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Numerical Analysis on a Constant Rate of Kinetic Energy Change Based a Two-Stage Ejector-Diffuser System

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Supersonic ejector energy flow devices are extensively used in various applications, such as pumping, mixing, compression, etc. The conventional single-stage ejector (SSE) design approaches are inefficient for modelling an efficient ejector because of their inefficiency in minimizing mixing losses in the mixing chamber, thermodynamic shock in constant area diffuser, and utilization of redundant discharged momentum at the exit of the first stage. The physics-based single-stage ejector design has better solutions because it minimizes irreversibility due to thermodynamic shocks. The present study utilizes the constant rate of a kinetic energy change physics-based approach to design a two-stage ejector (TSE) for water vapour. The computational fluid dynamics (CFD) tool ANSYS-Fluent has been utilized to predict flow characteristics. The performance of the ejector-diffuser system has also been compared with a single-stage ejector. It is found that the performance of TSE is 70 % higher than that of the performance of SSE.
Keywords: ejector-diffusor, constant rate of kinetic energy change, two-stage ejector, single-stage ejector, computational fluid dynamics

Highlights
- *The computation of a two-stage ejector-diffuser profile was performed based on the CRKEC approach.*
- *A comparison of a two-stage ejector-diffuser with a single-stage ejector was carried out.*
- *The performance of the two-stage ejector-diffuser is 70% higher than that of a single-stage ejector.*
- *The CRKEC approach helps in the computation of high-performance two-stage ejector geometrical profiles.*

0 INTRODUCTION

The ejector's simplicity and reliability are its key features and the reason it is widely used; however, the ejector has low efficiency. It is used to pump, induce, mix and/or recompress primary/motive and two secondary/induced flows. The ejector has numerous industrial applications, including refrigeration systems [1] to [4], bus air-conditioning [5] and [6], sea-water desalination systems [7] and [8], chemical lasers [9] and hydrogen fuel cells [10] and [11] others.

Conventional design ejectors are based on constant area mixing (CAM) [12] and constant pressure mixing (CPM) [13]. These ejectors were categorized based on the exit position of the nozzle in the mixing section. From previous studies, one of the major losses in conventional ejectors is due to thermodynamic shocks. To tackle the thermodynamic shock in the constant area section of a conventional ejector-diffuser, a one-dimensional gas-dynamic constant rate of momentum change (CRMC) approach was presented by Eames [14]. This approach helped reduce thermodynamic shock. Kitrattana et al. [15] studied the performance of three steam ejectors designed based on conventional and CRMC approaches. The result showed that the CRMC ejector performance is better than conventional ejectors. Furthermore, a complete ejector design approach with frictional effect is presented by Kumar et al. [16]. In another study, Kumar et al. [17] presented a physics-based ejector design approach, i.e., constant rate of kinetic energy change (CRKEC), to design a complete single-stage ejector. The CRKEC approach converts the constant area section convention diffuser section into a variable area and minimizes loss due to mixing and thermodynamic shocks.

The performance of the conventional (CAM/CPM) and physics-based (CRMC/CRKEC) single-stage ejectors remains low. Apart from utilizing different design approaches to improve the performance, many researchers have attempted to minimize mixing losses by optimizing the supersonic nozzle [18] to [20], nozzle exit positions [21], suction chamber [22], mixing chamber [23], and diffuser section [24]. Consequently, the present era of the ejector modified the single-stage ejector into a two/multi-stage ejector. The two-stage compression is another way to decrease throttling loss and improve system efficiency. The single-stage ejector always has a primary flow inlet, a secondary/induced flow

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inlet, a mixing chamber, and a diffuser. In the case of two-stage ejectors, the second induced/entrained flow enters at the exit of the mixing section of single stage ejector [25]. It better utilizes the redundant momentum discharging at the exit of the mixing of the first stage of the ejector (Fig. 1). The system usually comprises one motive stream inlet and two (primary and secondary) induced fluid inlets; the second induced fluid can be accelerated by the combined (primary motive and induced) flow of the first stage [26]. The process of the momentum exchange between the motive and the induced fluids and carry over the former by the latter is often termed "entrainment". The entrainment ratio is a global performance parameter, which is a ratio of the mass flow rate of induced flow to motive flow.

