Ejectors on the cutting edge: the past, the present and the perspective

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Abstract

The applications of ejectors are many and encompass the refrigeration, the power generation and the chemical sectors. On one hand, ejector technology needs limited maintenance, has low operational costs and has no restrictions concerning the working fluids; on the other hand, the complex single- and multi-phase fluid dynamics make ejector design and performance prediction a real challenge. This perspective explores the main advancements in ejector technology and proposes a critical discussion with an outlook for the future research; the proposed discussion is grounded on the multi-scale relationship between the "*local-scale*" phenomena and the "*component-scale*" performances. After a look at the past, this perspective examines the ongoing research activities and achievements regarding four state-of-the-art research areas, namely refrigeration systems, power conversion plants, chemical process and technology and computational methods. For the different research areas discussed, directions and opportunities for the future research activities are appraised. Finally, this perspective defines a fundamental challenge that needs be addressed in the forthcoming long-term activities: "*the multi-scale ejector challenge*"

Keywords. Ejector technology; Refrigeration systems; Power conversion systems; Chemical processes; Modeling approaches; Multi-scale ejector challenge

1 The past: an introduction

An ejector provides a threefold effect (namely, pressure lift, mixing and entrainment), it needs limited maintenance, has low costs and no constrains regarding the working fluids. Owing to these advantages, ejector technology is very attractive for many applications and the interest of the scientific community towards this component has exponentially increased during recent years. For example, its use to exploit solar energy and to retrofit gas heating systems, is of practical interest to reduce the primary energy consumption at the household-scale, thus supporting decarbonisation pathways. Unfortunately, ejectors are characterized by complicate single- and multi-phase fluid dynamics at the "*local-scale*", which determines the behavior at the "*component-scale*" and, in turn, the performances characterizing the "*system-scale*". In the past decades, lumped parameter and computational fluid dynamic (*CFD*) models were designed and applied to support designing, building and testing prototypes. Thanks to these research activities, some design criteria and concepts are nowadays well assessed, i.e., the shape of ejector operating curve. Unfortunately, the complex relationships between the fluid dynamic at the "*local-scale*" and the ejector design are not completely understood, thus making a rational-based description of the "*component-scale*" a challenge. Besagni et al. [1] proposed a comprehensive review of ejector performances and applications, collecting "*the past*" research activities. This perspective completes the previous literature survey, describing "*the present*" achievements and offering a glance towards "*the future*" research directions in the medium- and in the long-term future. In particular, this perspective defines a fundamental challenge that needs be addressed in all the forthcoming long-term activities: "*the multi-scale ejector challenge*".

2 The present: ongoing research activities and achievements

Herein, four state-of-the-art research areas are presented and, for the different topics, promising directions for future activities will be examined in the next sections.

2.1 Current achievements in ejector-based refrigeration systems

Ejectors reduce throttling losses, liquid overfeeding and lift the suction pressure of refrigeration cycles, thus decreasing the compression work. As the classification of ejector refrigeration systems (*ERSs*) was proposed by Besagni et al. [1], this section aims to discuss the ongoing achievements. Current achievements in *ERSs* research concerns the "*component-scale*" or the "*system-scale*"; on one hand, the "*component-scale*" research investigates design criteria and methods for ejectors and non-ejector components; on the other hand, the "*system-scale*" research models and tests novel *ERSs*.

