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REVIEW PAPER

A comprehensive exploration of ejector design, operational factors, performance metrics, and practical applications

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Abstract

The purpose of this paper is to provide the review details on the research attempt made in the field of ejector systems. This review paper provides details on design methodology, geometrical parameters, operating parameters effect, CFD studies, turbulence model selection, working fluid, and irreversibility of the ejector system. The journey of two-stage ejectors with their geometrical details and auxiliary entrainment positions is also presented. It gives a higher entrainment ratio as compared with a single-stage ejector. The new techniques, constant rate of momentum change and constant rate of kinetic energy, also came into the knowledge to design physics-based single and two-stage ejectors. This method helped in the design to create variable area geometry of the nozzle, mixing, and diffuser. This helps to remove the thermodynamic loss or irreversibility of conventional ejectors due to sudden area change at the exit/inlet of the diffuser section. In addition, the performance of the ejector, including entrainment ratio, nozzle exit position, and back pressure effect, is also presented. Finally, the effect of different working fluids on the performance of the ejector and application with various fields is also reviewed.

Keywords Ejector · Geometry · Operating condition · CFD · Entrainment · Working fluid

Abbreviations

CRKEC	Constant rate of kinetic energy change
CRMC	Constant rate of momentum change
CAM	Constant area mixing
CPM	Constant pressure mixing
CFD	Computational fluid dynamics
TVC	Thrust vector control
TR	Thrust reversal
AR	Area ratio
NXP	Nozzle exit position
RANS	Reynolds averaged Navier–Stokes
SSE	Single-stage ejector
TSE	Two-stage ejector
COP	Coeficient of performance
SST	Shear stress transport

1 Introduction

A thorough review of the literature on supersonic ejectors, in general, was carried out, emphasizing the impact of various performance characteristics. A review of the ejector design theory used in many fields was also undertaken for proper application. The whole chapter has been divided into four parts. The first section covers several studies on developing ejectors for various purposes. The second category describes the geometry that affects the system's performance, while the third describes the operating conditions that affect the system's behavior. The design process influences the ejector's performance in the fourth category. A variety of ejector-related parameters are discussed toward the end. The prior research has been rigorously scrutinized in terms of its findings. In the original one-dimensional ejector design theory, constant area mixing was anticipated in the ejector's constant area part [1]. It was easy to understand and use and based on a one-dimensional theory with an ideal gas equation of state. The nozzle exit position was preserved at the same plane as the mixing section intake, which was the constant area in

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this technique. The second design approach used constant pressure mixing (CPM) [2]. During the mixing of motive and entrained flow, static pressure is assumed to remain constant. This method is most typically utilized in design because of its relatively better results and lack of substantial production challenges. In this method, the nozzle plane ends at the mouth of a tapering suction chamber. The combined geometry of the CAM and CPM ejector is shown in Fig. 1.

In the intervening years, the CAM and CPM approach ejectors have been thoroughly explored and used in various applications. CPM ejectors outperform CAM ejectors, according to studies conducted in the intervening years [3]. However, the performance efficiency of CPM ejectors remains low, indicating constraints in further enhancing their performance [4]. The constant capacity characteristic of the ejector was studied using a semi-empirical design technique [5]. The ensuing research [6, 7] led to a better knowledge of the flow behavior of primary, secondary, and mixed streams, namely the fluctuation of static pressure and velocity. Ejectors find widespread usage in various industrial applications such as creating a vacuum, mixing gases or liquids, pumping fluids, and conveying materials. These devices can be categorized based on their primary functions and applications. According to design, ejectors can be broadly classified into two categories, namely single- and two-stage ejectors. Single-stage ejectors have a simple design, consisting of a convergent-divergent nozzle and a diffuser. They function based on the Venturi effect and are relatively easy to operate and cost-effective. On the other hand, two-stage ejectors consist of multiple stages arranged in series. They use motive fluid from one stage as the driving fluid for the next stage, resulting in higher efficiency and greater vacuum capacity, as illustrated in Fig. 2.

Figure 3 shows how the primary flow (P) fans out (i) as it passes through the nozzle without interfering with the entrained flow (S). The internal wall and the diverging flow come together to form a converging tube that acts as a nozzle I for induced flow (S). The entrained

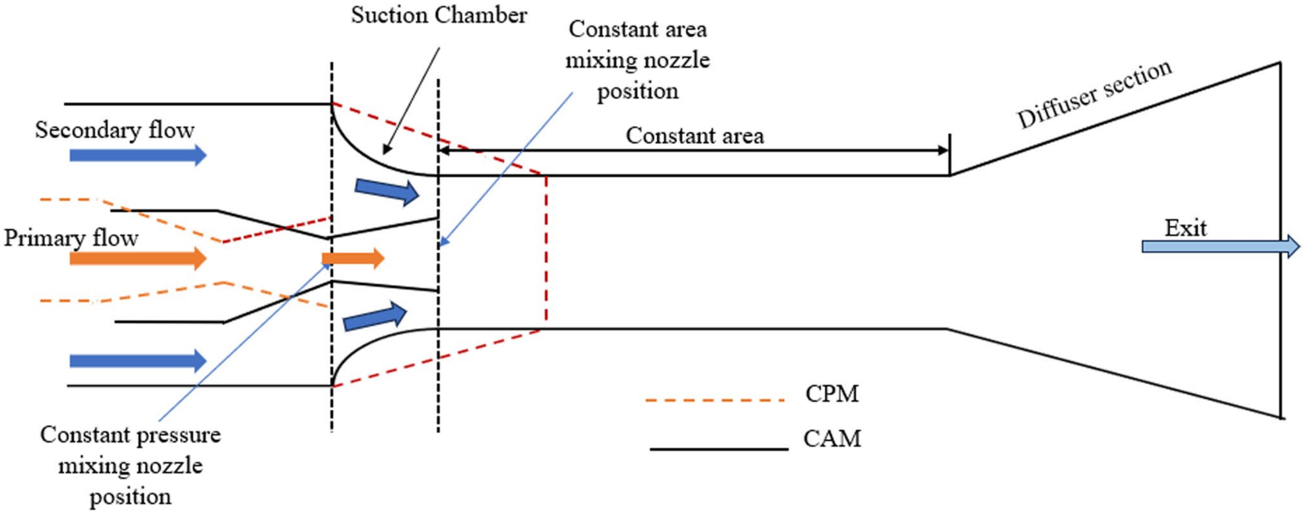

Fig. 1 Schematic geometrical profile of CAM and CPM ejectors

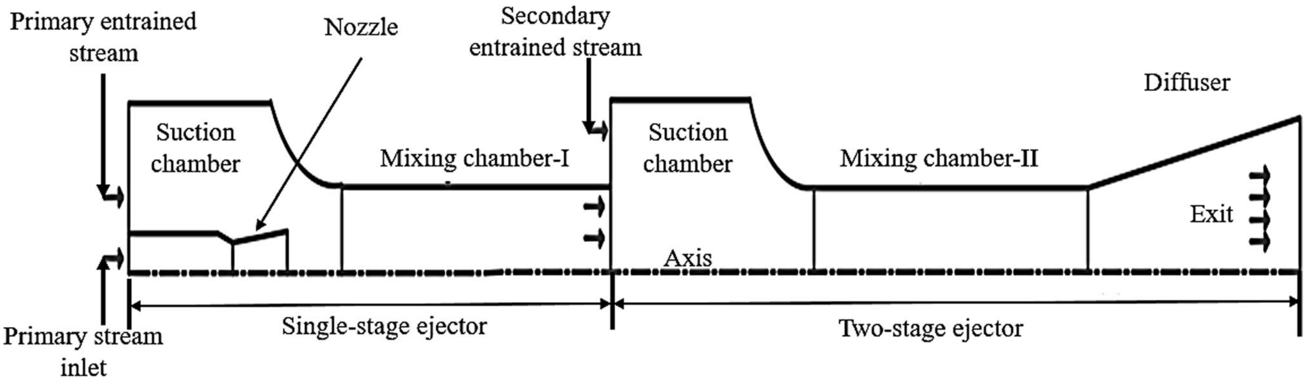

Fig. 2 Schematic geometrical configuration of multistage ejector

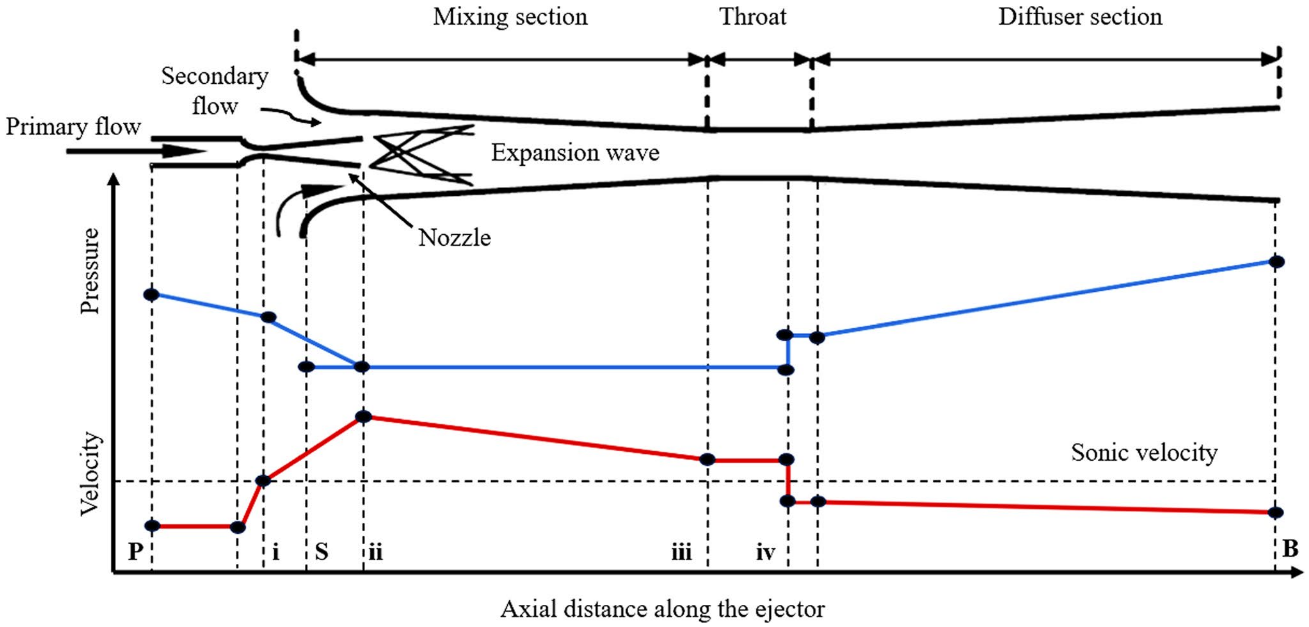

Fig. 3 Variation of pressure and velocity along the ejector [7]

fluid accelerates to Sonic velocity in a hypothetical throat (effective region) downstream of the primary nozzle position (ii). In the mixing chamber, these fluids are subjected to strong mixing, intended to occur at constant pressure until the inlet of the constant area, which is the end of mixing (iii). This is the ejector throat, long enough to hold a shock train of oblique shocks equivalent to standard shock induces. This results in a quick increase in pressure, causing a compression effect and a concomitant fall in flow from supersonic to subsonic at the downstream exit of the ejector's throat (iv). As the flow reaches a state of stagnation, more compression is achieved in the diffuser region (B).

