Review of ejector design parameters and geometry for refrigeration and air conditioning application

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Abstract: - This paper focuses and presents   literature studies on recent development in ejector cooling system also the enhancement of the performance. Some of researches have conducted and categorized in working fluid selections, simulation and mathematical modelling of the ejector, geometrical and operation conditions optimization. However, most of the experimental studies which have been done in last two decades are still insufficient if compared with simulation modelling; more experiments studies and big scale work are required in order to come out with good understanding in real application.

Key-Words: ejector design – working fluid –area ratio-geometry- cooling system-operating conditions

1 Introduction

A refrigeration system using an ejector is an interesting system because of its environmentally friendly operating characteristics. Low-grade thermal energy can be used to drive this system. An ejector can convert low heat energy obtained from solar energy or rejected heat from many factories or any heating processes to useful refrigeration, thereby the electrical energy consumption would be reduced for air conditioning and refrigeration systems. An ejector system also allows the use of water, which is the most environmentally friendly substance, as a working fluid in the system. Researchers are still trying to improve the ejector cooling system, investigating the effect of operating conditions on system performance, and attempting to improve the geometric design of the ejector.

Ejector refrigerators were applied to make vacuum in train braking systems since the 19th century. Ejectors have also been used to remove incondensable vapours from condensers. In 1930, ejectors were usedin air conditioning in trains and buildings. At present, ejectors can be found commercially in a wide range of formations in single or multistage applications [1]. A certain amount of literature was published on ejector refrigeration. The features of ejection refrigerators including the simplicity of configuration, environment-friendly refrigerants, and low investment cost. However, a fair comparison should be considered with competing system for some relevant shortcomings:

1. Low Coefficient Of Performance COP: Under the typical evaporator and condenser temperature used in air conditioning and refrigeration applications, the COP of an ejector is relatively low compared with adsorption, absorption, and conventional vapor compression chillers [2-5].

2. Low-flow high-pressure head feed pump: Fluids must be pumped from the condenser exit to feed the vapor generator. This procedure introduces a component that is not familiar to cooling systems experts. Moreover, the feed pump is prone to cavitation and must be able to deliver certain working fluids at high pressures.

Three interconnected factors strongly influence the performanceof ejector: operation conditions, ejector geometry, and the refrigerants properties. Since last two decades, considerable research effort has been conducted to investigate the influence these parameters.

The effects of operating conditions, that is, temperatures and pressures, on ejector cooling cycle performance are relatively well understood and have been the highlight of many studies. Several experiments such as those of Chunnamond and Aphornratara[6], Selvaraju and Mani [7], and Yapici et al. [8, 9] have been conducted. Theoretical works have also been conducted by Hemidi et al. [10, 11], Huang et al. [9], Varga[11], and Da Wen Sun [12] to evaluate the effect of generator, evaporator, and condenser conditions.

The effects of geometrical factors have been studied experimentally [4, 8, 13-15]. In most studies,

thearea ratio and nozzle exit position (NXP) have been identified as the most relevant variables that influence the ejector performance indicators. The geometry ofejector is strongly dependent on operating conditions, for example, Varga[14] and Yapici et al. [8]. An ejector with a constant geometry only operates at a high COP in a narrow operating temperature/pressure range. The solution to this matter has led to the concept of a variable geometry ejector. Sun [16] was one of the first authors that analysed the geometrical requirements for water as a working fluid. Varga et al. [17] reported an increase in ejector performance as high as 177% for low condenser pressures by using R600a and R152a refrigerant. Dennis and Garzoli[17]showed the results that obtained from a variable geometry ejector by using R141b in different variable operating conditions. The features of the concept were clearly described in both cases; however, there were no technical solutions provided. Potential technical implementations to adjust the area ratio between the constant area section and primary nozzle throat section can be found in studies by Kim et al. [18] for air, Elbel and Hrnjak[19] for carbon dioxide R744, and Ma et al. [20] and Varga et al. [14] for water as working fluid. The use of air as working fluid has limited applications in refrigeration cycles. R744 has low critical temperatures and high critical pressures; thus, R744 needs adequate technical features that can contribute to increase in the initial cost of the cooling system. Water is widely used as a refrigerant in ejector cooling, but results in relatively low COPs forreasonable generatortemperature when using simple collectors as primary heat source.

Comparative studies on cooling performance with different working fluids can be found in Cizungu et al. [21], Dahmani et al. [22], Romanand Hernandez [23], and Sun [16]. Hydro fluorocarbon, such as R152a or hydrocarbon (e.g., R600a) refrigerants, improve COP of the ejector considerably under identical operating conditions compared with water as working fluid. This finding is particularly true for cases when the generator temperature is relatively low ($< 120\,°C$) [17].

2 Ejector working principles

2.1 Ejector theory

The ejector is the heart of the cooling system. The idea of an ejector is quite old. Steam-driven ejectors were applied widely in power stations, chemical processes, and the nuclear stations for long time.