Ding et al. [27] utilized the CAM approach to design a two-stage ejector for sub-zero refrigeration for R134a working fluid. The operating temperatures of the generator were used in the range of 63 °C to 74 °C and 24 °C to 0 °C for the evaporator. The CFD study was carried out to find the best design parameters for a range of operating conditions. The results showed that using a two-stage ejector in sub-zero refrigeration applications could benefit cold-chain logistics systems. Kong and Kim [28] studied single-stage and two-stage ejectors and concluded that the two-stage ejector-diffuser system could be utilized to improve the inefficiency of conventional single-stage ejector-diffuser systems by reducing energy loss and utilization of redundant momentum of the discharge flow.

It is evident from the literature that the single-stage ejector-diffuser has low performance. It is also found that the conventional design ejectors have higher thermodynamic losses than physics-based ones. Therefore, the objective of the present study is to utilize redundant momentum and kinetic energy of discharged flow to induce secondary mass flow. It is expected that the two-stage ejector designed based on the CRKEC approach will further improve the flow mixing and entrainment performance of the ejector-diffuser system by installing a second stage. The numerical analysis is performed on the CRKEC design two-stage ejector-diffuser (TSED) and compared with the single-stage ejector-diffuser (SSED).

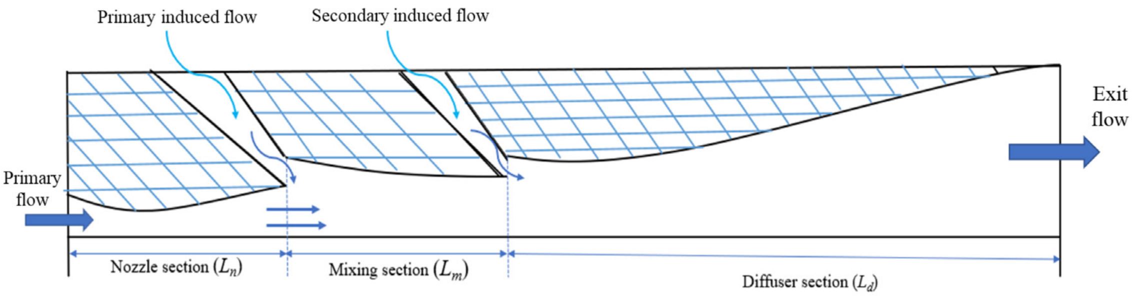

Fig. 1. *Axisymmetric two-stage ejector (TSE) system*

1 COMPUTATIONAL GEOMETRY

A supersonic ejector consists of three major components: supersonic nozzle, mixing chamber, and diffuser section. The CRKEC approach [17] for ideal gas was further manipulated using the Redlich-Kwong equation to model supersonic ejector for water vapour. The separate MATLAB of each component was made to compute variation in geometrical coordinates and flow properties at each small step 0.5 mm. The selection of CRKEC constants to compute geometry and flow properties for the given length was based on the recommendation of Kumar et al. [17].

The computed geometrical profile along the convergent-divergent nozzle is shown in Fig. 2. The profile of the nozzle is presented for the selected CRKEC constant. The CRKEC constant was selected based on the targeted Mach number (~2.5) and the convergent and divergent section length. The variation in radius is continuously decreased up to the throat. At the throat, the minimum radius is approximately 1.01 mm, and the inlet radius of the nozzle is 2.28 mm. The radius at the outlet of the nozzle is 5.307 mm.