Propose an improved one-dimensional gas dynamic CRMC technique to cope with the thermodynamic shock in the constant area portion of a typical ejector diffuser. It was based on the idea that low momentum changes at a constant rate within the diffuser passage of supersonic ejectors. At the design point operating circumstances, this approach should eliminate shock in the diffuser [8, 9]. Constant rate of kinetic energy change (CRKEC) is a new physics-based design approach that has shown significant improvement compared to existing models. To evaluate at critical mode, an ejector realization based on the shock circle model was presented. The shock circle model can be independent of the flows in the constant area chamber and diffuser when calculating ejector performance [10].

2 Geometrical parameters and their effects

One of the current concerns in ejector research is the effect of the shape of the ejector components on its performance. The geometrical characteristics of the primary nozzle, the mixing section, the diffuser section, and the ejector area ratio all have a significant impact.

2.1 Primary nozzle geometry

The primary nozzle geometry is critical for increasing the ejector's overall performance. The nozzle shape and NXP related to mixing geometry both play a role in improving system performance. The primary nozzle geometry is used to measure the performance of the ejector system. A novel primary nozzle design with varying area ratios was examined for the refrigeration application. It was discovered that the innovative nozzle design improves the COP and that better mixing occurs with increased conversion of kinetic energy into pressure at the diffuser's exit [11]. The effective area inside the mixing section is important for improving system performance, and it can be modified as the nozzle's exit position varies. Due to an increase in effective area, the entrainment ratio increases as the nozzle position is tuned toward the upstream direction. The effective area reduces as the nozzle location travels downstream, and the entrainment ratio drops [7]. The influence of nozzle exit diameter on ejector efficiency was investigated. In this study, various nozzle exit diameters with R134a as the working fluid was investigated. It was discovered that varied exit diameters have a negligible effect on system performance, with 2 mm being the ideal value for the best outcomes.

To achieve better entrainment at a given secondary flow, a unique nozzle design method was devised to minimize the mass flow rate of the primary fluid required. It also aids in the improvement of the pressure recovery ratio. Lobes were formed in a circular nozzle design to improve the mixing process, to induce vortices and flow instability. When compared to the traditional nozzle, the compression ratio was found to be more significant. However, the fundamental constraint of this sort of nozzle is its shape [12]. A numerical analysis of steam ejectors with variable primary nozzle geometry was performed [13]. The author claimed that the performance of the ejector with a conical nozzle was superior to that of other nozzle geometries. The conical nozzle also has a lower critical back pressure than the cross-shaped and square nozzles. The influence of nozzles with and without chevrons on ejector performance was examined numerically [14]. A chevron nozzle was employed in this investigation to allow shear action between the primary and secondary flow. When the findings obtained with the chevron nozzle were compared to those obtained with the traditional nozzle, it was discovered that the compression and entrainment ratios improved by up to 8.5% and 14.8%, respectively. The ejector system uses various types of nozzles, which can be seen in Figs. 4 and 5.

Introduced two innovative supersonic nozzle designs, the lobed and tip ring nozzles, to improve supersonic ejector mixing at high speeds. A comparison of the novel nozzle and a conventional nozzle with the same exit Mach number was carried out. This study showed the 3-D flow structure of such nozzle geometries using the laser scattering flow visualization technique on free jet flow. The results suggest that employing both nozzles resulted in a 30% improvement.

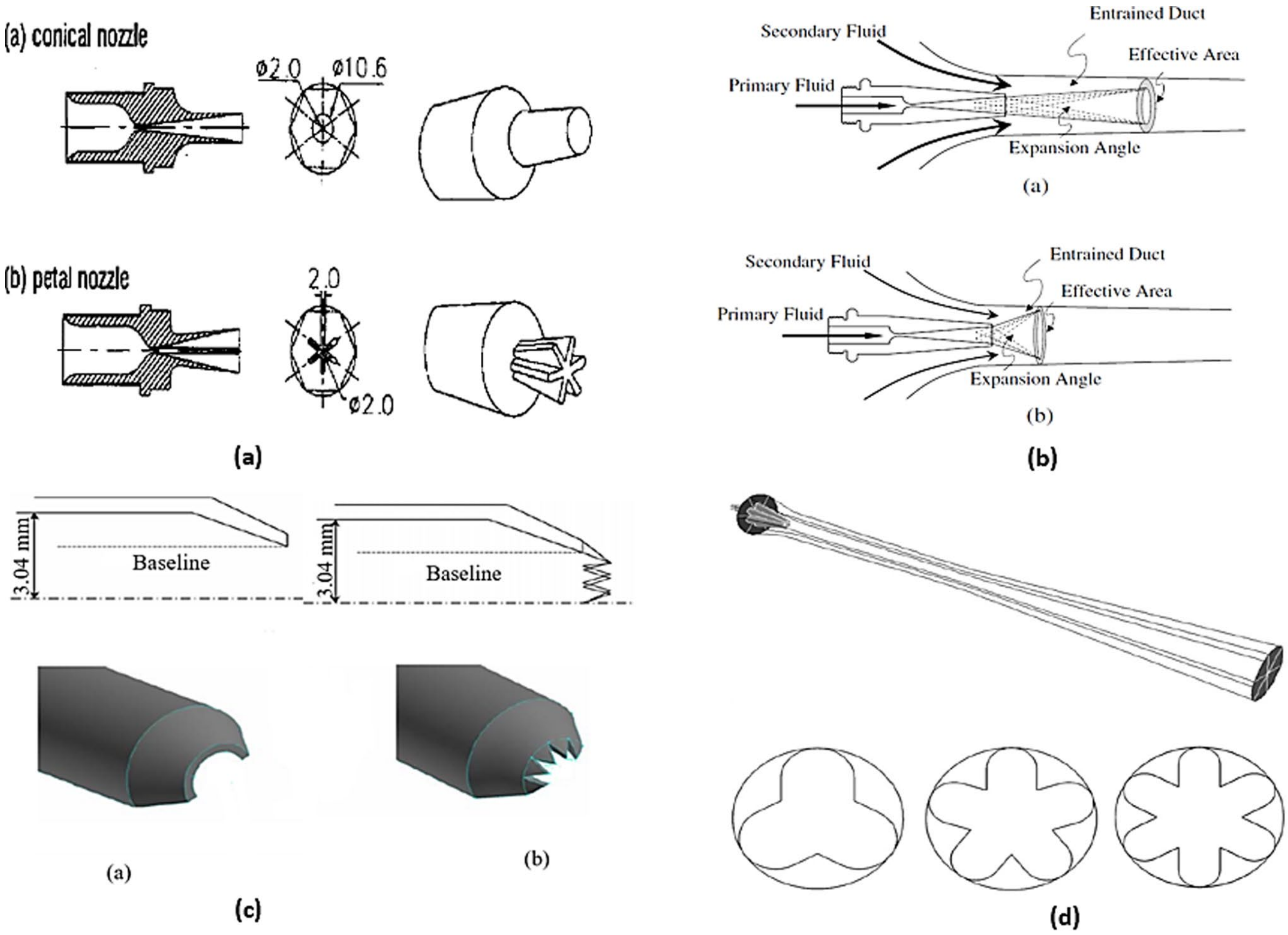

Fig. 4 Geometry of **a** conical and petal nozzle [11], **b** effective area and expainsion angle, [7] **c** conventional and chevron nozzle [14], **d** lobed nozzle [12]

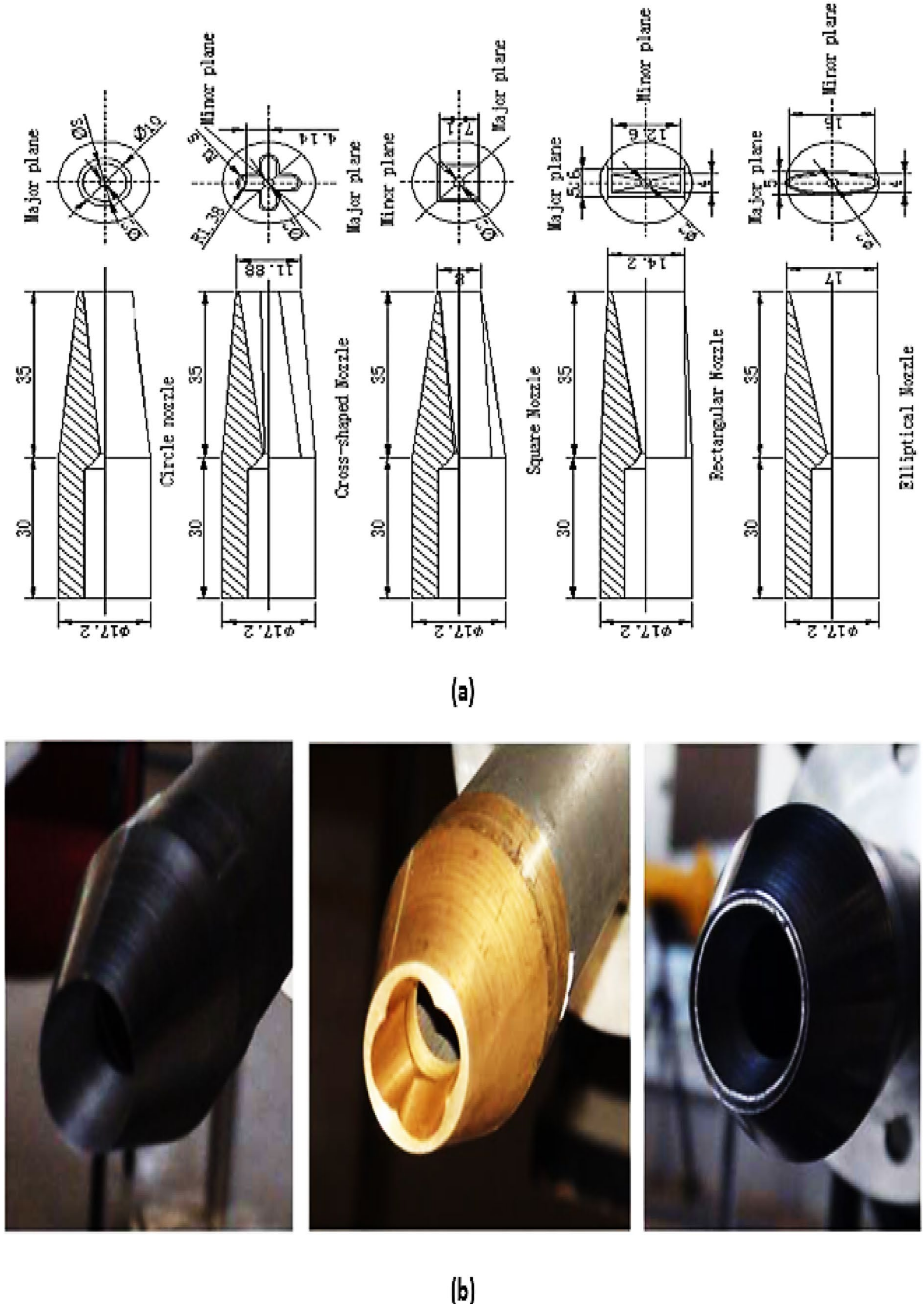

Fig. 5 Geometry of **a** different shapes of nozzle [13] and **b** different variants of primary nozzles[15]