The most known applications of steam-driven ejectors are in the production or maintenance of practical vacuums in gas-filled vessels. The main benefit of ejectors over conventional compressor units or pumps is that ejectors do not have moving parts and no need for maintenance.

The ejector is thebasic part in refrigeration and air conditioning system, desalination, and chemical processes. Ejectors also form an integral part of distillation columns, condensers, and other heat exchange processes. While the construction and operation principles of jet ejectors are well known, the following sections give a brief summary of the mainadvantages of ejectors. This summary is substantial for the subsequent discussions and analyses. The ejector mainly contains of a nozzle, mixing chamber, and diffuser (Fig. 1). The ejector has no moving parts and does not require additional energy sources. The nozzle and diffuser both have the geometrical of converging-diverging venturi. The diameters and lengths of various parts forming the nozzle, the diffuser, and the mixing chamber, together with the stream flow rate and properties, determine the ejector capacity and performance. The capacity of ejector could be defined in terms of the flow rates of the primary stream and secondary stream. The primary and secondary mass flow rates provide the total mass flow rate of the ejector. Several parameters are used to define the efficiency of the ejector. The most important variables for refrigeration applications are defined in terms of entrainment, expansion, and compression ratios. The entrainment ratio (ω) is the ratio between primary stream to secondary stream which can be obtained by dividing the primary stream on secondary stream. The expansion ratio (Er) is defined as the ratio of the primary stream pressure to the secondary stream pressure. The compression ratio (Cr) provides the pressure ratio of the compressed fluid to the secondary fluid[17].
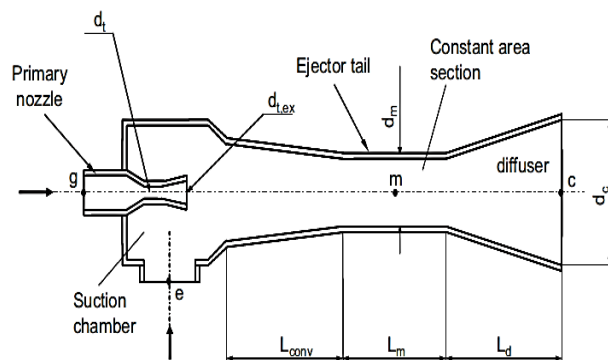

Fig.1, Schematic of a typical ejector

The entrainment ratio is related to the energy efficiency of a refrigeration cycle; the pressure ratio limits the temperature in which the heat can be rejected [24]. Therefore, an ejector should operate with the highest entrainment ratio and maintain the highest possible discharged pressure at specific operating conditions. During this procedure, the static pressure of the primary stream tends to rise gradually till reaching the pressure levels with the secondary fluidpressure. When mixing process is completed, the final shock would be happened somewhere in the constant area section or in the beginning of the diffuser, based on the operating conditions. The mixed flow becomes subsonic, and the pressure is raised in the diffuser towards the ejector exit. The out pressure is usually determined by the condenser conditions (Tc) of the ejector cooling cycle.

3 Operating conditions

The two parameters of the generator (temperature and pressure), evaporator and condenser are important parameters that influence the performanceof ejector. For specific evaporator and generator pressures, the operation of the ejector can be classified into three main regions depending on condenser pressure (Fig. 2). The first region is double choking flow in the mixing chamber, second is primary chock flow, and third is reversed flow [25].
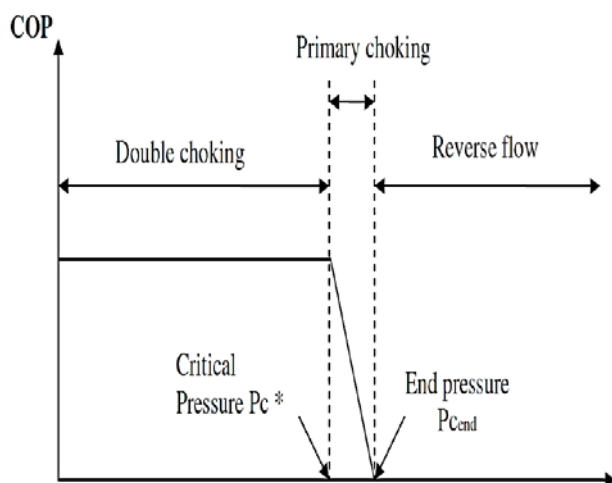

Fig. 2, Operational modes of an ejector

The COP and cooling capacity can be obtained as constant in the situation of "critical condenser pressure" at specific evaporator and generator pressures.Butincreasing the pressure in the

condenser higher than the critical pressure will move the thermodynamic shock wave to the mixing chamber and denies entrained streamto reach sonic velocity. Upstream conditions can then be transmitteddownstream, thus resulting in a decreasing in secondary flow, COPand entrainment ratio. The entrained flow eventually decreases to zero, the ejector is malfunctioned, and the motive stream will returnto evaporator.