The mixing section is a converging passage where primary motive and induced flows are mixed and exchange the fluids' momentum and kinetic energy. The actual mixing phenomena is very complex, which is difficult to quantify and explain. After mixing both primary motive and induced flow, it is tried to achieve an equilibrium condition at the exit of the mixing section. The computation mixing chamber geometry starts with the computation of equilibrium properties from exit to inlet of chamber. The variation in radius along the mixing section is shown in Fig. 3.

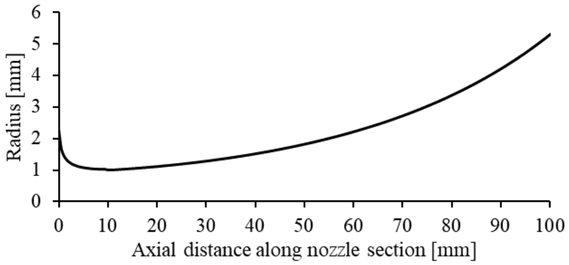

Fig. 2. *Variation in nozzle radius along with nozzle profile*

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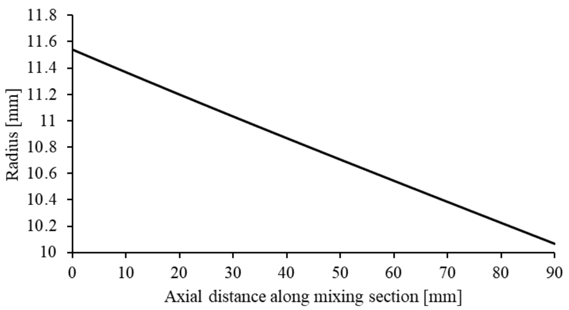

Fig. 3. *Variation in radius along mixing section*

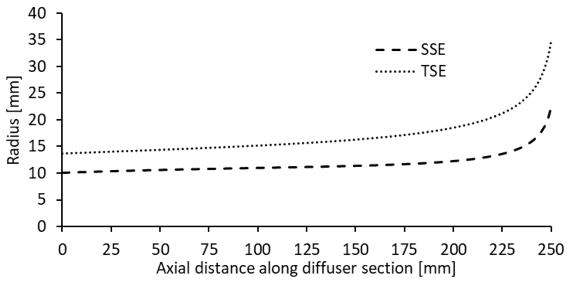

Fig. 4. *Radius variation along diffuser section*

The diffuser is a continuous increasing passage from the inlet to exit. The main function of the diffuser is to convert the kinetic energy of fluid into pressure energy. For the selected CRKEC constant and diffuser length, the computed inlet and outlet radius for SSED is 10.063 mm and 22.45 mm and for TSED is 13.64 mm and 33.6 mm. The rate of change in the radius is nearer to the outlet. The variation in radius along the diffuser is shown in Fig 4.

2 COMPUTATIONAL STUDIES

The actual flow through the ejector systems considered in this work is an axisymmetric, steady turbulent compressible flow. All the flow variables are expected to vary along with axial and radial directions. One-dimensional gas dynamics theory can be considered equivalent to area-averaged axisymmetric flow. Computational fluid dynamic (CFD) tool has been utilized to estimate flow characteristics and ejector parameters using the geometry generated using one-dimensional analysis. The conservation equations governing the fluid flow in an ejector are considered, assuming compressible, steady-state, axisymmetric flow. The Favre-averaged Navier-Stokes equations are the most suitable for variable density flows and will be used in the present study. The total energy equation including viscous dissipation is also included and coupled with the ideal gas law set. The standard k-ε model is a semi-empirical model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). Turbulence models used in the present study rely on the Boussinesq hypothesis, which is based on an eddy viscosity assumption, making the Reynolds stress tensor averaging proportional to the mean deformation rate tensor.