The study of non-ejector components is a raising topic of research and two areas are identified: oil recirculation and evaporator design criteria. The former was addressed by Zhu et al. [2], who mentioned that a precise description of oil circulation is needed to avoid the reduction of performance and the compressor reliability. The latter was discussed by Lawrence and Elbel [3], who proposed a "*pressure drops/heat transfer model*" evaporator model and, subsequently, applied it to different cycle configurations and refrigerants (R134a, ammonia). As the coupling between system the operating conditions and the ejector design determines the "*system-scale*" performances, a large number of studies focused on ejector design criteria. For example, Poirier et al. [4] experimentally observed (steam ejector) that, for given boundary conditions, the optimal outlet pressure can be imposed by an appropriate geometry; they also obtained ejector operating curves and performance maps for a wide range of boundary conditions. It follows that, to keep the entrainment ratio at high level, variable-geometry technologies should be applied. This concept is well-known and different solutions were proposed so far, i.e., vortex [5], sub-cooling [6] or variable-geometry [7] control systems. Despite these methods extended the operating range, a comprehensive regulation strategy is far from being achieved and an a-priori knowledge of the "*local-scale*" is needed. A work pointing towards this direction has been presented by Wang et al. [8], proposing an "*auto-tuning area-ratio/nozzle-exit-position*" concept to adjust the ejector design based on the fluid dynamics imposed by the boundary conditions. In this respect, the relationships between the ejector design and the fluid dynamics imposed by the boundary conditions was discussed by Xiaodong et al. [9] and Han et al. [10], who examined the relationship between the boundary layer separation, shock wave formation and the decay of performance, depending on the ejector design (i.e., throat diameter and the nozzle-exit-position). Future studies may extend the auto-tuning concept by taking into account the suction chamber shape and mixing zone and their integration with the primary nozzle position and shape. To this end, the numerical/experimental study proposed by Ramesh and Sekhar [11] (suction chamber angle, nozzle exit position) and the numerical study proposed by Metin et al. [12] (nozzle exit position and converging angle of the mixing section) may provide an assessment regarding the effects of these geometrical parameters on the "*local-scale*" and "*component-scale*". These studies support the above-mentioned findings of Poirier et al. [4]. Generally, there is an increasing awareness that the relationships between ejector design operations can be understood by linking the "*local-scale*" to the "*component-scale*". An example of such multi-scale approach is proposed by Haghparast et al. [13] who described an experimental/numerical study to study the local exergy losses for different operating conditions: the highest exergy losses are located in the mixing chamber and in the primary nozzle, thus supporting the need auto-tuning ejector systems.

Another research line concerns the experimental/numerical study of novel *ERSs*. One of the most promising and challenging application concerns ejectors in CO_2 commercial refrigeration. The use of ejector in CO_2 systems is widely recognized as attractive, as demonstrated in the successful proposal of Elbel and Hrnjak [14] (viz., ejector was applied to reduce throttling losses in transcritical CO_2 systems). Since this proposal, a large number of papers studies different system layouts and, at present, the state-of-the-art activities aim demonstrating the practical feasibility of ejector-based systems at different climatic conditions. For example, Purohit et al. [15] and Gullo et al. [16] compared different system layouts and found that the multi-ejector one is a promising solutions for "*warm-climates*" compared with other commercial solutions. CO_2 ejectors systems can be also applied to improve the performances of high-temperature heat pumps, so to retrofit existing heating systems; for example, Bodys et al. [17] demonstrated that, owing to a proper system design, the cooling capacity can be ensured without additional compressor. Besides CO_2 applications, ejectors are considered to exploit solar-energy in households. Li et al. [18] analytically studied a solar-based ejector-cascade heat pump (coupling a R134a, R1234yf, R141b ejector cycle with a R1234yf vapor compression system); Khaliq et al. [19] analytically studied the integration of a solar-based organic rankine cycle (R141b, R600a, R290, R717, R143a) with a NH_3-$LiNO_3$ ejector-absorption cycle. Yilmaz et al. [20] proposed a screening of refrigerants (R134a, R1234yf, R245fa, R290, R32, R717, R600a) to assess the performance of a novel *ERS* with a subcooling. Despite above-mentioned references proposed just a simple view regarding ongoing activities, it is clear that the use of low-*GWP* refrigerants in ejector systems is a matter of intense discussion. Both the exploitation of the solar energy and the retrofitting of gas heating systems, help reducing the primary energy consumption at the household-scale to support decarbonisation pathways. Despite above technical solutions are interesting, field studies are needed to verify the feasibility of these solutions in large-scale applications and in field tests, with a particular attention on the relationships between all the different scales characterizing the system. Thongtip and Aphornratana [21] simulated, designed, built, and tested an R141b *ERS* for "*warm-climates*"; the proposed multi-scale approach may be considered by future researchers too. Another line of research concerns low-temperature systems where auto-cascade systems are a promising layout. Bai et al. [22] (R23/R134a) experimentally studied an ejector auto-cascade system and observed a shorter pull-down time and lower internal temperatures compared with a baseline system; Jeon et al. [23] (R600a) experimentally studied a domestic refrigerator-freezer coupled with a condenser-outlet-split ejector cycle; owing to the pressure lifting, the proposed system showed lower energy consumption compared with a baseline one.