3.1 effect of condenser pressure

The condenser pressure should be at or below the critical condenser pressure for an ejector to perform at double choking mode. The COP and cooling capacity firstly will rise sharply after that remains constant with decreasing condenser pressure, thus indicating that the double choking mode has been achieved [26-29]. In such an operating system, given that the primary vapour pressure at the output of nozzle is greater than of entrained vapour[30]. Thus, the entrainedvapour will choke and its mass flow rate becomes independent of the back (condenser) pressure. The cooling capacity and COP are unaffected by decreasing in back pressure. The operating system, including all cases in which secondary vapour is not choked, the entrained stream cannot reach level of sonic speed in mixing chamber of the ejector; thus, the back pressure influences the mass flow rate of secondary vector, as well as the system COP and cooling capacity.

3.2 Effect of evaporator pressure

The evaporator temperature effect on system is shown in Fig. 3. Both cooling capacity and COP increase almost linearly with evaporator temperature [26, 29, 30]. The mass flow rate remains fixedwhile the primary stream is choked in the primary nozzle. On the contrary, the entrained flow rate rises with evaporator pressure, thereby increasing the cooling capacity and COP of the system. However, operating the ejector at high evaporator temperature significantly reduces the cooling ability of the system [26].
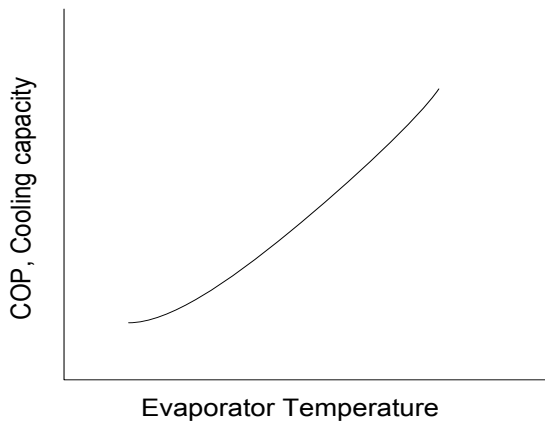
Fig. 3, Effect of evaporator temperature/pressure on COP at a constant area ratio, generator pressure, and condenser pressure

3.3 Effect of generator pressure

According to Selvaraju and Mani [7], the entrainment ratio, cooling capacityandCOP first increase, and then decrease with increasing generator temperature (Fig. 4). This behaviour has been observed by other researchers [1, 31]. For the known evaporator and condenser temperatures, each ejector with specific configuration has an optimal generator temperature wherein the optimal COP can be reached. Fig. 3 illustrates the difference of the system. The performancerises with increasing generator temperature at specified condenser and evaporator temperatures and continues to increase until a particular value of the generator temperature where both primary and secondary flows reach the choked condition. This phenomenon is attributed to the increase in primary flow with the generator temperature, thus resulting in high nozzle velocities and improved suction. However, as the generator temperatureincreases toa point where the secondary flow is choked, further increases in primary flow is no longer beneficial because the secondary flow is already at maximum velocity; hence, the COP, entrainment ratio, and cooling capacity decreases. When the temperature of condenser and evaporator are given, in this case any ejector with specific configuration has an optimal generator temperature wherein the optimal COP can be reached.

Similar result was shown by Ma et al. a novel 5 kW ejector refrigerator that is adequate for solar thermal implementations. There was a spindle introduced to control motive stream and fine-tune the ejector. The maximal cooling capacity and optimal COP reached ata generator temperature of92.8 and90 °C, respectively.[20], they observed that when generator temperature increases, it does not always increase system efficiency.
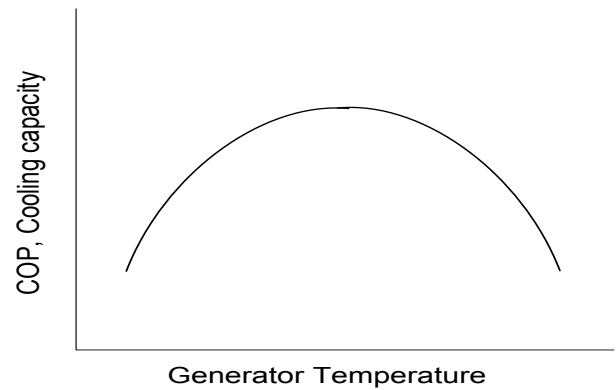
Fig. 4, Effect of generator temperature on COP at constant area ratio, evaporator pressure, and condenser pressure

3.4 Critical operating condition for fixed geometry ejector

As explained in the previous paragraph, for each given geometry and operating conditions, a single condition exists wherein the COP of the ejector is at peak condition. The relationship between the operating conditions is shown in Fig. 4.
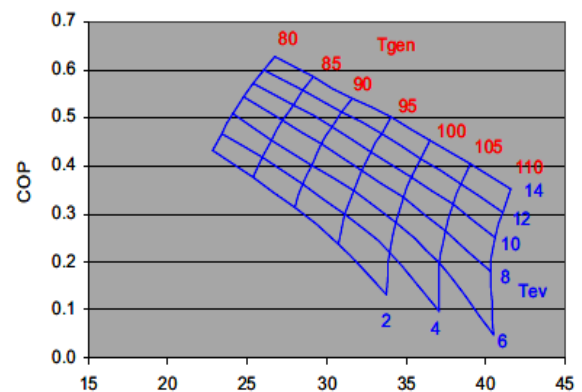