A lobed nozzle's compression loss ratio can be as high as 15%, while a tip ring nozzle can be as high as 50% [15]. A CFD model was utilized to investigate the impact of nozzle outlet diameter and diverging section length on the steam ejector system at varied secondary flow pressures. The nozzle diameter grows, and the entrainment ratio increases until it reaches an optimum value, after which it begins to decline as the outlet diameter increases. According to the author, the magnitude of the diverging component has a more negligible impact on system performance [16].

The ejector system was analyzed numerically to optimize the primary nozzle shape, including the angles and lengths of the convergent and divergent portions of the nozzle, and comparing the CFD results to available data. Numerical analysis were utilized to determine the best primary nozzle geometry dimension. When building the ejector system, it was discovered that more attention should be paid to the primary nozzle design to achieve a higher entrainment ratio [17].

2.2 Mixing section geometry

The geometry of the mixing section is one of the most important factors affecting ejector performance. As a result, it was also taken into consideration in the literature. Designing the mixing section to improve the ejector's performance is a critical challenge. Many assumptions were considered to build an efficient mixing section, including constant area mixing [1, 18–22] and constant pressure mixing [2, 5, 10, 23–26]. Several researchers have investigated the effect of mixing section convergence angle, throat ratio, and length on ejector performance. However another study was conducted to stress the angle of convergence of the mixing section, concluding that 0.5° may be adequate for the best outcomes [27] suggested 10° [28], observed 6°–8°[29], indicated 1.45°–4.2° [30], offered 28° [31] and studied 6° [32] as the ideal value.

Researchers used numerical and experimental methods to explore the impact of the second throat ratio, also known as the ejector area ratio, on ejector performance. It was also one of the geometrical variables that impacted the results. Under the same operating conditions, the two-ejector models CAM and CPM ejectors were compared and optimized [33]. They claimed that the optimum COP and area ratio could be established using the constant area ejector model. The results were more significant than previously published constant pressure ejector results. For the same area ratio, the COP of the CPM ejector is larger than the COP of the CAM ejector. The flow behavior and performance of steam ejectors employed in the refrigeration system were studied numerically. The entrainment ratio was observed to increase to its maximum value but reduces critical backpressure proportionally [34]. Along the same lines, the effect of area ratio on the performance of steam ejectors was analyzed and discovered that the ejectors working parameters determine the ideal area ratio [35]. Further investigation of area ratio effect on the performance of an air-cooled ejector and performed and suggested optimum area ratios. In this work, the ideal area ratio was between 3.69 and 4.76, lower than those advised in the literature [36]. Many researchers have performed similar work [37–41] and suggested that the area ratio influences the system performance. The mixing segment length impacts performance and the NXP, which must be tuned [42]. According to ESDU, the empirical relation for mixing section length $L_{\text{mix}} = 7D^{*}_{\text{diff}}$ often produces the best results in ejector performance studies (1985) where D^{*}_{diff} is the ejector throat/minimum diffuser diameter/characteristic dimension. Inline with ESDU, they proposed a relationship for designing the mixing section length for the CRMC ($L_{\text{mix}} = 7.33D^{*}_{\text{diff}}$) and CRKEC ($L_{\text{mix}} = 7.48D^{*}_{\text{diff}}$) ejectors, respectively [9, 43]. Additionally, the mixing length behavior of steam ejectors was investigated quantitatively. Different mixing section lengths with a fixed length of constant area and diffuser were investigated. According to the theory, when the mixing section length is increased, the entrainment ratio and critical back pressure rise initially and then reduce. The steam ejector performs well when the mixing section length is between 40 and 80 mm [44] and 85–100 mm [45]. The CFD analysis presented in Fig. 6 shows how the performance of an ejector is affected by the length of the mixing section.

2.3 Diffuser section geometry

The diffuser section's efficient design and selection are critical since they aid in pressure recovery while reducing kinetic energy. According to the previous study, the thermodynamic shock was observed as the cause of the irreversibility in the recovery of the back pressure ratio. Therefore, an isentropic 1D gas dynamic approach to building a diffuser to prevent thermodynamic shock. This method assumes that the rate of momentum change along the diffuser is constant [8]. The influence of diffuser length on ejector performance has been analyzed numerically. The entrainment ratio increases as diffuser length increases for a primary flow pressure up to the optimum value [45]. As the diffuser length expands, the ejector's volume and weight will increase. As a result, shortening the diffuser properly up to a certain point, which decreases may be advantageous [29, 46], while other studies suggested that 5^0 diffuser divergence angles would be better to improve the ejector performance [47]. Furthermore, physics-based CRMC and CRKEC ejectors with diffuser divergence angles 3.82° and 5.16° were suggested as optimum values at which the ejector would play a significant role [9, 43]. Figure 7 shows the variable area diffuser section.

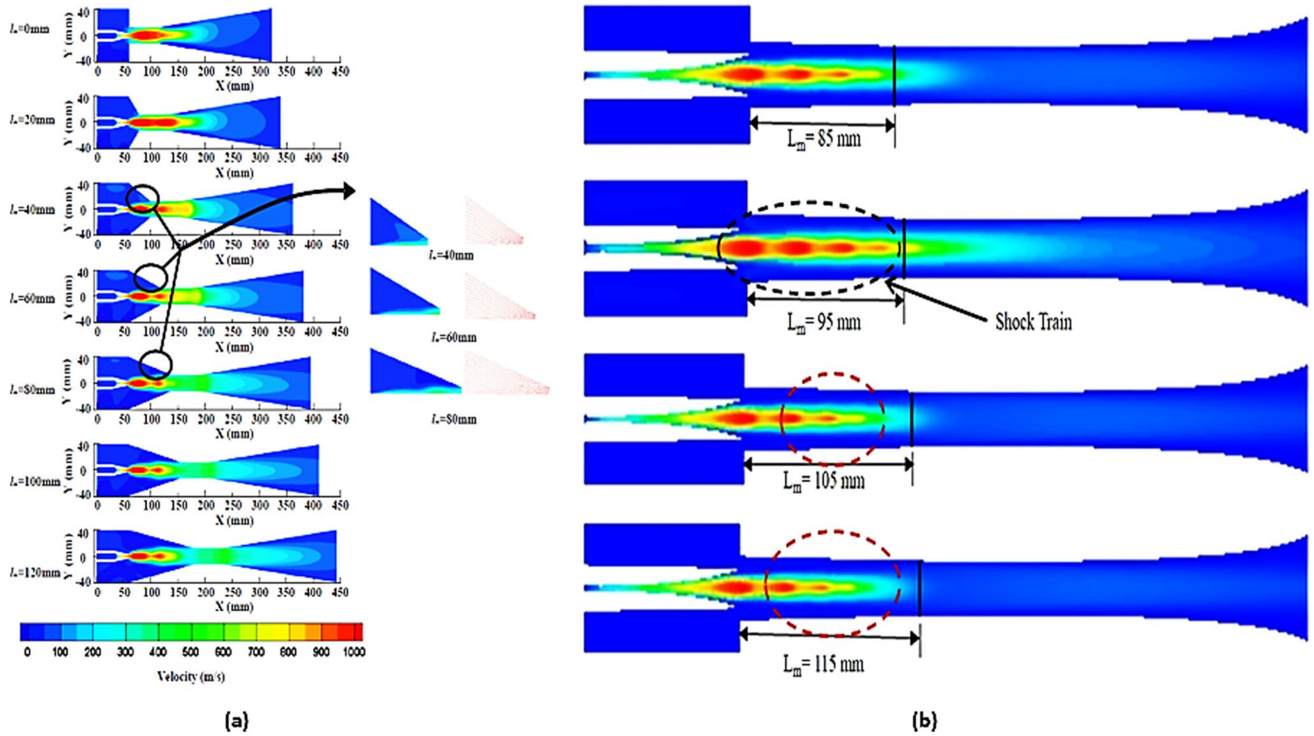

Fig. 6 Velocity contours of different mixing section lengths [44, 45]