Elakhdar et al. [24] (R290/R600a) theoretically studied an enhanced *VCR* refrigerators/freezers; the proposed system exhibits improved *COP* and cooling capacity compared with a baseline one. Similarly, Liu and Yu [25] (R290/R170) studied an ejector-expansion auto-cascade *ERS*, showing an increase of the COP and refrigeration capacity, compared with a baseline system. Another system layout to provide low-temperature was presented by Lee et al. [26], who theoretically studied an ejector Joule-Thomson system (nitrogen/neon) and built a prototype; they obtained a performance map of the system and proposed an exergy analysis, to relate the "*component-scale*" to the "*system-scale"*. Besides above-mentioned systems, other researchers are studying compression-ejection hybrid refrigeration system as presented by Zhao et al. [27] by Sun et al. [28].

2.2 **Current achievements in ejector-based systems in energy conversion plants**

Ejectors can be applied either to improve the efficiency of existing power conversion or to develop novel layouts. The applications are many and the most promising activities cover two areas: ejector-recirculation in fuel cells and ejector-assisted CO_2 cycles.

The use of ejectors in the anodic/cathodic fuel cell recirculation is attractive to replace compressor-based systems (e.g., owing to the limited issues at high temperature operation). Despite ejector advantages are widely accepted, there is no agreement regarding the design/control criteria and methods applied in *ERSs* are used in fuel cell recirculation. This issue is a main drawback as ejector highly influences the system performance, so that ad-hoc operation strategies and design procedures should be applied. In particular, Chen et al [29] studied suitable operation strategies; conversely, Ferrari et al [30] studied the design procedures. Chen et al [29] (anode/cathode ejector recirculation) studied different operation strategies for a hybrid solid oxide fuel cell-gas turbine: to ensure an appropriate operation strategy all the main system parameters should be adjusted to control the anode/cathode temperature difference and turbine inlet temperature. The regulation strategies rely on a precise modeling of ejector performances and, to this end, Ferrari et al [30] (anodic recirculation) presented a *CFD* model to predict ejector performances in a solid oxide fuel cell; the proposed approach was validated by experimental data and can be used to support the design and control of ejectors in fuel cell systems. It is worth noting that the use of an ejector in proton exchange membrane fuel cell need to consider gas management and water-control strategies. Beside the design of ejectors, research activities should focus on the whole system and, to this end, Yosaf and Pzcan [31] proposed technical/economic analysis of an integrated proton exchange membrane electrolyzer-absorption power cycle.

The use of CO_2 in power generation cycles is a cutting edge topic and it is attractive owing to its peculiar characteristics (i.e., physical properties making possible compact heat exchanger, the *p-T* relationship to exploit low-grade heat sources). Owing to the low critical temperature, CO_2 cycles cover sub-critical, trans-critical and supercritical conditions, making the use of ejectors attractive to reduce the exergy losses; unfortunately, this topic is still poorly addressed in the literature. Xia et al. [32] proposed an ejector-based transcritical CO_2 cycle, to exploit low-grade heat sources; a parametric analysis was performed to assess the effects of "*component-scale*" parameters on the "*system-scale*" performances. Palacz et al. [33] investigated the design criteria and performances of ejector for a supercritical Brayton CO_2 cycle, as a follow-up of Padilla et al. [34]. Palacz et al. [33] used a previously validated CFD code to verify if the design criteria of Padilla et al. [34] were adequate to meet the requested performances. It was found that that a significate re-design of the ejector should be conducted and, thus, they studied the influence of design parameters to propose a novel design. They also concluded that an ejector able to guarantee an extreme pressure lift, theoretically required by that system, and simultaneously guarantee an entrainment ratio approximately equal to almost 1 may be impossible to design. Owing to the p-T relationship of CO_2 the ejector operating conditions are likely characterized by high temperatures and, thus, the heat losses at the walls might not be negligible. To this end, Haida et al. [35] numerically and experimentally studied the influence of walls heat transfer of a CO_2 ejector on the ejector performances: the non-adiabatic inner walls degraded ejector performance (i.e., the mass entrainment ratio decreases up to 13%).