Fig. 5, COP at a given ejector operating pressure

Fig. 5 shows the relationship between the generator, condenser, and evaporator temperature on the critical COP and entrainment ratio (double choking) of the ejector on a fixed geometry ejector[12]. At any given two operating temperatures, only one temperature point will result in the highest COP and entrainment ratio of the ejector[26-28, 30]. The COP increases at high evaporator temperatures withreduced generator temperature and constant critical condenser temperature requirements. The effect of evaporator temperature to critical COP is evident at high condensing temperatures.(Table1) summarizes recent the studies on the impacts of operating conditions on the ejector refrigeration systems performance.

Table1. Experimental results of ejector refrigeration system under various operating conditions

Reference	Cooling capacity (Kw)	Working fluid	Evaporator temperature °C	Condenser temperature °C/pressure	Generator temperature °C	COP	Conclusion
Chunnanond & Aphornratana [6]	3	Water	5:15	22:36C	110:150	0.28:0.48	(1) A decrease in generator pressure increases the cooling capacity and COP but decreases the critical condenser pressure. (2) An increase in the evaporator pressure increases the critical condenser pressure, cooling capacity, and COP but decreases the desired cooling temperature.
Selvaraju and Mani [7]	0.5	R134a	2:13	26:38C	65:90	0.03:0.16	For specific condenser and evaporator temperatures, every ejector with particular configuration has an optimum generator temperature wherein the maximum COP can be obtained.
Sankarlal and Mani [32]	2	Ammonia	5:15	30:36C	62:72	0.12:0.29	COP increases with increasing expansion ratio and decreasing compression ratio.
Chaiwongsa and Wongwises[33]	1.8 to 3	R134a	8:16	26.5:38.5C	50:60	0.3:0.48	Cooling capacity varies inversely with the heat sink (where the condenser rejects the heat to the cold water) temperature but varies identically with the heat source (where the evaporator is supplied by hot water) temperature.
Yapıcı et al. [34]	2	R123	0:14	108 kpa: 142 kpa	83:103	0.12:0.39	Generator temperature higher than 97 °C results in a constant cooling capacity but low COP.

4 Working fluids

Selecting the suitable refrigerant is playing an indispensable role when design the ejectorrefrigeration system. Certain requirements should be considered in choosing the appropriate working fluid:

1. Thermo properties

a. A high refrigeration effect per kilogram of evaporated refrigerant is advantageous. The product of the latent heat of vaporization and mas flow rate dictates the system capacity. A higher latent heat of vaporization for a given capacity leads to lower mass flow, thus reducing the pumping energy, pipe size, and overall system cost.

b. The saturation pressure at the generator pressure should be low to obviatethe heavy construction of the pressure vessel and decrease pumping energy.

c. Transport characteristics that affect heat transfer, for instance, thermal conductivityand viscosity, should be convenient. Small molecular mass value of the fluid needsrelatively bigger ejectors for the same cycle capacity. The barriers to the construction of small-scale ejector components supposed to be observed. However, high molecular mass increases the entrainment ratio and ejector performance.

2. Environmental influence. Working fluid should have no environment impact with relatively low ozone depletion potential and global warming potential.

3. Safety. Refrigerant should have chemical stable.

4. Availability and economics. The cost of refrigerant should be low and has high market availability.
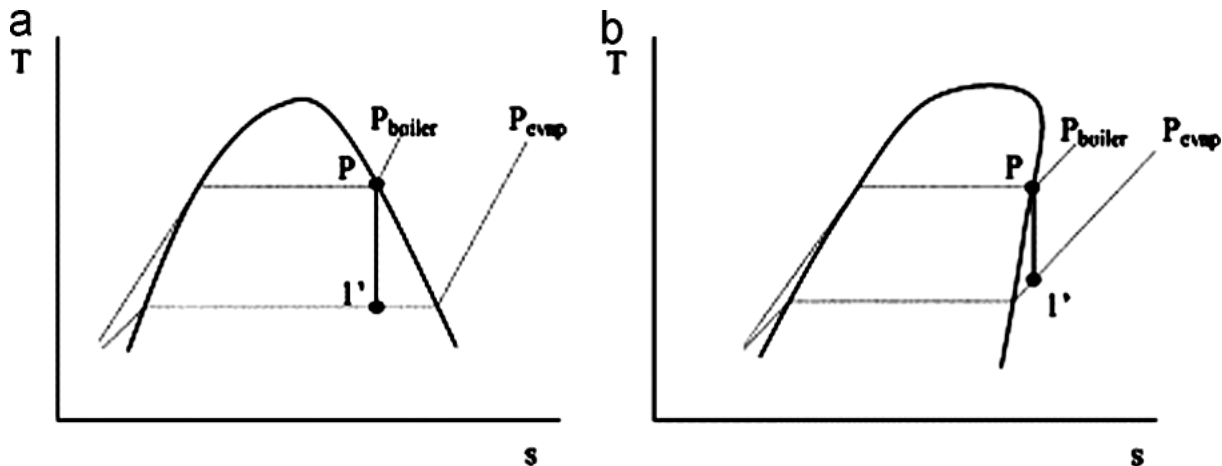
Fig. 6, Expansion process of refrigerant through the primary nozzle [14]. (a) Wet Fluid; (b) Dry Fluid

