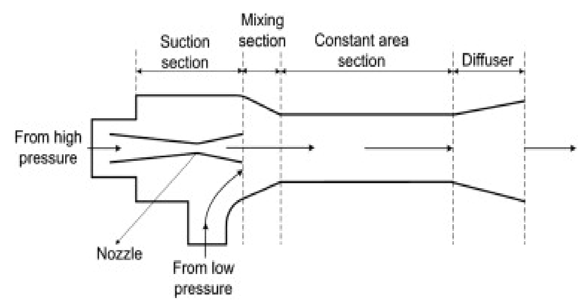

Fig. 3 (2) constant pressure mixing ejector.

2.2 Ejector working modes

The occurrence of chocking in a system is conventionally defined as the maximum mass flow rate as a function of downstream pressure. Two choking phenomenon exists in the ejector performance. One in primary flow through the nozzle and other in the secondary flow (entrained flow). Huang et al. [8] analyzed chocking condition with constant pressure mixing ejector and showed that 1-D model accurately predict the nature of ejector. The experimental research have been carried out on ejector refrigeration shows that at each different operating condition at primary and secondary inlet, the working mode or operating of ejector classified into three regions.

a. Double chocked flow or critical flow mode ($P_c \leq P_c$*)

This happens when discharge pressure or back pressure (P_c) at fixed suction pressure (P_e) and fixed primary flow pressure (P_g) is less than the critical back pressure.

When primary and entrained flow are both at chocking condition, the entrainment ratio (ratio of secondary mass flow rate to the primary mass flow rate) remains constant. Furthermore, the cooling capacity and coefficient of performance (COP) also remains fixed.

b. Single chocking or subcritical mode or primary chocking (P_c*<P_c<P_{co})

Further increase in back pressure or condenser pressure more than the critical pressure, this phenomenon happens. In this case only primary flow is chocked.

Due to increment in the back pressure above the critical back pressure the thermodynamic shock wave moves into the mixing chamber and prevent the secondary flow reaching sonic velocity.

Entrainment ratio changes with the back pressure P_c.

c. Back flow or reverse flow or malfunction ($P_c \geq P_{co}$)

Now if $P_c \geq P_{co}$,upstream condition can now be transferred to downstream which will result in no chocking in primary flow as well as secondary flow and secondary flow reverse back into the evaporator and ejector losses its function. Zero Yielding in Entrainment ratio (ω).

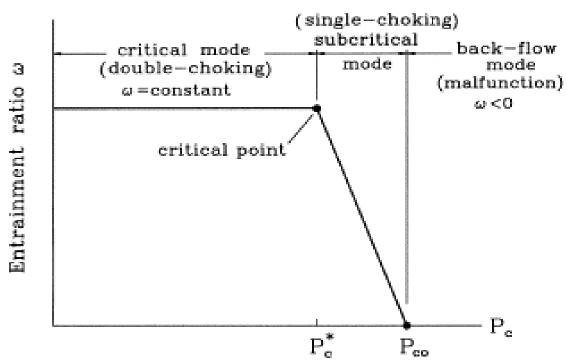

Fig. 4 Ejector working mode [8]

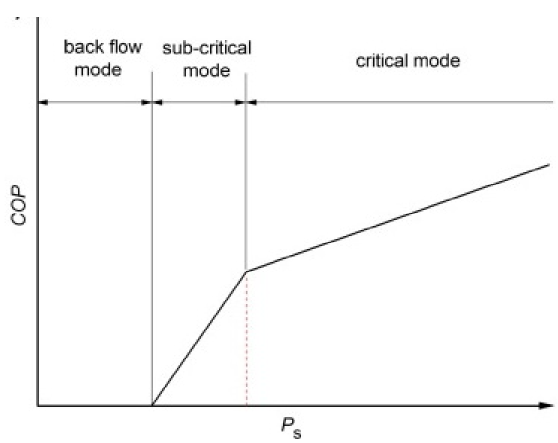

Fig. 5 Variation of COP with back pressure [8]

3. DIFFERENT CONFIGURATION OF VCRC WITH EJECTOR

3.a Ejector on heat driven refrigeration-

To be very specific, the heat recovery cycle may include the low-grade energgy from waste heat from power plant exhaust, automobile exhaust and have been extended to solar driven ejector and ejector-adsorption system.