The grid independence test is generally used to select optimal grid size for CFD analysis. In general, local flow variables predicted by the CFD studies are used to decide the optimal grid size. This study utilized the global performance parameter of ejector "entrainment ratio (ω)" at design conditions. Various mesh sizes (30,000 to 80,000) were used to perform grid independence tests on a two-stage ejector. The standard, k–ε turbulence model, has been utilized to study the grid-independent test. The gradient mesh was employed near the wall and dense mesh within the mixing section to resolve shocks, expansion waves, and mixing phenomena. All the mesh sizes demonstrated close agreement with the analytical one with a small deviation. It is also observed that further refinement of mesh is not required. Therefore, considering computational time and accuracy, all further studies were carried out using 45,476 cells for both ejectors.

3 RESULTS AND DISCUSSION

The design of ejector components and their computations are discussed in Sections 2 and 3, respectively. The computed geometries for SSE and TSE ejectors have been compared and presented for design conditions. A detailed discussion on the physics of flow through specially designed two-stage ejector (TSE) in comparison to single-stage ejector (SSE) are discussed in this section. The nozzle exit position (NXP) relative distance of the primary nozzle outlet to the mixing chamber inlet was fixed at zero for all the studies.

The static pressure variations along the mixing-diffuser section for SSE and TSE is shown in Fig. 5. A strong pressure pulsation has been observed in the mixing section of both the ejector sections. This pulsation is due to the mixing of primary supersonic flow with incompressible subsonic primary/secondary induced flow [21]. The primary and induced fluids undergo intense interaction inside the mixing section. The intense interaction can be seen from fluctuations in the prediction of centreline static pressure in the mixing section. During this interaction, both fluids exchange their momentum and kinetic energy and reach an internal equilibrium, resulting in an almost uniformly mixed flow. As the flow travels downstream, the pulsation of static pressure is diminishing and almost negligible at the exit of the diffuser.

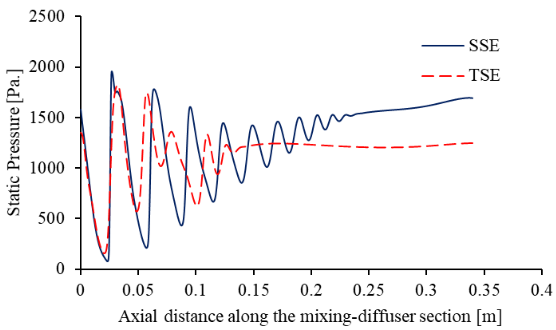

Fig. 5. *Axial variation of centreline static pressure along mixing-diffuser section*

The CFD centreline Mach number and temperatures variation are shown in Figs. 6 and 7. The intense interaction of primary and secondary flow can be seen in the mixing section. From the Mach number plot (Fig. 10), the presence of alternate oblique shocks and expansion waves can be seen. Because of the presence of the oblique shocks, the Mach number remained largely supersonic and showed significant pulsations followed by shockless diffusion in both the ejectors. Due to the oblique shocks and expansion waves in the mixing section, the average values of static pressure and temperature (Figs. 5 and 7) are nearly passing through the centres of pulsations. However, the local average Mach number predicted by the 1D model is less than the centreline Mach number predicted by CFD. The pressure loss in the mixing section is higher than in the diffuser section because of the oblique shocks and expansion waves. The Mach number and static temperature variations predicted by the CFD centreline for both the ejectors qualitatively match each other. There is a minor mismatch in a quantitative variation of these parameters at the exit of the diffuser.