According to Chen et al.[35], the working fluid for an ejector refrigerator can be classified as dry vapour and wet vapour. Fig. 3 shows the difference between the two vapours. The saturated line of the wet vapour indicated as negative slope in the T-S diagram. The phase of the dry vapour fluid is unchanged during the expansion process in the motive nozzle. Meanwhile, small droplets from wet vapour fluids could be formed at the nozzle exit that may reduce the impact area and ejectorperformance. Superheating the fluid before entering the nozzle may eliminate the problem. However, superheating slightly decreases ejector efficiency; hence, dry vapour is more desirable than wet vapour fluid.

On the basis of chemical elements, Refrigerants can be specified to the following categories:

1. Halocarbon selection: R245ca, R245fa, and R152a,R11, R113, R114, R134a.
2. Hydrocarbon selection: cyclopropane (RC270), butane (R600),methane (R50), ethane (R170), propane (R290) isobutene (R600a), and ethylene glycol.
3. Mixed refrigerants: R407A, R407B, and R410A.
4. Other types of refrigerants: water (R718), carbon dioxide (CO_2), and ammonia (R717).

After the protocol of Montreal some of working fluids for ejector refrigeration systems, for example, R11, R12, R113, or R114, are now banned because of their environmental effect. New refrigerants, such as halocarbon compounds (R134a, R152a, R245fa, and so on), hydrocarbon compounds (R290, R600, and R600a), carbon dioxide (R744), and ammonia, are currently being investigated. Cizungu et al. [21] conducted a simulation for a jet refrigerator with different refrigerants, including R123, R134a, R152a, andR717. By using the same ejector, R134a and R512a are suitable for 70 °C to 85 °C heat sources, whereas ammonia is suitable for heat

sources whose temperature is greater than 90 °C. An analysis of an ejector refrigerator with environmentally friendly refrigerants was implemented by Selvaraju et al. [7]. Comparisons of ejector performance with five working fluids, namely, R134a, R152a, R290, R600a, and R717, were performed. Among these selected refrigerants, R134a (COP = 0.31) has been proven to yield the highest performance, followed by R152a (COP = 0.27), R290 (COP = 0.25), R600a (COP = 0.23), and R717 (COP = 0.05), at a generator temperature of 85 °C, condenser temperature of 25 °C and evaporator temperature of 5 °C. A similar experimental analysis on a solar-assisted ejector refrigeration system was presented by Nehdi et al. [36] with R134a, R141b, R142b, R152a, R245fa, R290, R600, and R717 as refrigerants. Comparative calculations show that R717 offers the highest performance (COP = 0.408), followed by R152a (COP = 0.385), R134a (COP = 0.379), and R290 (COP = 0.372), at a generator temperature of 90 °C, condenser temperature of 35 °C and evaporator temperature of 15 °C. However, the simulation conducted by Roman [23] with low ecological impact refrigerants indicate that R290 (COP = 0.66) demonstrates the highest performance, followed by R152a (COP = 0.58), R134a (COP = 0.56), R600a (COP = 0.48), and R600 (COP = 0.47), at a generator temperature of 90 °C, condenser temperature of 30 °C, and evaporator temperature of 10 °C. Eames et al. [37] and Yapici et al [8] used R245fa and R123 as refrigerants in their experimental studies on ejector refrigerators, respectively. The results indicate that both R245fa and R123 are practical working fluids for jet–pump refrigeration systems.

Ejector refrigeration systems that use low temperature and halocarbon compounds as

refrigerants allow systems to be driven by low-grade heat sources (such as solar energy, waste heat, and exhaust gas from automobiles). A solar-driven ejector refrigeration system with R600a as refrigerant was studied by Pridasawas et al. [38]. The COP of the cooling sub-system was around 0.48. Boumaraf et al. [39] conducted a simulation program on an ejector refrigeration system with R142b and R600a as refrigerants. R142b produced higher performance than R600a because R142b is heavier than R600a. This result further supports the conclusions made by Holton et al. [40], who showed that an ejector performs better with a high molecular weight fluid

5 Influence of geometry design on ejector performance system

Ejector geometry has major influences on ejector performance. Many researchers have achieved ejector geometry design optimization on system performance [8, 14, 20, 41-43]. Among the geometrical parameters studied are area ratio, nozzle diameter, nozzle exit position, constant area length, and diffuser angle.