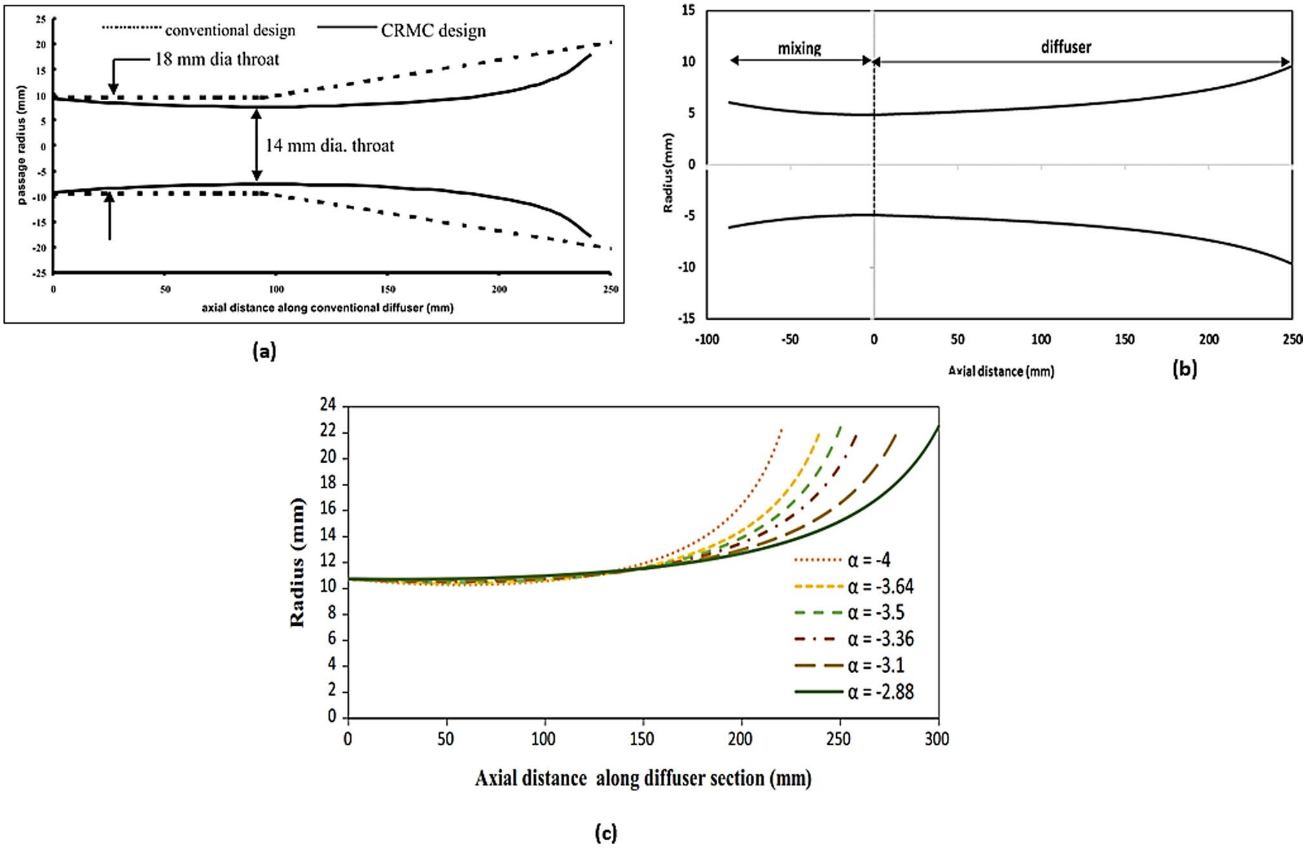

Fig. 7 Passage variation of diffuser section **a** CRMC [8], **b** CRMC with frictional [9], **c** CRMC with real gas equation [45]

In addition, the effect of diffuser length on various ejector applications was numerically evaluated, and the results were compared experimentally. The entrainment ratio increases rapidly with increasing diffuser length but declines when diffuser length exceeds the optimal length [48]. A 3D ejector model analysis numerically is to determine the optimal diffuser section length. This study examines the performance of ejectors with diffuser lengths varying from 50 to 300 mm and intervals of 55 mm. Because critical back pressure does not increase as diffuser length approaches 200 mm, it can be enhanced by extending it, but not to an excessive degree [44].

3 Effect of operating parameters

Operating parameters for fixed-shape ejectors [49–54] impact the performance and overall behavior. Any sector system is designed to operate optimally within a specific range of operating conditions beyond which off-design operation happens. The most important operating parameters are mentioned further down.

3.1 Primary flow total pressure and temperature

For various condenser pressures, the effect of primary flow pressure (boiler pressure) on the performance of the ejector was analyzed computationally. They discovered that as boiler pressure increased from 1.6 to 4 bar, critical back pressure increased, indicating that the ejector can function at a higher critical temperature when employing dual chocking mode [55]. The impact of primary flow pressure on the performance of the ejector has been observed and analyzed. In this particular case, the primary nozzle has a throat diameter of 1.7 mm and a Mach number of 4.0. The saturation temperature of the boiler varied between 130 and 150 °C, while the evaporator temperature remained fixed at 7.5 °C. As the saturation temperature of the boiler increased, the primary mass flow rate also increased, resulting in reduced secondary flow entrainment. This overall led to a decrease in the entrainment ratio [56]. Subsequently, the influence of boiler and evaporator temperatures ranging from 120 to 140 °C and 5–15 °C on the performance of an ejector refrigeration system utilizing water as the working fluid was explored [4].

The ejector system's performance was discovered to alter when the operating conditions changed. With a smaller entrainment ratio, the greater boiler temperature resulted in higher critical back pressure. The performance of a vapor refrigeration system was examined and quantitatively assessed [57]. The system's COP improves when the boiler temperature for fixed area ratio, evaporator, and condenser temperature rises. Through an evaluation of an existing steam jet ejector system under various operating conditions, the effect of those conditions on the system's performance was studied. The primary focus of the study was to determine how to enhance the system's performance. The results showed that reducing the motive pressure led to a 51% increase in entrainment ratio and a decrease in the ejector critical back pressure [58].

3.2 Secondary flow total pressure and temperature

The performance of the vapor refrigeration system was examined and analyzed quantitatively. With an increase in secondary flow temperature for fixed area ratio, evaporator, and condenser temperature, the system's COP improves [57]. They investigated the influence of secondary flow pressure experimentally varying inlet heights on starting pressure while maintaining a constant throat area of a supersonic ejector. It was discovered that there is an optimum secondary flow entrance height at which the initial pressure is lowest, resulting in a higher entrainment ratio [59]. However, another study looked into the effect of secondary flow pressure on the off-design entrainment ratio of the CO_2 ejector [60].

The entrainment ratio rises for constant primary and back pressures as secondary flow pressure rises. In a subcritical mode, the entrained secondary flow is susceptible to the primary flow pressure of an ejector system. As a result, the optimum entrainment ratio is achieved when the ejector is in critical mode. Operating conditions on ammonia ejectors with subcritical and critical working modes were investigated [61]. Based on the calculations, the secondary flow pressure ranged from 0.45 to 0.65 MPa. The findings indicate that as the primary flow pressure decreases, the entrainment ratio increases from 0.35 to 0.65. However, the effective area and secondary mass flow rate decrease due to the formation of a small vortex near the ejector wall.

3.3 Exit/back pressure effect

The researchers analyzed how the secondary flow phenomenon affected the ejector's performance because of the choking issue. The performance of the ejector is examined in three different modes of operation. Double chocking (critical mode), single chocking (subcritical mode), and back flow mode are shown in Fig. 8. A steady entrainment ratio was observed at subcritical mode, with increasing back pressure not affecting the entrainment ratio up to critical back pressure. With an increase in back pressure, the entrainment ratio began to fall. The dual chocking mode is the only mode within the critical mode, which led to the better performance of the ejector. After that, only primary flow was chocked within the off-design subcritical mode. The dual chocking mode is the only mode within the critical mode, which led to the better performance of

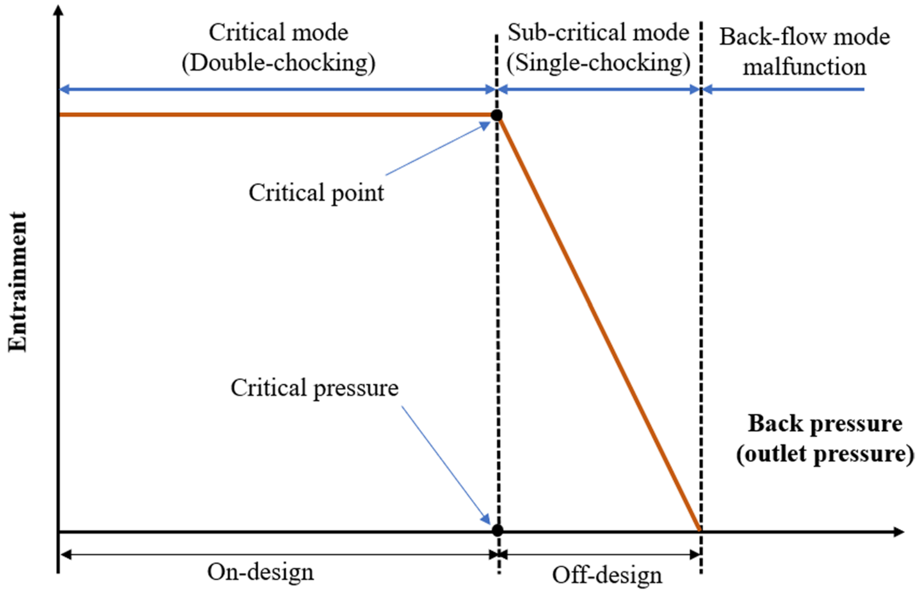

Fig. 8 Characteristic curves with different operating zones of the ejector

the ejector. After that, only primary flow was chocked within the off-design subcritical mode.

They conducted an experiment to observe the impact of back pressure on ejector performance. They claimed that the entrainment ratio remains constant when the ejector runs within the critical backpressure range. Then, it alters dramatically as backpressure rises above the critical value [36]. A reduced area ratio with high critical pressure is desired to achieve optimal ejector performance. The shock positions of the mixed stream inside the mixing section [56] are highly important in analyzing the ejector's performance. The second shock location is pushed toward the mixing process inside the mixing section when the back pressure exceeds the critical value. Due to shifting shock, the effective area is disrupted, and the secondary flow is no longer choked. When back pressure rises, the entrainment ratio drops dramatically. The effect of back pressure (condenser pressure) on the performance of the ejector was studied and analyzed numerically. By increasing the condenser pressure to the critical value, they observed a continuous increase in entrainment ratio within the critical mode of operation. As the condenser pressure rises, the entrainment ratio falls dramatically [55]. The influence of critical back pressure on the performance of the ejector with various primary flow pressures was explored experimentally. Based on critical backpressure, the ideal value of primary flow pressure was discovered, at which the ejector achieved the highest entrainment ratio [62]. Table 1 presents a summary of the ejector parameters affecting system performance.

4 Computational fluid dynamic (CFD) studies on ejectors

Numerical simulation has been presented as the most reliable and cost-effective tool for studying the fluid flow inside the ejector. It can be used to identify the ejector's best performance when operating outside of its design parameters. Shock waves, compressibility, boundary layer, mixing, complicated flow, and supersonic flow are among the flow phenomena that CFD modeling can predict. The researchers extensively used it to better understand the ejectors hydrodynamic behavior, resulting in improved design and optimization [13, 16, 63, 64, 66, 77–85].