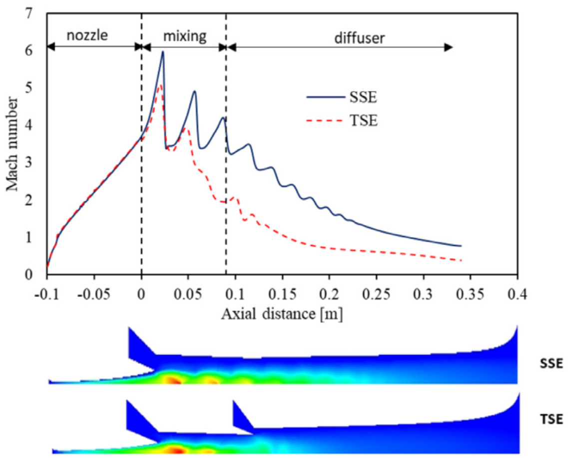

Fig. 6. *Axial variation of centreline Mach number along mixing-diffuser section*

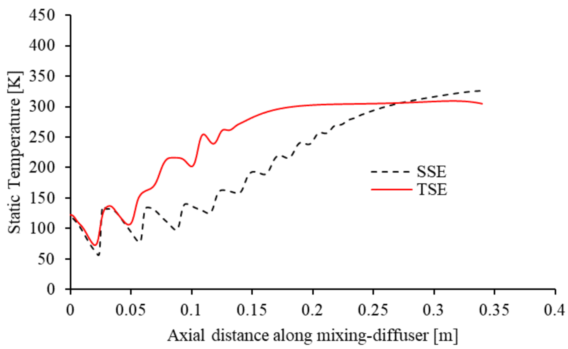

Fig. 7. *Axial variation of centreline static temperature along the mixing-diffuser section*

The entrainment ratio (ω) is a well-known and key performance parameter of the ejector system. The CFD on-design value of entrainment ratio for both the single-stage and two-stage ejectors are shown in Fig. 8. The two-stage ejector entrainment ratio ω is higher than that of the single-stage ejector. The TSE entrainment ratio compared to SSE at on-design is 70 % higher. This is due to the utilization of the redundant flow energy at the second stage for inducing secondary induced flow in a two-stage ejector.

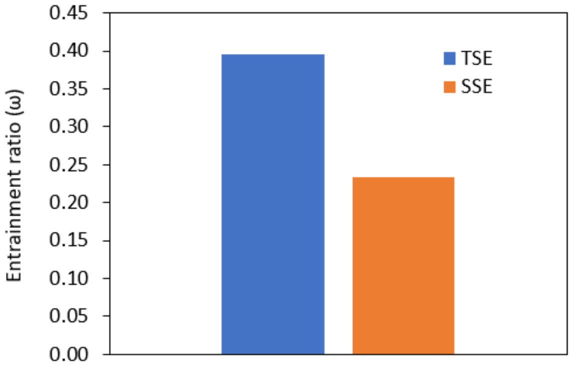

Fig. 8. *Entrainment ratio (ω) at on-design for SSE and TSE*

4 CONCLUSIONS

This study developed an analytical model for a two-ejector design. The coordinates of the ejector profile and flow properties were computed based on the CRKEC approach using MATLAB. The computed geometrical profile has been utilized for the CFD study. The performance of a two-stage ejector is compared with a single-stage stage ejector designed based on the same analytical model. The analytical results and CFD results for both the ejectors have been presented and compared at on-design conditions. The results showed that the two-stage performance is 70 % higher than that of the single-stage ejector. The entrainment region is one of the most crucial components of the ejector, as it causes significant loss due to the mixing of supersonic primary and subsonic induced flow. The CRKEC approach can help compute geometrical profile and flow characteristics in small steps.

5 REFERENCES

[1] Yari, M. (2009). Performance analysis and optimization of a new two-stage ejector-expansion transcritical CO_2 refrigeration cycle. *International Journal of Thermal Sciences*, vol. 48, no. 10, p. 1997-2005, **DOI:10.1016/j.ijthermalsci.2009.01.013**.

[2] Yan, J., Wen, N., Wang, L., Li, X., Liu, Z., Li, S. (2018). Optimization on ejector key geometries of a two-stage ejector-based multi-evaporator refrigeration system. *Energy Conversion and Management*, vol. 175, p.142-150, **DOI:10.1016/j.enconman.2018.08.110**.