The main obejctive of heat driven EVCRC is to replace compressor on the vapor compression refrigeration cycle. Eastimated temperature range of promary fluid through motive nozzle typically greter than 80 ˚C and for entrained flow it should be in between 0-15 ˚C, the state of entrained or secondary flow must be vapor. The resulting mixture comes out from the exit of ejector (diffuser section) lies in vapor state with tmperature range 35-55 ˚C. operating state for both primary and secondary fluid must be in vapor state so that it can work with diffuse flow. It is also be the reason for knwoing this as single phase vapor compression refrigeration system.

Researchers have been shown in their research that the use of this heat driven EVCRC is only in the field of air-conditioning.

3.b Ejector on condenser-

Assistance of ejector in vapor compression cycle just befor the condenser partially reduces the mechanical work done by the copression hence inhanced the COP of the cycle without affecting the refrigeration effect.

In this cyle, ejector is a two-phase jet device in which a subcooled refrigerant in a liquid state from suction inlet with tempreature slightly less than 20 ˚C, mixes with its vapor phase from primary inlet from nozzle with tempreature slightly less than the 35 ˚C, producing a two-phse steam at the outlet of diffuser with pressure is higher than the pressure of either of the two inlet fuid stream.

Compressed superheated refrigrent vapor (primary flow) from the exit of compressor enters the ejector through primary nozzle and thus creation primary flow and subcooled refrigrent (secondary fluid) pumped from the seprator which flows into the ejector. Mixing takes place first in convergent section and then into the constant area section of ejector. High rate of heat and momentum transfer take splace between these two fluid stream because of high tempreature diffrence and high realtive velocity. The vapor phase quickly condensed and liquid phase quickly evaporates, creating a mixed liquid-vapor mixture at high pressure.

This double phase fluid further passes through condenser and throttled in expansion device. the advatage of using ejector is, it helps in raising the pressure of compressed vaopor by the primary compressor, resulting in reduction in compressor work.

It is noted that the frefrigreant flow inside the evaporator reduces. This type of EVCRC can be used in both air-conditioning and refrigeration.

3.c Ejector as an expansion device-

Capillary tube, thermostatic exapansion valve an automatic expansion valve all are used in vapor compression cycle as an expansion device. Typically, in VCRC the expansion process are isenthalpic in nature. However this isenthalpic process causes a decrease in the evporative cooling capacity due to the enery losses in expansion process.

An efficiency improving option was suggested to prevent this energy loss by changing expansion process from isenthalpic to isentropic with the use of ejector. The tempreature range for primary fluid exiting from primary nozzle in liquid state is typically less than 5 ˚C and -5 ˚C and for suction flow with vapor state ranging 0-15 ˚C & -40 to -5 ˚C for air-conditioning and freezing porpose respectively. The diffuser flow results in two-phase flow with tempreature ranging between 0-15 ˚C ans in some cases greater than -40 ˚C and less than -5 ˚C.

Using ejector as an expansion device improve the COP in both manner. Power input to the compression also reduces with the use of ejector as a pre-compression device and evaporative cooling capacity also gets improved by changing expansion process from isenthalpic to isentropic.

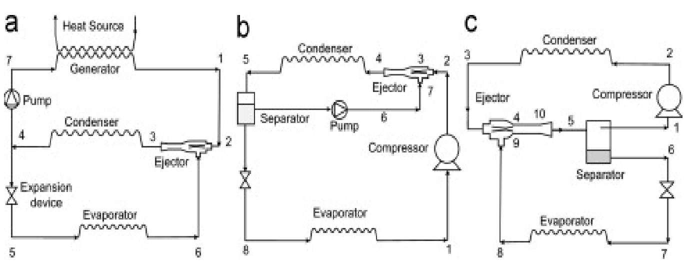

Fig.6(i). schematic diagram of three application of ejector augmented VCRC. [11]

(a) Ejector on heat-driven refrigeration, (b) ejector on condenser side, (c) ejector as an expansion device.

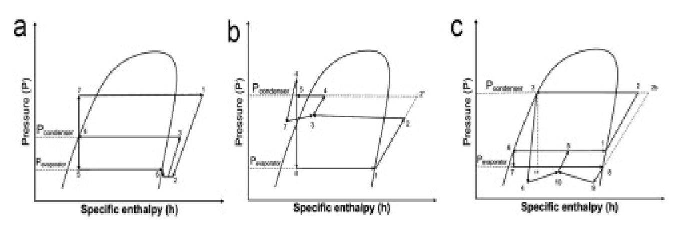

Fig. 7. p-h diagram of three ejector application of ejector augmented VCRC. (a) p-h diagram of ejector on heat-driven refrigeration cycle, (b) p-h diagram of ejector on condenser cycle, (c) p-h diagram of ejector as an expansion device. [11]

3.d Ejector in multi evaporator VCRS

Ejectors in multi evaporator vapor compression system can be used in two ways.**(i)**single compressor with multiple evaporator or condeser outlet split ejector cycle (high temprature and high tempreature evaporator) **(ii)**double compressor(low tempreature compressor and high tempreature compressor) with multi-evaporator.