Current CFD studies of ejector performance in various applications have mostly focused on operating circumstances, geometry, and their impact on working fluid. The performance of the ejector system was studied using CFD models for various working fluids [65, 86, 87] and claimed to be able to forecast comprehensive flow physics for an ejector. Mazzelli et al. [88] investigated the ejector's performance numerically and experimentally to determine the efficacy of the computational tool for predicting flow behavior, indicating that a 3-D examination of the ejector model is ideal for off-design ejector performance modifications. They investigated the reason for boundary layer separation and its impact on the performance of the steam ejector using numerical modeling. They discovered that throat diameters that are too small or too large, as well as NXP, influence the system's performance. The

Table 1 Review of operating conditions, geometrical parameters, and working fluids used in ejector studies

Refs	Primary conditions	Secondary conditions			Working fluid	Exit conditions		Ejector Dimensions			Performance	Concluding remarks
	Pressure (bar)	Temp. (K)	Pressure (bar)	Tem. (K)		Pressure (bar)	Tem. (K)	Nozzle (mm)	Mix. (mm)	Diff. (mm)	Entrainment	
Jiya et al. [36]	23.5	381	4.43	283	R134a	8.4	306	37	28	70	0.26	Observed dependency of area ratio with boundary condition of ejector system
Yapici et al. [40]	7.524	371	–	283	R-123	1.25	307	–	–	–	0.29	A 6.5 to 11.5 ejector area ratio was observed as the optimum value for better performance
Kumar et al. [43]	5.7	306	0.7	300	Air	0.103	306	100	86.5	250	0.53	Utilized CRKEC approach to design air ejector
Dong et al. [44]	1.9867	393.15	0.01228	283.15	Steam	0.01228	283.15	–	160	200	0.466	Back pressure and entrainment ratio get affected beyond the optimum length of ejector components
Subramanian et al. [50]	1–3	573–973	atm.	atm	Air	0.5–2.5	–	100	–	–	1.202,1.435 and 1.595	Studied with and without blower numerically and experimentally with a 6% to 8% deviation
Cai et al. [51]	16	556.85	0.1	315	Steam	0.33170	–	–	485	305	0.68	Ejector geometry is more compatible with real fluid as compared with an ideal fluid
Wen et al. [54]	2.433	276	0.844	251	R134a	1.0128	304	14	10	15	2.6	Performance of ejector influenced by evaporator temperature

Table 1 (continued)

Refs	Primary conditions	Secondary conditions			Working fluid	Exit conditions		Ejector Dimensions			Performance	Concluding remarks
	Pressure (bar)	Temp. (K)	Pressure (bar)	Tem. (K)		Pressure (bar)	Tem. (K)	Nozzle (mm)	Mix. (mm)	Diff. (mm)	Entrainment	
Ramesh et al. [55]	2	393.2	0.0122	283	Water vapor	0.045	304	–	114	180	0.342	The entrainment angle or suction chamber angle influences the performance
Guangming et al. [60]	95	308	39	283	CO2	46	–	11	32	23	0.40	Effect of operating condition on entrainment ratio
Wang et al. [62]	22	345	3.88	281	R134a	7.9	304	37	28	70	0.42	Optimum pressure geometry proposed for better performance
Wu et al. [63]	6	–	0.15	–	Steam	200–455	–	35	86.1	101	0.43	Optimum length and convergence angle for mixing chamber identified
Haghparast et al. [64]	4.855	78.8	1.108	28.3	R245fa	202.4	60.8	206.04	250.5	28.12	0.44	Ejector dimension and operating conditions optimized to obtain maximum performance
Zhang et al. [65]	8–9.5	–	4.8–5	299	Ammonia	5000–5400	281	37	37	72	0.5	Optimized primary pressure to identified maximum performance
Han et al. [66]	3–4	–	2330–3170	–	Water vapor	3500–7000	-	100	212.2	210	0.3	Cause of Ejector failure was identified
Smierciew et al. [67]	11.7	336	2.03	283	R-1234ze(E)	4.2	315	27.4	200	286	0.35	Geometry parameters and operating conditions studied

Table 1 (continued)

Refs	Primary conditions	Secondary conditions			Working fluid	Exit conditions		Ejector Dimensions			Performance	Concluding remarks
	Pressure (bar)	Temp. (K)	Pressure (bar)	Tem. (K)		Pressure (bar)	Tem. (K)	Nozzle (mm)	Mix. (mm)	Diff. (mm)	Entrainment	
Ji et al. [28]	2.67	402.5	0.136	273	Steam	0.176	70.7	800	1200	800	0.65	Effect of geometry and operating pressure on flow structure studied
Chen et al. [68]	130	–	20	–	Methane	52	–	58	85	224	0.58	Increment in performance of SSE system Observed by adopting TSE system
Chen et al. [69]	130	–	20	–	Methane	52		58	44	236	0.58	By-pass ejector system proposed to hance the performance of the system
Xue et al. [70]	6	448	–	328	Water-vapor	1	338	170	305	415	–	Shows Improvement in the performance of desalination system
Yan et al. [71]	3.746	290	2.433	278	–	0.9115	260	15	20	50	0.66	System performance dependent upon the second stage nozzle throat area
Wang et al. [72]	26.33	361	1.06	298	R134a	6.6	298	14	23	72	0.29	Area ratio observed as design parameters to achieve subzero refrigeration effect
Maghsoodi et al. [73]	5.8	298	2.8	353	Hydrogen	3	298	-	38.40	153.60	2.70	NXP and mixing section length play an important role in performance improvement

Table 1 (continued)

Refs	Primary conditions	Secondary conditions			Working fluid	Exit conditions		Ejector Dimensions			Performance	Concluding remarks
	Pressure (bar)	Temp. (*K*)	Pressure (bar)	Tem. (*K*)		Pressure (bar)	Tem. (*K*)	Nozzle (mm)	Mix. (mm)	Diff. (mm)	Entrainment	
Sharifi et al. [74]	7.5	443	0.1	318	Wet steam	1	298	122	493	385	–	Steam condensation reduces Mach number when its flow in supersonic regions
Hao et al. [75]	30	373–383	3.5	288–303	Water vapor	16	586–327	–	148	183.05	0.45	Hybrid system adopted
Yan et al. [76]	2.433	278	0.844	253	–	1.0176	265	14	20	15	1.7	Optimum key geometry of the ejector was obtained

highest performance can be noticed within a specified range of throat diameter, or NXP [66]. They studied high-performance ejector for a genuine working fluid using a computational fluid dynamics (CFD) approach. They analyzed how operating conditions and geometry parameters affected the ejector's performance and established a 0.5% linear relationship between pentane expansion and compression ratio. CFD studies reveal that a small area ratio leads to a high compression ratio with a hot environment application [89].

4.1 Turbulence model selection

The Reynolds averaged Navier–Stokes (RANS) approach is used in most circumstances. However, no substantial agreement on a specific turbulence model has yet been obtained in terms of turbulence modeling. Various numerical investigations on the performance of the ejector with various turbulence models have been undertaken [67, 90–92]. Studied various turbulence models (k-epsilon standard, k-epsilon realizable, k-epsilon RNG, k-omega standard, k-omega SST, and RSM) on the performance of the supersonic air ejector. These turbulence models' outputs were compared. The best predictors of flow behavior and centreline pressure recovery were k-epsilon RNG and k-omega SST [93]. They utilized two turbulence models to perform a CFD analysis on a supersonic air ejector (k-epsilon standard and k-omega SST). The k-epsilon standard is more accurate than the k-omega SST in terms of results. They also claimed that the k-epsilon standard and k-omega SST show close agreement in findings with global performance parameters for local flow parameters [94].

They utilized a pair of turbulence models in a CFD analysis for a steam ejector, k-epsilon realizable, and k-omega SST. The k-omega SST model outperforms the others regarding entrainment ratio and essential operating conditions. k-Epsilon realizable results demonstrate good agreement with experimental data [13]. Considered a real fluid (R134a) technique to explore the impact of multiple turbulence models (k-epsilon standard, k-epsilon realizable, k-epsilon RNG, k-omega SST) on the performance of an ejector. The turbulence model k-omega SST predicts slightly higher velocity in the mixing region than previous turbulence models [95]. A numerical analysis performed to assess the performance of a supersonic 3-D ejector model and the turbulence model. The k-epsilon standard, k-epsilon realizable, k-omega SST, and RSM turbulence models were employed in this investigation. According to the author, all turbulence models forecast promising on-design results, while the k-omega SST and RSM have the lowest off-design performance [88].

They compared the numerical study of the turbulence model [96] influence to the experimental benchmark [97].

This study compared the performance of four turbulence models (k-epsilon standard, k-epsilon realizable, k-epsilon RNG, and k-omega SST), with the k-epsilon standard coming out on top in terms of entrainment prediction. To examine the performance of the steam ejector benchmark published [23, 98] used a k-epsilon standard, k-epsilon realizable, k-epsilon RNG, k-omega standard, k-omega SST, and transition SST. SST had the best outcomes out of all the studied model transitions. Furthermore, the k-omega standard has a low agreement with experimental data, whereas others have a higher agreement on design performance. Additional investigations [88, 97, 99] have shown that SST k-omega better representation of their case studies across diverse situations and fluid conditions. The details of CFD studies are presented in Table 2.

4.2 Computational mesh

The numerical study must carefully choose various parameters to accurately forecast results with the least error and computing cost. Grid selection must always be carefully considered to balance computational cost and simulation quality [4, 104–106]. Grid refinement is an essential stage in the computational domain to forecast the intense interaction of primary and secondary flow, shocks, and boundary layer separation [107–113]. In the mixing and shock region, a high gradient mesh has been used adjacent to walls or zones of the shear layer [31, 34, 114, 115]. For automatic adjustment, specific criteria were used [17, 28, 93, 116, 117]. A quadrilateral mesh is best for the 2-D model since it is easy to maintain over the full domain. These mesh types allow for improved mesh-to-flow direction matching [118].