[3] Grazzini, G., Rocchetti, A. (2002). Numerical optimisation of a two-stage ejector refrigeration plant. *International Journal of Refrigeration*, vol. 25, no. 5, p. 621-633, **DOI:10.1016/S0140-7007(01)00063-9**.

[4] Işkan, Ü., Direk, M. (2021). Experimental investigation on the effect of expansion valves in a dual evaporator ejector refrigeration system using R134a and R456a. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **DOI:10.1080/15567036.2021.1982076**.

[5] Ünal ,S. (2015). Determination of the ejector dimensions of a bus air-conditioning system using analytical and numerical methods. *Applied Thermal Engineering*, vol. 90, p. 110-119, **DOI:10.1016/j.applthermaleng.2015.06.090**.

[6] Ünal, S., Yilmaz, T. (2015). Thermodynamic analysis of the two-phase ejector air-conditioning system for buses. *Applied Thermal Engineering*, vol. 79, p. 108-116, **DOI:10.1016/j.applthermaleng.2015.01.023**.

[7] Qamar, A., Kerdi, S., Ali, S.M., Shon, H.K., Vrouwenvelder, J.S., Ghaffour, N. (2021). Novel hole-pillar spacer design for improved hydrodynamics and biofouling mitigation in membrane filtration. *Scientific Reports*, vol. 11, art. ID 6979, **DOI:10.1038/s41598-021-86459-w**.

[8] Suresh Kumar, S.M., Duraibabu, D., Subramanian, K. (2014). Studies on mechanical, thermal and dynamic mechanical properties of untreated (raw) and treated coconut sheath fiber reinforced epoxy composites. (2014). *Materials & Design*, vol. 59, p. 63-69, **DOI:10.1016/j.matdes.2014.02.013**.

[9] Singhal, G., Rajesh, R., Mainuddin, Tyagi, R.K., Dawar, A.L., Subbarao, P.M.V, Endo, M. (2006). Two-stage ejector based pressure recovery system for small scale SCOIL. *Experimental Thermal and Fluid Science*, vol. 30, no. 5, p. 415-426, **DOI:10.1016/j.expthermflusci.2005.09.002**.

[10] Yang, Y., Du, W., Ma, T., Lin, W., Cong. M,, Yang, H., Yu, Z. (2020). Numerical studies on ejector structure optimization and performance prediction based on a novel pressure drop model for proton exchange membrane fuel cell anode. *International Journal of Hydrogen Energy*, vol. 45, no. 43. p. 23343-23352, **DOI:10.1016/j.ijhydene.2020.06.068**.

[11] Chen, F., Hou, M., Li, J., Pei, Y., Wang, Y. (2021). Proton exchange membrane fuel cell ejector test platform design and ejector test analysis. *World Electric Vehicle Journal*, vol. 12, no. 3, art. ID 103, **DOI:10.3390/wevj12030103**.

[12] Keenan, J.H., Neumann, E.P. (1942). A Simple Air Ejector. *Journal of Applied Mechanics*, vol. 9, no. 2, p.A75-A81, **DOI:10.1115/1.4009187**.

[13] Nguyen, V.V., Varga, S., Dvorak. V. (2019). HFO1234ze(e) as an alternative refrigerant for ejector cooling technology. *Energies*, vol. 12, no. 21, art. ID 4045, **DOI:10.3390/en12214045**.

[14] Eames, I.W. (2002). A new prescription for the design of supersonic jet-pumps: The constant rate of momentum change method. *Applied Thermal Engineering*, vol. 22, no. 2, p. 121-131, **DOI:10.1016/S1359-4311(01)00079-5**.

[15] Kitrattana, B., Aphornratana, S., Thongtip, T., Ruangtrakoon, N. (2017). Comparison of traditional and CRMC ejector performance used in a steam ejector refrigeration. *Energy Procedia*, vol. 138, p. 476-481, **DOI:10.1016/j.egypro.2017.10.229**.