2.3 **Current achievements in ejector-based systems in chemical and process industries**

Ejectors can be applied to reduce the energy-intensity of chemical and process industries. Among the different applications, three macro-areas are considered: gas spargers in multiphase reactors, chemical processes, systems to exploit low-grade heat sources.

In multiphase reactors the gas sparger imposes the prevailing size distribution of the dispersed phase thus determining the prevailing flow regimes, given the system design (i.e., column diameter, gas sparger openings and aspect ratio) and the phase properties. Despite the qualitative effect of the gas sparger on the fluid dynamics is well assessed, the gas spargers design criteria are matter of intense discussions. Indeed, compared with other distributors, ejectors are less studied, even if promising to generate micro-bubble dispersions, thus increasing the interfacial area to obtain compact reactors. Some recent achievements were discussed by Seo et al. [36] and Park et al. [37]. The former investigated the local multi-phase fluid dynamics (i.e., bubble size and shapes, void fraction, bubble velocity and coalescence/break-up phenomena) and the latter investigated the mass transfer, proposing a novel correlation. Concerning chemical processes, ejectors can be applied in different plants and, in the following, a brief overview is proposed. Ashrafi et al. [38] applied ejector technology in the Selexol™ process to reduce the overall energy consumption. Tang et al. [39] studied an ejector-based desalination system, where the ejector is critical to determine the overall system performance. As mentioned in Section 2.1, ejector regulation is a matter of ongoing discussion and, for this application, Tang et al. [39] proposed a multi-scale *CFD*-based method to calibrate a pressure regulation method to weaken the shock wave, optimize the entrained flow passage and, thus, improve the system performance. Another application of ejectors concerns drying technologies and Zhang et al. [40] proposed a multi-stage ejector pump coupled with an absorption refrigerator, exhibiting better performances compared with a baseline system. Ejection devices can be used in foulant-water separations with hydrocyclones; their "*local- and component-scale*" behavior as well as the "*system-scale*" performances (i.e., removal efficiency) was studied by Tian et al. [41] (numerically) and by Song et al [42] (experimentally). To reduce the energy consumption related to liquids and gases pumping, Rogovyi [43] presented, by an experimental-numerical study, a vortex chamber supercharger. Besides above-mentioned applications, heat transfer enhancement is a matter of intense research as these systems are complex and their design requires the integration of many engineering disciplines. Wang et al. [44] experimentally studied an immersed spray cooling system integrated with an ejector, showing superior performances compared with the traditional methods. Finally, Shan et al. [45] proposed a numerical-experimental study to design a piccolo-tube multi-nozzles ejector to match the geometric feature of the air-cooled passage in an oil radiation.

Finally, ejectors can be applied to exploit low- and ultra-low-grade heat sources. For example, Hao et al. [46] coupled a hybrid auto-cascade system (R170/R600a) with an *ERS* to exploit high/low grade heat sources; compared with a baseline system, the proposed one reduces by 50 % the energy consumption. Mondal et al. [47] replaced the throttle valve in an organic flash cycle with an ejector, thus reducing the throttling losses; as a result, the performance of the system improved by the 9.5 % compared with a baseline system. In Section 2.3, the use of a transcritical CO_2 cycles have been described to exploit low-grade heat sources.

2.4 **Current achievements in analytical and computational methods**

On one hand, lumped parameter models (*LPM*s) are essential to predict ejector performance; on the other hand, *CFD* simulations help understanding the underlying fluid dynamics. Ongoing activities cover four directions: numerical closures, theoretical studies, design optimization methods, and multi-phase modeling.