5.1 Area ratio
The area ratio between the primary nozzles is consideredas the most important factors influencing ejectorefficiency. For fixed ejector area ratios and operating conditions, increasing the mixing section area results in greater flow for the entrained stream. The entrainment ratio then increases but with low compression pressures and critical condenser pressures. The optimal value of the area ratio exists, thus allowing for the maximization of ejector performance at critical condenser pressures. Several researchers have investigated the effect of area ratio on ejector performance with different refrigerant and operating conditions [8, 42]. Yapici et al. [8] investigated the performanceof R123 and found that the optimum area ratio increases linearly when the generator temperature is between the range of 83 °C to 103 C°. Jia et al. [42] presented an experimental investigation by using R134a with a replaceable nozzle having different ejector area ratios from 2.74 to 5.37. They found the best system performance with an area ratio from 3.69 to 4.76.

The area ratio can be classified as a single optimum geometrical parameter that causes the ejector to operate on critical mode for a given condenser temperature; this operating condition requires

various ejectors for various operating conditions. To overcome this problem, Ma et al. [20] and Varga et al. [43]implemented and tested a new feature, namely, a spindle. By changing the spindle position, the area ratio can be changed when the spindle tip moves forward, the primary nozzle throat area decreases, and the area ratio increases. CFD simulation was applied by Varga et al. [14] to analyse the influence of area ratio on ejector performance. They indicated that ejectors with area ratios varying from 13.5 to 26.4 may obtain an entrainment ratio from 0.18 to 0.38. They also mentioned that changing the spindle position of an optimal area ratio can be obtained in a single ejector. Ma et al. [20] conducted an experimental investigation for spindle systems by using water as working fluid. The results demonstrated that an optimum entrainment ratio of 0.38 can be achieved when the spindle position is 8 mm inside the mixing chamber; this optimum entrainment ratio is less than the maximum value of the CFD modelling obtained by Varga et al. [14] at nearly the same working conditions. The group [32] later outlined and compared the experimental results with CFD data and concluded that the CFD and experimental primary flow rates agreed well (average relative fault of 7.7%).

5.2 Primary nozzle diameter
A relationship exists between the nozzle diameter and generator temperature. At a given generator temperature and pressure, the maximum mass flow rate through a nozzle operating at choking condition is governed by the nozzle diameter. The effect of nozzle diameter on ejector performance has been investigated by many researchers. The optimum value of the primary nozzle diameter decreases with increasing generator temperature [16, 33, 44].

5.3 Nozzle exit position
The nozzle exit position (NXP) at the front or back of the mixing chamber affects both the entrainment ratio and pressure ratio performance of ejectors. Previous experiments[6, 33, 45]andCFD simulation studies[46-51] indicated that moving the nozzle exit into the mixing chamber reduces the COP and cooling capacity. Eames et al. [37] recently obtained a clear optimum of the entrainment ratio at 5 mm from the entrance of the entrainment chamber where the COP increases up to 40%.
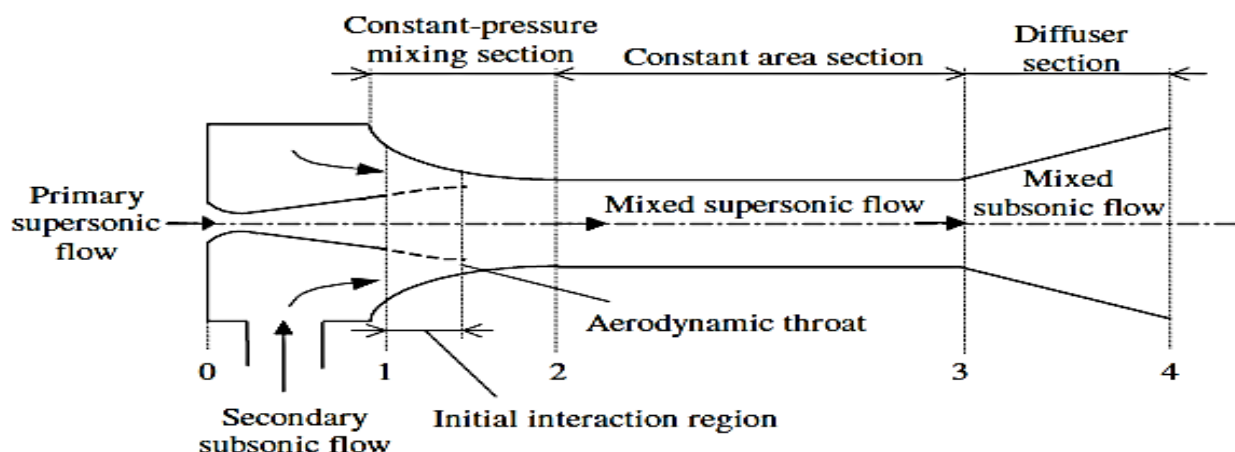
Fig. 7, Schematic of the ejector with design parameters