[16] Kumar, V., Singhal, G., Subbarao, P.M.V. (2013). Study of supersonic flow in a constant rate of momentum change (CRMC) ejector with frictional effects. *Applied Thermal*

Engineering, vol. 60, no. 1-2, p. 61-71, **DOI:10.1016/j.applthermaleng.2013.06.045**.

[17] Kumar, V., Singhal, G., Subbarao, P.M.V. (2018). Realization of novel constant rate of kinetic energy change (CRKEC) supersonic ejector. *Energy*, vol. 164, p. 694-706, **DOI:10.1016/j.energy.2018.08.184**.

[18] Vereda, C., Ventas, R., Lecuona, A., Venegas, M. (2012). Study of an ejector-absorption refrigeration cycle with an adaptable ejector nozzle for different working conditions. *Applied Energy*, vol. 97, p. 305-312, **DOI:10.1016/j.apenergy.2011.12.070**.

[19] Kong, F.S., Kim. H.D., Jin, Y., Setoguchi, T. (2013). Application of Chevron nozzle to a supersonic ejector-diffuser system. *Procedia Engineering*, vol. 56, p. 193-200, **DOI:10.1016/j.proeng.2013.03.107**.

[20] Atmaca, A.U., Erek, A., Ekren, O. (2020). One-dimensional analysis of the convergent-divergent motive nozzle for the two-phase ejector: Effect of the operating and design parameters. *Applied Thermal Engineeering*, vol. 181, art. ID 115866, **DOI:10.1016/j.applthermaleng.2020.115866**.

[21] Kumar, V., Subbarao, P.M.V., Singhal, G.(2019). Effect of nozzle exit position (NXP) on variable area mixing ejector. *SN Applied Sciences*, vol. 1, art. ID 1473, **DOI:10.1007/s42452-019-1496-y**.

[22] Bartosiewicz, Y., Aidoun, Z., Desevaux, P., Mercadier, Y. (2005). Numerical and experimental investigations on supersonic ejectors. *International Journal of Heat and Fluid Flow*, vol 26, no. 1, p. 56-70, **DOI:10.1016/j.ijheatfluidflow.2004.07.003**.

[23] Sierra-Pallares, J., García del Valle, J., Paniagua, J.M., García, J., Méndez-Bueno, C., Castro, F. (2018). Shape optimization of a long-tapered R134a ejector mixing chamber. *Energy*, vol. 165, p. 422-438, **DOI:10.1016/j.energy.2018.09.057**.

[24] Kong, F., Kim, H.D. (2016). Optimization study of a two-stage ejector - diffuser system. *International Journal of Heat and Mass Transfer*, vol. 101, p. 1151-1162, **DOI:10.1016/j.ijheatmasstransfer.2016.05.129**.

[25] Kumar, A., Kumar, V., Subbarao, P.M.V., Yadav, S.K., Singhal, G. (2021). Numerical assessment on the performance of variable area single- and two-stage ejectors: A comparative study. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 236, no. 1, p. 114-125, **DOI:10.1177/09544089211033129**.

[26] Yadav, S.K., Pandey, K.M., Kumar, V., Gupta, R. (2020). Computational analysis of a supersonic two-stage ejector. *Materials Today: Proceedings*, vol. 38, p. 2700-2705, **DOI:10.1016/j.matpr.2020.08.483**.

[27] Ding, Z., Wang, L., Zhao, H., Zhang, H., Wang, C. (2016). Numerical study and design of a two-stage ejector for subzero refrigeration. *Applied Thermal Engineering*, vol. 108, p. 436-448, **DOI:10.1016/j.applthermaleng.2016.07.104**.

[28] Kong, F., Kim, H.D. (2015). Analytical and computational studies on the performance of a two-stage ejector-diffuser system. *International Journal of Heat and Mass Transfer*, vol. 85, p. 71-87, **DOI:10.1016/j.ijheatmasstransfer.2015.01.117**.