A drawback of numerical models regards the closures: (i) *LPMs* require ejector component efficiencies, whose selection is a debated topic, and eventually including non-uniformity effects: these two topics should be addressed in the future to develop *LPMs* able to predict all the operating range of ejector operations; (ii) *CFD* simulations needs turbulence models and eventually multi-phase simulation strategies. Regarding turbulence modeling, there is a general agreement towards the *k-ω SST* model [11]; conversely, an agreement regarding multi-phase simulation strategies is not reached (see below). The difficulty in defining these closures arises from the lacks of knowledge concerning the "*local-scale*" phenomena and high-resolution data are needed in single- and multi-phase operations as, for example, demonstrated in the studies of Karthick et al. [48] (schlieren visualization and wall static pressure measurements) and Wang et al. [49] (image analysis). These observations might also support theoretical studies (viz., the second research direction) to describe the physics of ejector fluid dynamics. Since some pioneering studies, many theories have been proposed, mainly following the constant-area-mixing and the constant-pressure-mixing approaches. Because of the many decades of studies, some general concepts are generally accepted, e.g., the limitation of the entrainment ratio in on-design operations. Unfortunately, the choking phenomena and the structures limiting the secondary flow rate are not clearly understood A cutting-edge research regarding the entrainment limitation was described by Lamberts et al [50], proposing the compound-choking theory to predict ejector performances, summarized as follows "*a nozzle flow with two streams at different stagnation pressures may be choked with a subsonic stream if the other one is supersonic*".

The third direction regards the use of *LPMs* and *CFD* to optimize ejector design. The underlying concept behind these studies is the multi-scale view, as the ejector design needs to be related to the "*local-scale*". For example, Kumar et al. [51] suggested that ejector shape should be designed to maintain a constant rate kinetic energy change. Kumar and Sachdeva [52] proposed, and validated, a *LPM* to design a single-phase ejector, by considering local phenomena (i.e., Kelvin-Helmholtz instabilities, Baroclinic effect, Prandtl's mixing length, Prandtl-Meyer expansion wave). In general, *LPM* approaches, owing to their low computational time, can be used to derive performance maps; for example, Lu and Chen [53] obtained ejector design curves for a cylindrical mixing chamber—which may support design methods.

Compared with *LPMs*, *CFD* simulations provide a detailed description of the "*local-scale*" to support a high-performance ejector design, as discussed by Palacz et al. [54], when proposing a *CFD*-based genetic-algorithm optimization of the ejector shape. Sierra-Pallares et al. [55] developed a *CFD*-based shape optimization procedure for long-tapered mixing chambers, based on the minimization of the internal entropy generation, coupling a one-dimensional model (to generate a baseline geometry) with single-phase *CFD* simulations. Carrillo et al. [56] proposed a shape optimization of a single-phase ejector by coupling a multi-objective evolutionary algorithm with a surrogate model based on *CFD* simulations. Finally, Saleh et al [57] proposed a *CFD* study of a hydrocarbon ejector performance and recommended a set of pareto frontier performance curves to design *ERSs*.

As mentioned above, simulations of high-speed multi-phase flows are really challenging and state-of-the-art issues in both industry and academia to find a-priori the optimum operating conditions depending on the boundary conditions of the system [58]. Generally, homogeneous equilibrium and homogenous relaxation models can be used. The former was applied by Taleghani et al. [59], whereas the latter was applied by Colarossi et al. [60], implementing the relaxation time based on the work of Angielczyk et al. [61]. Recently, Giacomelli et al. [62] proposed and validated a mixture model for CO_2 high-speed flows through nozzles, encompassing subcritical, supercritical, and metastable regions; their approach was based on dedicated look-up tables. Dang Le et al. [63] proposed a mixture approach considering thermal non-equilibrium, showing promising results. Bi et al. [64] validated an Euler-Lagrange approach for flash boiling atomization and applied it to investigate the effect of the operating parameters and phase properties on the atomization process. Sharma et al. [65] proposed an Euler-Euler modeling approach and studied the role of the turbulent dispersion on the fluid dynamics. Finally, Wang et al. [9] compared ideal gas and wet stream modeling approaches: the latter improved the prediction of the primary pseudo-shock (they considered the condensation phase by liquid-phase mass-fraction, and the liquid-droplets number density transport equations).

3 The perspective: "*the multi-scale ejector challenge*"

Based on the previous discussion, regarding "*the present*" achievements, this section offers a glance towards "*the future*" research directions and perspective. In particular, it defines the subjects to be contemplated in the medium-term research agenda and it proposes a precise pathway to be followed in the long-term research activities.