In this situation, the ejector tail was designed by a constant momentum rate change method and the refrigerant was R245fa. Varga et al. [14] obtained similar conclusions from numerical investigations: the CFD modelling indicated that an optimal entrainment ratio of 0.33 can be obtained while the nozzle exit position was 60 mm downstream. The optimum NXP is proportional to the mixing section throat diameter and increased with increasing motive flow pressure. Zhu et al. [52] indicated that ejector performance is sensitive to the converging angle (θ) of the mixing area. Although NXP was within its optimum range, the optimum converging angle was in the range of 1.45° to 4.2°. A relatively large (θ) is required to maximize ejector performance when the motive flow pressure increases. By contrast, Rusly et al. [46] and Pianthong et al. [25] conducted CFD analyses and showed that NXP only has a small effect on entrainment ratio in the NXP of an ejector with refrigerant R141b as working fluid compared with the base model. Moving the nozzle inwards the constant area section decreases the entrainment ratio, whereas moving the nozzle outward does not affect the entrainment ratio. They also claimed that the 1.5 diameter optimum NXP of the constant area section has enhanced performance. Pinthong et al. [25] applied NXP ranging from -15 mm to 10 mm from the mixing chamber inlet. The entrainment ratio increases slightly as the NXP moves farther from the inputt section. The optimal primary nozzle position or converging angle cannot be predefined to meet all operating conditions, and the operating conditions are different from the design point. NXP should be adjusted to maximize ejector performance. An ejector with a movable primary nozzle can provide flexible NXP when the conditions are the same as the design point [53]. Yapici et al. [34]conducted an experimental

investigation on an ejector refrigerator with a movable primary nozzle.

Therefore, the optimum primary nozzle exit should be -5 mm from the mixing chamber inlet. No general agreement can be achieved with various studies because of the varying nature of operation conditions and varying ejector geometries.

5.4 Constant area section length
Studies by [39, 54] showed that the constant area section length has no effect on the entrainment ratio. Pianthong et al. [25] indicated that the critical back pressure increases along(L_m) thus allowing the ejector to operate in double chocking mode in a wide range of operating conditions. A thermodynamic shock wave occurring within the ejector geometry can cause a sudden decrease in total pressure across the shock, thus reducing the maximum pressure ratio of the constant area ejector. To overcome this shortfall, Eames et al.[53] enhanced and developed the constant rate of momentum change method (CRMC) to achieve a diffuser geometry that removes the thermodynamic shock process through the diffuser at the designated operating conditions. The simulation results described in recent papers indicate specific improvement ratios that are achievable from an ejector designed with conventional methods. The experimental data presented by Worall et al. [54] also supports the theoretical findings. Vineet V. [55] found that the variable area ejector has better performance and higher critical condenser pressure than the constant area ejector for identical boiler temperatures at an evaporator temperature of 10 °C. However, the constant area ejector exhibits high performance at an evaporator temperature of 15 °C. The constant area ejector performance improves by approximately 49% when the evaporator temperature increases from 10 °C to 15 °C.