4.3 Ejector system irreversibility

Several researchers identified the major causes of ejector system losses to thermodynamic irreversibility. As a result, the causes of loss within each process must be quantified to enhance the ejector design. Normal and oblique shock wave losses, interaction loss between primary and secondary flow inside the mixing section, and kinetic energy losses are the primary contributors to irreversibility [7]. They offered an ejector study based on the entropy production approach, claiming that the entropy production is similar to the performance losses within the ejector system. As a result, it can be used to assess the ejector's performance [119]. They performed a CFD analysis of ejector flow irreversibility using R744 as the working fluid. A novel technique was presented to measure the local irreversibility of overall entropy increases. They also discovered that the mixer mass flux has a global impact on the ejector's performance [120]. They proposed a polytropic efficiency technique to build an

Table 2 Computational Fluid Dynamics (CFD) ejector studies

Refs	Design approach	Turbulence model	Concluding remarks
Subramanian et al. [50]	CMRC/CPM	Standard k-ε	Studied with and without blower numerically and experimentally
Cai et al. [51]	CAM	k-w turbulence	Ejector geometry is more compatible with real fluid as compared with an ideal fluid
Ji et al. [28]	CPM and CAM	k-ε model	Effect of geometry and operating pressure on flow structure studied
Chen et al. [68]	CPM	SST k-omega	Production of low-pressure natural gas can be improve by utilizing TSE system
Xue et al. [70]	CPM	Realizable k-ε	Performance of desalination system can be improve with TSE system
Wang et al. [72]	CPM	RNG k-ε	Area ratio observed as design parameters to achieve subzero refrigeration effect
Chandra et al. [100]	CRMC	Realizable k–e	The pressure lift ratio was reported to increase by up to 40% when utilizing a variable area ejector. This is the result of the ejector's removal of shock phenomena
Maghsoodi et al. [73]	CPM and CAM	RNG k-ε	A modification in the length of the mixing tube can alter the entrainment ratio by up to 27%
Suvarnakuta et al. [101]	TSE	SST k-w turbulence model	Observed 0.77. entrainment ratio with TSE design
Bartosiewicz et al. [93]	SSE	k-epsilon RNG and k-omega SST	Agreed with experimental results
Del et al. [95]	SSE	k-omega SST	Revealed better results as compared with other turbulence model in terms of Higher velocity,
Kumar et al. [9]	CRMC/CPM	k-ε model	Observed better synchronization with experimental results
Kumar et al. [43]	CKREC/CPM	k-ε model	Utilized CRKEC approach to design high performance ejector
Zhang et al. [102]	CRMC/CPM	k-ε model	0.59 entrainment ratio observed with CRMC technique
Rao et al. [103]	CAM	k-omega SST	Ejector operating with a low ratio of entrainment

ejector model. The influence of polytropic efficiency on ejector dimension and mixing efficiency was investigated, and it was discovered that as mixing efficiency falls, overall exergy losses increase linearly [121].

A novel theoretical model (actual gas characteristic) of the ejector was proposed [122], which was analyses the impact of internal irreversibility on the ejector's performance. The system's performance was assessed using the entrainment ratio, ejector efficiency, and exit back pressure metrics. They claim that the irreversibility effect of primary flow in the C-D nozzle and secondary flow expansion in the suction chamber significantly impact the entrainment ratio. In contrast, the mixing and diffuser section has a minor impact. As a design criterion, they looked into the effect of ejector geometry on the entropy generation rate. They suggested that the throat diameter of the convergent-divergent nozzle is more effective than the other geometrical parameters that determine entropy [123]. Previous studies [124–132] attempted to account for the losses by adding consistent isentropic efficiencies for various ejector elements, such as the primary nozzle, mixing, and diffuser. In several studies [23, 57, 124, 131, 133], the coefficient of friction was also used to account for the loss owing to wall friction.

5 Effect of working fluids

Selecting a working fluid is also critical when designing an ejector in terms of operation and performance. Aside from thermodynamic factors, the working fluid should be environmentally benign, non-hazardous, readily available, and inexpensive, with performance being the essential factor. For a long time, researchers [134–136] have employed air and water as working fluids and a blend of synthetic refrigerants from other groups (CFC, HCFC, and HFC). They investigated the influence of several refrigerants (CFCs, HCFCs, HFCs, RC318, R500, and water) on the performance of the traditional ejector cycle under identical operating conditions [137]. To select the best refrigerant, the coefficient of performance was used. R152 was discovered to have the best performance, according to them. Other studies [138, 139] looked at the performance of azeotropic and zeotropic mixtures, which combine two or more pure refrigerants in varying amounts. Selvaraju and Mani [133, 140] categorized different refrigerants (R134a, R152a, R290, R600a, and R717) based on COP and entrainment, claiming that R134a performs better than the others. They conducted a more recent study on working fluid selection (R236ea, R123, R245fa, R365mfc, and R141b) using a combined cycle of organic Rankine and ejector heat pump. R236ea was recommended as a better-working fluid for similar type coupled cycles [141].

6 Two-stage design based ejector

With the conversion of a single-stage ejector (SSE) to a two-stage ejector, a new era of ejector design begins. In this situation, the second entrained stream exits the mixing section for better discharging flow surplus momentum usage at the end of the first-stage ejector's mixing. One motive stream intake and two induced fluid inlets usually are present in the system. The first-stage ejector's combined (motive and first-induced) flow accelerates the second-induced fluid [101]. A two-stage ejector model was numerically explored for refrigeration purposes, and it was discovered that improving operational parameters might improve ejector performance [142]. Chemical laser [143] used a TSE-based pressure recovery mechanism. In the application of venture scribers, the performance of single and two-stage ejectors was investigated. According to the research, mounting the second-stage ejector aids in pollution removal and absorption efficiency [144]. On the other hand, the TSE cooling system for buses provided better performance with lower fuel usage than the SSE system [145]. According to this research, TSE could be preferable for vapor-compression refrigeration. For low-induced pressure, a lower area ratio of TSE performs better than a larger area ratio [68].

The TSE system performed significantly better than the SSE system in this investigation. The geometry of the two-stage ejector is optimized and numerically analyzed using various turbulence models. The impetus performance of two-stage ejectors was four times that of single-stage ejectors [78, 146, 147]. Testing the ejector system with dual by-pass inlets post-mixing section exit revealed superior performance of the two by-pass inlet ejector over the original one [69]. Optimization and validation of a two-stage vacuum ejector system for multi-effect distillation, involving seven models, were conducted using CFD and experimental methods [70]. Published data from researchers highlight the advantageous impact of the two-stage ejector model on system performance across various applications [71, 72, 148–153]. The main objective is to ensure that the two-stage ejector runs steadily and consistently throughout a wide range of primary flow pressures. The entrainment ratio of the two-stage ejector is 79.4% higher than that of the conventional single-stage ejector [154]. This study investigated the impact of the radius of the equal-area mixing chamber on the lowest pressure within the chamber and the two-stage diffuser using the three-dimensional numerical simulation approach. After that, it is discovered that the auxiliary entraining effect depends on the minimum pressure [155]. The performance analysis of a two-stage ejector refrigeration system with R1234yf refrigerant is presented in this research. The performance

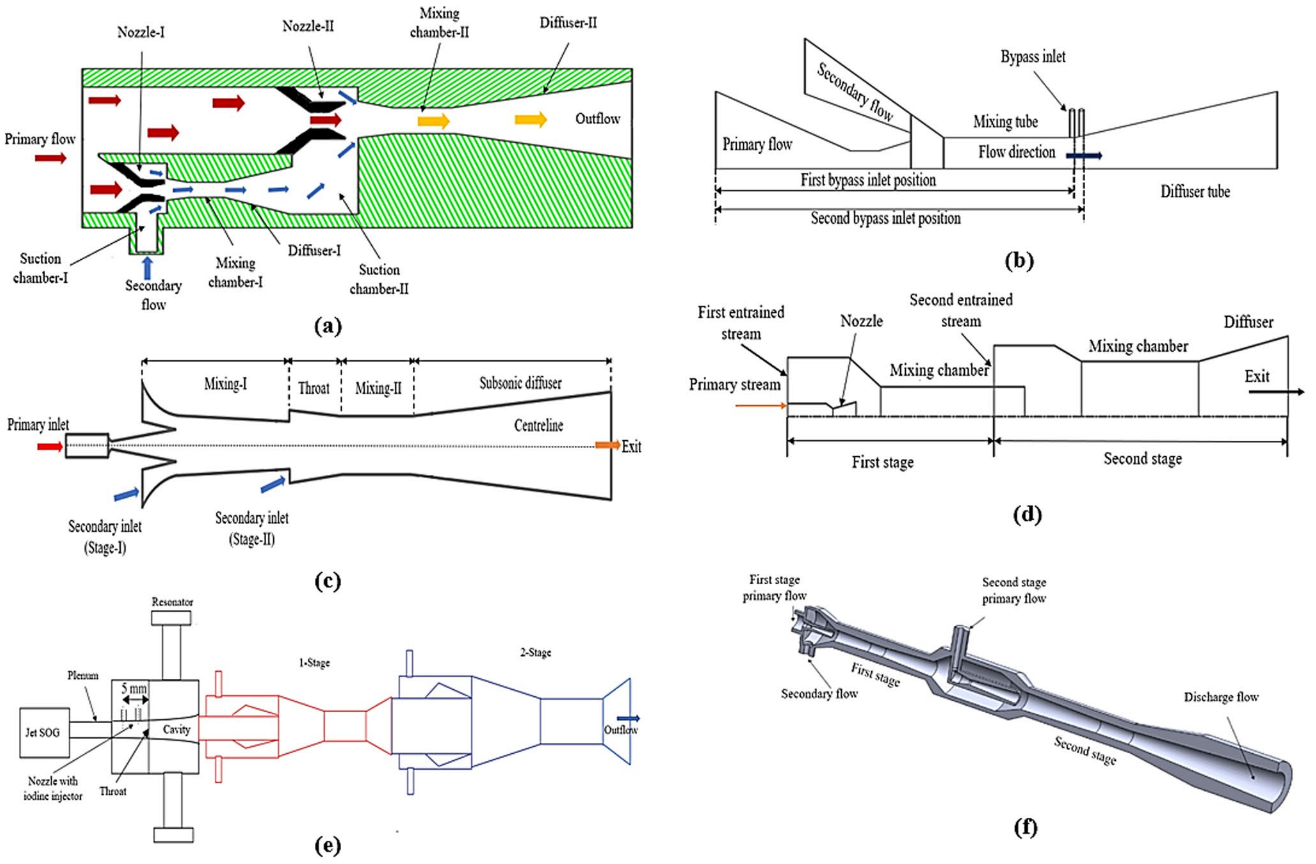

Fig. 9 Two-stage geometry **a** Schematic of TSE [142], **b** TSE with by-pass [69], **c** TSE domain [101], **d** two-stage ejector system [146] **e** coil-based TSE [143], **f** cross-section view of two-stage ejector [70]

of the system is examined in relation to various operating conditions in this article [156]. Figure 9 shows the resent development in ejector technology.