3.1 The medium-term perspective

The discussions proposed in Section 2 demonstrated that ejector-based systems are quite mature technologies. For example, it is recognized that solar-assisted *ERSs* can be deployed to support the decarbonisation policies; similarly, ejector systems can be used to reduce the primary energy consumption in the process industrynowadays. More importantly, their main advantages/disadvantages are known and some design criteria and concepts are well assessed. The main barrier triggering a large-scale ejector application market, in the medium-term, is ascribed to the lack of "*predictive control systems*", encompassing the different scales. Such control systems aim to maintain the "*system-scale*" performances (i.e., the overall first and second law performances), by adjusting the "*component-scale*" behavior (i.e., by modifying the boundary conditions and the ejector geometry), in turn predicting and controlling the "*local-scale*" phenomena (i.e., i.e., shock waves, boundary layers subject to adverse pressure gradients, under-expanded jets, recirculation, turbulence mixing phenomena bounded by near-wall regions, flow reparation …). To this end, the forthcoming activities should develop novel regulation strategies, replying on multi-scale numerical approaches. In addition, this regulation method should couple the ejector beheviour with the regulation strategies of non-ejector components (i.e., electronic expansion valves, compressors, flooded/non flooded evaporators, internal heat exchangers, …) and should consider the effect of the refrigerant properties and charge. Of course, a predictive control system should be developed also for ejectors in fuel cell recirculation systems; in this case, forthcoming studies should integrate the ejector regulation strategies with the fuel cell controls and constrains.

Beside developing a "*predictive control systems*", an ongoing challenge is to improve the performances of existing ejector-based systems, for refrigeration, low-grade heat recovery and power cycles. First, a lack of experimental studies regarding *ERSs* systems with low-*GWP* refrigerants, and promoting the application of ejectors in smaller and low-charge CO_2 systems (i.e., the so-called water-loop systems). Of course, research activities simulating innovative system layouts should continue, especially coupling ejectors systems with other system configurations, in particular if considering multi-energy systems. Second, if considering low-grade heat recovery, an optimization of the ejector geometry and ejector cycle, depending on the heat source in both on- and off-design modes should be carried on (especially in the case of multi-heat sources). Third, when considering ejector-based power cycles, the use of ejectors in CO_2 systems is interesting but still poorly investigated and forthcoming activities should address this topic.

Coming to the simulation strategies, the medium-term research activities are encouraged to focus on the modeling closures. On one hand, concerning *LPMs*, a physical-based formulation of ejector component efficiencies, also considering the local phenomena and the non-uniformity effects. On the other hand, a shared strategy to simulate multi-phase ejectors should be carried on, as successfully proposed by Lucas et al. [66] for bubbly flows in vertical pipes. In this respect, a case-by-case selection of the modeling closures need to be avoided and, instead, a baseline approach, considering all known phenomena and defining all modeling parameters, should be proposed. Such baseline approach needs to be applied to different experimental benchmark and, subsequently, detailed studies to explore the discrepancies between simulation results and experimental data should be carried on. A modification of the proposed baseline model should be justified only if it is based on physical considerations and if it improves the overall performance of the model compared with all available benchmarks. Thus, forthcoming activities should propose baseline model for simulating single- and multi-phase ejectors. In addition, future studies should enhance available modeling approaches by a physical-based interpretation and formulation of the relaxation time. Finally, an integrated *LPM-CFD* approach to optimize ejector shape to optimize may be derived and applied, thus coupling the advantages of *CFD* approaches and the low-computational efforts of *LPMs*.

3.2 The long-term perspective and research statement

A fundamental challenge should be addressed in the long-term research and should guide all ongoing and forthcoming research activities: “*the multi-scale ejector challenge”*, aiming to describe and link the flow phenomena and performances at the different scales based on first-principles. To reach this challenging goal, three research lines should be strengthen simultaneously in a long-term perspective: (a) obtaining *CFD*-grade experimental datasets, to clarify the local fluid dynamics and phase change phenomena, (b) developing and validating high fidelity baseline single- and multi-phase simulations, (c) studying the first principles relating the flow phenomena at the different scales. In conclusion, this perspective starts “*the multi-scale ejector challenge”*, which should be the background in all the future research activities. In conclusion, the forthcoming research activities and papers are encouraged to introduce their research and findings within this research statement.

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