Table 2, Summary of some studies conducted on ejector geometry

| References	Working fluid	Te/Pe	Tc/Pc	Tg/Pg	Area ratio	Conclusion
Yapici et al. [8]	R123	10C	125 kpa	83 : 103 C	6.5: 11.5	The optimum area ratio increases linearly within the studied generator temperature range. At an obtained area ratio, an optimum generator temperature exists at the COP obtained from the ejector refrigeration system.
Jia et al. [42]	R134a	4.4 bar	7.8 bar	17.5 bar	2.74 : 5.37	The optimal area ratios are 3.69 and 4.67, and the maximum COP are 0.24 to 0.30. The operating condition and cooling capacities are related to the area ratios and nozzle diameters, whereas COP depends only on the area ratios.
Cizungu et al. [44]	Ammonia	4.5 C	32 C	80 : 130C	4 : 12	A quasi linear dependence exists between the area ratio and driving pressure ratio (generator pressure to condenser pressure).
Varga et al. [14, 43]	Water	10C	4.25 : 5.63 kpa	70.1 : 101 kpa	13.5: 26.4	Changing the spindle position influences the nozzle area, and the area ratio can be adjusted to the optimal value with a single ejector.
Ma et al. [20]	Water	10C	25 : 65 mbar	84 : 96C		The critical back pressure increases slowly with increasing evaporator temperature. The maximum cooling capacity was found at the boiler temperature of 92.8 °C. The maximum entrainment ratio and COP are found at the boiler temperature around 90 °C.
Jia Yan et al. [42]	R134a	8.5 : 11.5C	32:35C	68 C:74C	4.84	The most important geometries that most influence and sensitive to the performance of ejector are the area ratio and nozzle exit position. The average improvements in the entrainment ratio of the new ejector compared with the initial designed ejector are 13.4%, 23.4%, and 41.2% for evaporating temperatures of 11.5, 10, and 8.5 °C, respectively.
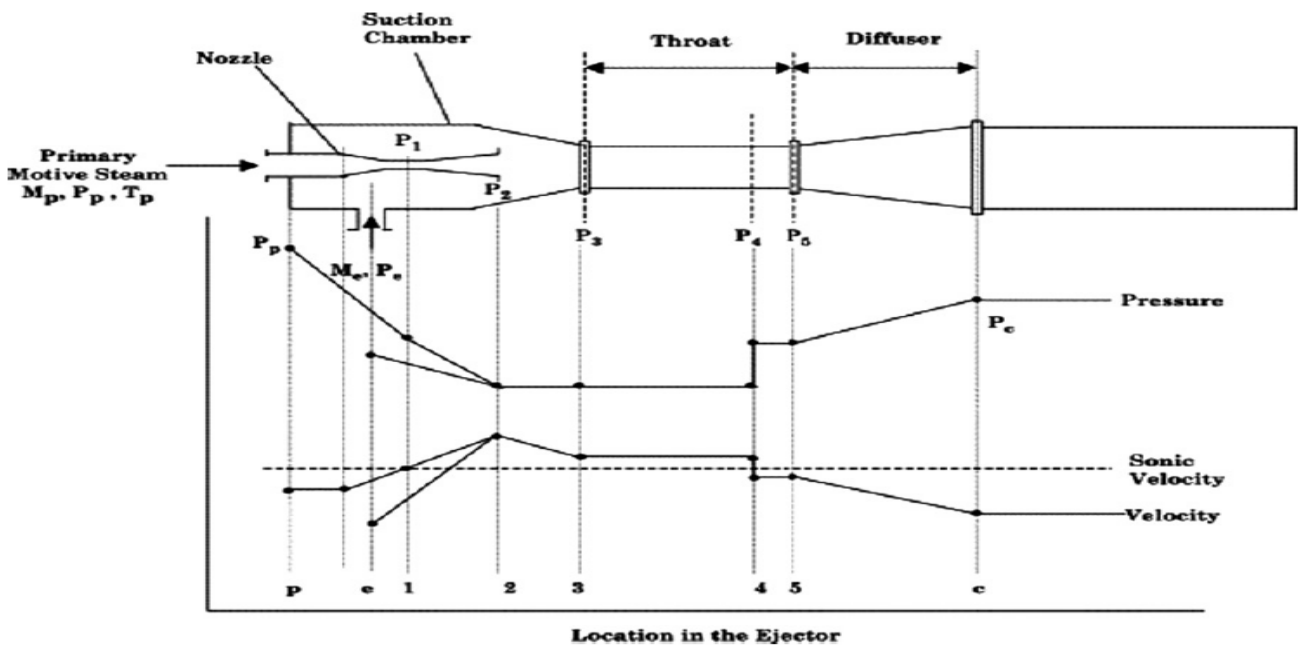
Fig. 8, Schematic of a typical supersonic ejector

However, the variable area ejector performance improves by 5% only but with a considerable increase in critical condenser pressure; thus, the variable area geometry is robust to varying operating conditions relative to the constant area ejector by eliminating the shocks from the ejector.

6 Conclusion

Studies on ejector refrigeration systems over the last two decades involve system modelling, design, refrigeration selection, fundamentals, and system optimization. The optimal geometry parameters of ejectors depend on the working fluids and operating conditions. Other parameters such as the length of the constant area mixing section ((L_m)) and the converging angle of the constant pressure mixing section (θ) are less studied because of their small influence on ejector performance. The research and development are broad, productive, and focuses on performance and feasibility enhancement by combining the ejector refrigeration system with other systems. This paper presents the principles for ejector design and the recent enhancements and development in ejector refrigeration technologies. The following conclusions are obtained on the basis of the reviewed studies:

1. Ejector refrigerators are mechanically simple and have low investment costs. However, such refrigerators have relatively low COP than other conventional refrigeration technologies.
2. At any given evaporator, condenser, and generator temperatures, only one unique geometry will result in the highest COP and entrainment ratio of the ejector.
3. Dry fluid refrigerants, such as butane, iso-butane, R113, R114, and R141b, yield better performance and require less excessive energy for superheating than wet fluids and isentropic fluids at the same operating temperatures.
4. Ejector geometry.
   - The area ratio between primary nozzles is an important non-dimensional factor that affects ejector performance. The optimum area ratio depends on the operating conditions and refrigerant type.
   - The optimum value of the primary nozzle diameter decreases with increasing generator temperature.
   - The optimum primary nozzle position or converging angle cannot be predefined to meet all operating conditions, whereas the operating conditions are different from the

design point. The NXP should be adjusted to maximize ejector performance.
   - Constant area section length has no effect on entrainment ratio.
   - Variable area geometry ejectors based on CRMC methods are robust and operate at high critical condenser pressures.

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