7 Recent advancement in ejector technology

Conventional ejectors design has typically centered around CAM and CPM consideration. The occurrence of shock series inside the constant area and at the inlet of the diffuser section is the primary concern with this type of ejector design. It was the primary cause of the drop in overall pressure. Shocks should be eliminated or minimized while designing a high-performance ejector. Many scholars in the literature believe that the ejector system's performance could be improved by avoiding constant area zones. The constant area ejector's performance can be significantly affected by changes in operating conditions, and optimum performance can only be reached for a limited set of working parameters. A slight change in the operating state can cause the ejector's performance to deteriorate significantly. Studied fixed geometry ejectors theoretically and empirically. They claimed that the system's cooling capacity depends on operating conditions within a specific range [8]. In another investigation, the influence of ejector geometry on performance was examined through a combination of theoretical and experimental research [157]. The finding indicates that the fixed geometry ejectors function well under on-design conditions, while the performance parameters of variable geometry ejectors change gradually, whereas a dramatic decline has been seen with fixed geometry ejectors. Additionally, there has been an examination a variable area geometry ejector employing air as the working fluid. This innovative approach utilized a movable cone cylinder to modify the conventional ejector's throat area ratio, behaving like a variable area ejector. However, it is worth noting that this type of ejector is plagued by significant pressure losses [158].

In an experimental investigation, the impact of a movable spindle within a primary nozzle on steam ejector refrigeration systems was examined. This spindle was utilized to regulate the flow rate of the nozzle. This study revealed that as the spindle position gets closer to the nozzle throat, the primary flow rate decreases, resulting in less cooling capacity and a large increase in critical back pressure [159]. Consequently, the ejector system was able to withstand higher condenser pressure. To explore the effects of varying geometry of ejectors in cold storage applications, computational techniques were employed. Solar energy was used as a power source for testing the ejector performance. The results revealed that the variable geometry ejector outperformed the fixed geometry ejector by 8–13% in terms of efficiency. This improvement was achieved by employing interchangeable primary nozzle outlets to enhance the mixing of primary and secondary flow by extending the nozzle's exit perimeter [160]. A variable geometry ejector mechanism of the ejector system was studied numerically. In comparison with a conventional ejector, an increase of 8.23% in entrainment ratio was observed [161]. Furthermore, this study introduced and investigated the CRMC approach for steam ejectors for the first time. The experimental results revealed that a slight alteration in the exit pressure to secondary pressure had a significant impact on the entrainment ratio [162].

Eames proposed a new theory, constant rate of momentum change (CRMC), to design an ejector diffuser with a continuous variable cross-sectional area [8]. This theory replaced the ejector's conventional design (CAM and CPM) with the CRMC ejector. This theory eliminates the pressure losses caused by shock compression of mixed flow in the baseline ejector. The flow's momentum must change at a constant rate as it moves downstream of the ejector. The shocks inside the mixing section get eliminated and thus conserved more pressure and converted into actual static pressure. Seehanam utilized the methodology proposed by Eames [8] to conduct a numerical analysis of CRMC ejectors to evaluate flow behavior and performance [163]. The findings of the CRMC ejector were numerically compared to the results of the constant pressure mixing (CPM) ejector. The CRMC ejector's centreline velocity covers a longer distance along with the ejector than the CPM ejector. It is also worth noting that the CPM ejector's velocity shift is more gradual than the CRMC ejectors. As a result, the ejector in CRMC theory has a constant velocity gradient.

Investigated the influence of primary nozzle geometry and nozzle exit position on the CRMC refrigeration ejector system under various operating conditions. These variables, they claimed, have a significant impact on the ejector's performance [164]. They conducted an experimental comparison of the CPM (traditional) and CRMC ejectors. This study considers boiler temperatures of less than 1250^0C and evaporator temperatures of less than 150^0C. They claimed that a CRMC ejector boosted the pressure lift ratio by up to 40% compared to a CPM (traditional) ejector [100]. A modified CRMC approach proposed for designing the supersonic ejector, which was computationally and experimentally evaluated. A frictional effect was considered inside the cross-sectional area of the ejector. The study revealed that numerical results were in close agreement with experimental results at double choking mode [9].

The conventional and CRMC ejectors using air as a working fluid under the same operating circumstances were investigated computationally and experimentally [165]. CRMC ejector simulation results were compared to conventional CFD findings. They found a 15% increase in overall pressure compared to standard ejectors, which they attribute to the principal shock flow structure rather than an improvement in the compression process within the diffuser. A comparative study of CRMC and conventional ejectors was performed experimentally and observed that CRMC ejectors have a higher entrainment ratio of around (37%- 40%) than conventional ejectors, with a slight variation in back pressure [166]. Recently they improved the CRMC ejector prototype by adding a conical zone in front of the mixing section. The design of the ejector was based on real-world fluid qualities, including friction. According to tests, CRMC ejectors have a 20% higher back pressure than conventional ejectors [102]. An innovative ejector design for refrigeration with a high entrainment ratio and COP is presented. A numerical analysis of the ejector's performance is also presented [167]. Considering the growing demand for heating, high-efficiency heating in combined heat and power (CHP) systems is thought to be a realistic approach to reduce emissions and save energy [168]. This paper uses an adaptive differential evolution technique to optimize a hybrid ejector-vapor compression refrigeration system. The technique is applied to maximize the system's performance in various operating scenarios [169]. An experimental investigation into the operation of a supersonic ejector with various mixing sections is presented in this work. The effectiveness of the ejector is examined in relation to the geometry of the mixing section [170]. Figure 10 represents the novel design of the ejector system.

8 Recent application of ejectors

An ejector is a stationary device used for fluid and gas transfer, mixing, and compression, employing a gaseous or liquid media as the principal force. As a result, the ejector had many applications in recent domains [171]. Figure 11 depicts some of the most critical applications in various fields. It works by using convergent-divergent nozzles to convert pressure energy into velocity. Other names include vacuum pumps, thrust augmenters, and jet pumps. The steam jet pump removes air from the turbine condenser and refrigeration system by creating a vacuum. Thermo-compressors are widely employed in industries like food processing, paper making, and petrochemicals to elevate low-pressure fluids to a reusable intermediate pressure using surplus steam. Similarly, jet engines produce thrust by expelling fluid at a pressure higher than the surroundings through an exhaust nozzle to enhance thrust.

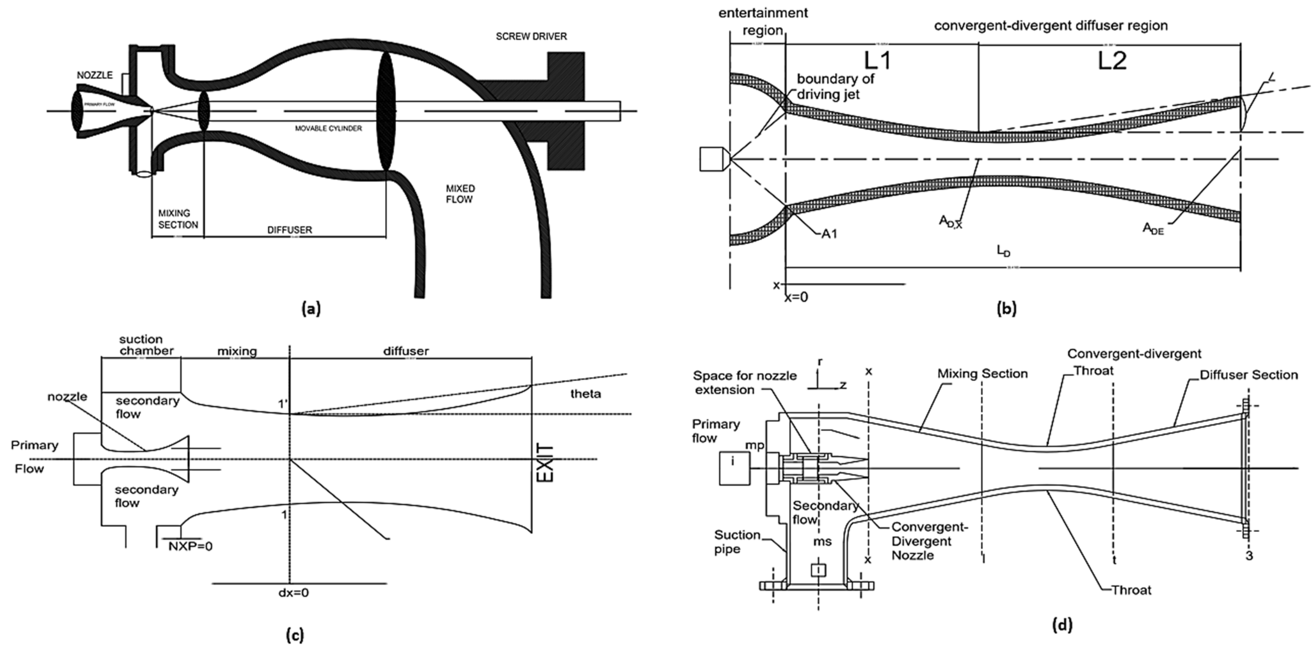

Fig. 10 Geometry of **a** variable area ejector [158], **b** CRMC jet pump [8], **c** CRMC variable area ejector, [9] **d** jet pump with C-D throat [162]

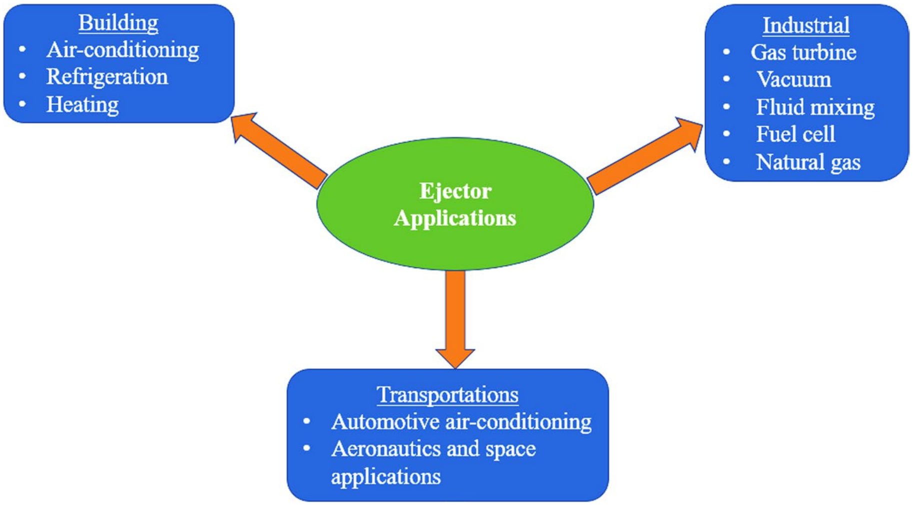

Fig. 11 Ejectors different fields of applications

For the past two decades, efficient ejector systems have been in great demand for refrigeration and air-conditioning systems. As a result, steam and low-boiling refrigerants have favored jet-pump refrigeration. A supersonic jet pump compresses and pumps the working fluid from the evaporator to the condenser through the primary fluid in a refrigeration system.