In condenser outlet split ejector cycle (COSEC), refrigerant at the outlet of condenser is splitout and divided into two fluid stream, one stream becomes the motive flow of the ejector while other stream is throttled isenthalpic into expansion device and sent to evaporator. The two phase flow at tha outlet of ejector is passed to a second high tempreature evaporator before entering to the compressor. This cycle is used where the refrigerant undergoes transcritical state (performing at both states i.e critical and sub-critical state) and this is often case when CO_2 is the refrigerant.

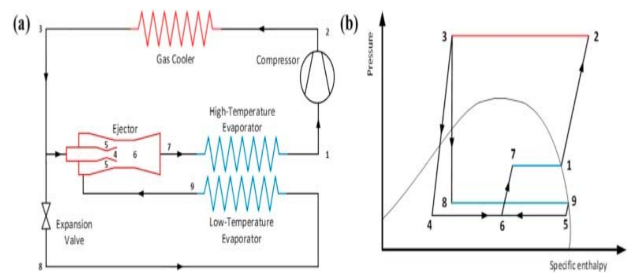

Fig. 8 Alternate ejector cycle for trancritical operation, (a) shematic diagram (b) pressure specific enthalpy diagram.[15]

Multi-evaporator refrigeration system with multi-compression, refrigerants must operates under sub-critical state. Sarkar [13], proposed the novel configration with double compression and 3 evaporator system with R32 as a working fluid and obtained the result which reflects 19.3% more COP and 24.3% more volumetric cooling capacity than coreesponding basic two-stage compression cycle and 116.7% more COP and 69.1% more volumeric cooling capacity than corresponding basic single-stage compression cycle.

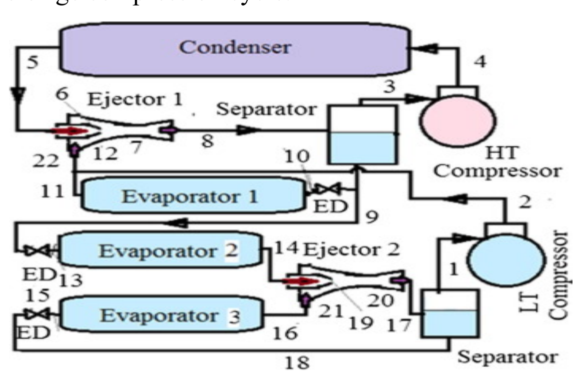

Fig. 9 (a) ejector enhanced three evaporator two-stage compression refrigeration system

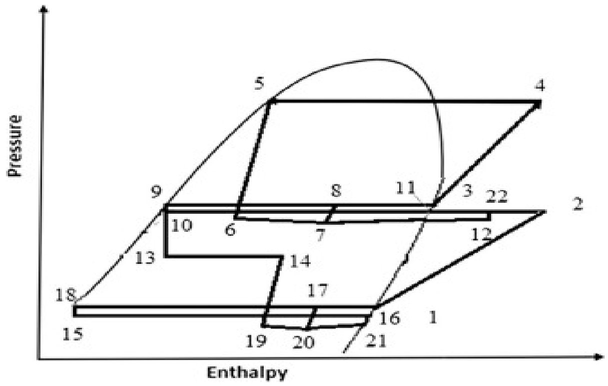

Fig. 9 (b) pressure enthalpy diagram

4. CONCLUSIONS

Study on ejector refrigeration system carried out over several past decades. Ejector system modelling, design, refrigerant selection, and optimization of system involves efficient operation of ejector refrigeration system.

It has been noted with the present literature review that the use of ejector in vapor compression refrigeration system improve COP and makes it efficient by minimizing throttling losses when ejector used as an expansion device. VCRC are coupled up with ejector and reflects the improvement over the conventional cycle. Numerical simulation shows that the improvement in COP is above 20% however the experiment results reveals it is only 10-16%.

Many recent studies present theoretical analyses of different ejector cycle but majority of these cycle do not reveal on what practical advantages, if any, are offered by these cycle. Moreover, the lack of experimental investigation over the simulated results give some uncertainty and the root cause of this problem lies within the domain of improvement in ejector design, geometry and selection of working fluids according to the demand and optimal requirement. Ejector enhanced VCRC can be an alternative substitution of conventional vapor compression system.

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