8.1 Air-conditioning, refrigeration, and heating

This system's main objective is the suction of secondary flow. Entrainment and mass flow rate of secondary fluid drawn into the ejector and compression are the major performance requirements [34, 172]. It functions as a heat rejection mechanism by extracting refrigerant vapor from the evaporator or flash chamber and compressing it in the condenser. Most researchers have emphasized ejector air-conditioning research [20, 134, 173–177]. The prototype model was erected and tested [178] in a building office. Recently they constructed and tested a prototype ERS system in a laboratory with a capacity of 4.5KW with R141b as the working fluid for hot climate conditions [179].

8.2 Air-conditioning in automotive

One of the current study areas where ejectors can be used is in automotive vehicles air-conditioning. The I.C. engine consumes up to 17% of its fuel energy owing to heat dissipation in this situation. The radiator coolant temperature was around 80 °C, which is adequate to operate an ejector for air-conditioning in automobiles. Many scholars [145, 180–182] conducted and proposed experiments on heat recovery from the radiator to power the supersonic ejector in automobiles.

8.3 Aeronautics and space applications

Several applications in this field have been documented in the existing literature. These application have been utilized to enhance the power output of the propulsion engine, enssure through mixing, and dissipate heat from the oil radiator [183–185]. In the past two decades, researchers have undertaken numerous experimental and numerical investigations focused on reducing noise levels in high-speed civil aircraft, particularly through the concept of a mixer-ejector. One such investigation involved the development of a numerical model for a 2-D ejector nozzle to investigate the ejector's complex flow characteristics. Their finding indicates that secondary flow pumping is a function of the area ratio [186]. A similar investigation was carried out to design an exhaust ejector for infrared signature suppression [187]. This ejector induced a vacuum effect [107, 188–190]. An ejector was employed in aeronautical engineering to create a vacuum in the test chamber to examine the impact of the propulsion system at high altitudes [116]. Furthermore, another study focused on the optimization of the shape of a supersonic ejector for use in supersonic wind tunnel propulsion using a computer modeling technique. In this study, multiple nozzles are positioned at the mixing section inlet to improve the ejector system performance [181].

8.4 Vacuum creation

To create a vacuum effect, the ejector system's secondary flow is reduced or blocked. The nozzle jets generate a suction zone at the intake of the mixing section in this example [191, 192]. It is also a vacuum augmentation device employed in railway vacuum braking systems and turbine condensing plants for a long time [118]. Ejectors are used in the petrochemical industry to keep the vacuum in chemical reactors and distillation columns. To obtain low pressure, the ejectors can be connected in series.

8.5 Performance enhancement of gas turbine

The ejector was used to improve the performance of the gas turbine in a similar way to how it was used to improve the automobile performance. This example used flue gases as the motive flow to trigger the supersonic ejector. Before feeding the compressor, it cooled the input air. It claimed that lowering the input air temperature by 10 °C enhanced the system's output by roughly 0.7% [193] and increased the gas turbines total efficiency by 15% [194]. Because of their adaptability, they mix and separate various fluids in the chemical industry. [195, 196].

An ejector could be a suitable replacement for pumping recovery devices of hydrogen because there is no moving part. Such replacement, no electricity required as a pumping device, and it also helps to improve the performance [73, 74, 103, 197, 198].

It is also a significant energy-saving device by substituting compressors in natural gas transit through the pipeline. The ejectors use high-pressure gas as a motive force to help boost the low-pressure gas [199]. Natural gas can also activate it, which raises waste gas pressure and lowers explosive chemical concentrations [200]. Desalination plants use solar-activated ejectors to recompress water vapor before condensation to produce distilled water [63, 201–205].

8.6 Refrigeration and air-conditioning

The ejector arrangement heavily influences the performance of the steam jet ejector refrigeration system. Various studies have been carried out to investigate flow dynamics inside the ejector and improve performance by improving the ejectors' geometrical and operating parameters [206–213]. They studied the influence of various refrigerants (R11, R12, R13, R21, R123, R142a, R134a, R152a, RC318, R500, and water) on the ejector refrigeration cycle. In terms of global performance criteria, such as entrainment ratio and COP, it was discovered that the R12 produces better results. Adopting a refrigerant with a high latent heat was also proposed to improve the system's efficiency. The effect of methanol on a steam jet refrigeration system with a temperature range of 110–130 °C was investigated in analytical research [214]. It was discovered that as the generator pressure rises, the system's cop reduces. Another study on transcritical ejector refrigeration systems using several refrigerants (CO_2, R1270, R32, R143a, R125, and R115) found that refrigerant R1270 performs better throughout a medium operating pressure range [205]. A solar-assisted absorption cooling system with LiBr-H2o as the working fluid was explored and compared to a standard one. They discovered that a system with a lower condenser temperature and a higher evaporator temperature performs better [215]. The solar jet refrigeration system was numerically investigated using low environmental impact refrigerants (R1234yf, R1234ze, and R600a), with the R1234yf and R600a providing better results. R1234ze was employed for collector sensitivity analysis simultaneously [216].

A numerical analysis was undertaken on a transcritical refrigeration system using R744 as the working fluid. Geometrical optimization was used to evaluate the system's performance. According to the author, the transcritical refrigeration system with parallel compression is superior to traditional parallel compression [217]. A solar-driven subcritical and transcritical ejector refrigeration system analyze experimentally and numerically [218]. In this study, the refrigerant R32 was used as a working fluid, and the performance of the ejector system was evaluated under various operating situations. Compared with the subcritical ejector system, the transcritical ejector system showed a better higher-pressure lift ratio. They developed a cooling/power cogeneration ejector refrigeration (CPC-ER) model combining CER with the organic Rankine cycle. Using isobutane refrigerant as a working fluid, the system's performance was evaluated in exergy and energy. The CPC-ER system has a higher COP than the CER system, ranging from 41 to 71% [219].

A simple ejector refrigeration cycle was used for the cascade refrigeration system and examined experimentally and conceptually [75]. The system was tested under diverse operating conditions and high evaporation temperatures. A CFD study was conducted to assess the performance and operational flexibility of two-stage ejectors in the refrigeration system. The performance of the TSE was evaluated using the temperature of the generator and evaporator. With a modest drop-in critical backpressure, TSE was found to have a greater entrainment ratio [101]. A numerical study was conducted to explore the effect of ejector geometry on the performance of the ejector system, with water vapor as the working fluid. They discovered that as the entrainment ratio increased, the rate of entropy formation decreased, and COP occurred [220]. They designed and numerically studied a two-stage ejector with two single-stage ejectors [76]. The effect of geometrical parameters on the performance of the two-stage ejector was investigated, and it was discovered that there is an optimum geometry for the system's best performance. Theoretically, a two-stage ejector based on an expansion transcritical refrigeration cycle was studied. The working fluids in this experiment were ethanol and CO_2. When ethanol refrigerant was used as the working fluid, the COP and second law efficiency increased from 9.37 to 9.47% [221] compared to CO_2 refrigerants. The ejector refrigeration system was constructed using the equivalent temperature approach [222]. The analysis was carried out in this investigation without regard to the working fluid.

Experiments were conducted to determine the effect of the area ratio on the performance of the ejector refrigeration system. As a working fluid, R141 refrigerant was employed. It has been proposed that there are two crucial evaporator temperatures: lower and higher critical evaporator temperatures. Mach number and primary fluid mass flow rate were also essential factors in the ejector's performance [223]. A computer study was conducted on auto-tuning NXP and area ratio ejectors for performance examination under various operating situations. The optimal area ratio grows as primary flow pressure increases, but NXP decreases as primary pressure increases [224]. The performance of the ejector refrigeration system was tested using R134a refrigerant as the working fluid. Exit back pressure was found to affect system performance substantially[225]. The horizontal axis tidal turbine's (HATT) power coefficient is fixed at 0.593 by the Betz constraint. Nevertheless, the addition of a diffuser or lobe ejector can increase the turbine's efficiency. In this study. At various tip speed ratios (TSR), the power and thrust coefficients of the original turbine and the turbine with a lobe ejector have been calculated. [226]. Additionally, this research presents a new design for a high-performance ejector for refrigeration applications. The design focuses on achieving a high entrainment ratio and high coefficient of performance (COP). The report also includes a numerical analysis of the ejector's performance [227].

9 Summary and future recommendation

This study provides a literature survey of research on ejector systems, structured into seven parts. The first part summarizes an ejector design approach, while the second and third parts examine the geometrical and operating effects on the ejector's performance. The study focuses on key factors such as entrainment ratio, pressure lift ratio, and flow behavior. The review covers various geometrical parameters such as the convergence angle of the mixing section, divergence section of the diffuser section, length of the nozzle, nozzle exit position and area ratio. The fourth part of this study is dedicated to reviewing computational studies, including a selection of turbulence models and independent grid tests to investigate the inside flow behavior of the ejectors. The fifth part reviews the effect of different working fluids on the system's performance, as well as presenting an experimental review. The sixth part focuses on novel ejector designs, such as two-stage or auxiliary entrainment ejectors. Although much research has been done on ejectors and their applications in various industries, further work is needed to overcome research gaps.

- The ejector's design underwent extensive research to improve performance and reduce losses. Recently, a researcher proposed a CRMC and CRKEC physics-based approach, which utilizes the mixed fluid's momentum to increase entrainment and optimize performance.
- The combined effect of CRMC and CRKEC approaches must be explored because fluid flows affect both momentum and kinetic energy together.

- Further research is needed to determine the ideal length of the nozzle, mixing, and diffuser sections for a range of design and operating conditions. It is also necessary to study and modify the geometrical profile in order to reduce mixing losses. Additionally, the design and impact of suction chamber geometry and profile must be investigated.
- CFD studies in the ejector field by considering in transient state have been observed limited. The conventional method is also needed to study computationally because multiple primary nozzle and cascade refrigeration studies have not yet been performed.
- A new design concept for ejectors involves modifications to the geometry of the ejector. This modification creates a secondary inlet at the exit of the mixing section, which allows for the entrainment of a secondary fluid, resulting in a two-stage ejector system. In some research articles, the exit pressure of a single-stage ejector was used to entrain secondary fluid in another single-stage ejector, but this approach resulted in a bulky and heavy system.

It has been observed that the refrigeration area is the most suitable place where the ejector can work effectively. Recently, several papers have been published on the application of the ejector in the field of hydrogen refueling. Researchers are exploring the use of an ejector system in rocket engines due to their simple construction and the fact that they do not require any power to operate.

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