Optimization of Steam Ejector Design and Performance

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***Abstract*— This work presents a computer simulation model of steam ejector is used to enhance the performances of absorption chiller. The 1D model is developed based on thermodynamic equations governing perfect gas flow correlations is used in the current study to improve the ejector: design and performance. Actual study specifies the constant-pressure ejector flow model at critical operating mode for steam as working fluid. The effect of design parameters, particularly the primary nozzle area ratio and the ejector area ratio, and operating conditions of primary, secondary and back pressure are used to evaluate the ejector operating zone according to entrainment ratio calculations. Besides that, the effect of pressure exiting nozzle and the area ratio on ejector performance are discussed and optimized.**

***Keywords*—Ejector; Performance, Design, Steam, back pressure, and optimization.**

I. INTRODUCTION

Steam ejectors are used in vapour compression refrigeration and absorption chillers technology to enhance machines performances [1-5]. Ejectors are classified based on the state of the working fluid (gas-liquid ejector, gas-gas ejector) or based on geometry (constant area ejector [6] or constant pressure ejector as described below). Experimental works and a computational Fluid Dynamics (CFD) model are conducted to predict the ejector performances by studying the effect of the primary nozzle and the mixing chamber diameters [7] on the entrainment ratio. Other CFD works were conducted [8] to analyze ejector's performance using different roughness nozzles levels with experimental values. It was find that the performance of the ejector is noticeably influenced by the friction also that the rise of roughness values will lead to increase in temperature, whereas the Mach number drops working flow in varying proportions and degrades the ejector performance. Other CFD studies, analyzing multi-factor effect on the performances of the ejector and its design [9], results show that after optimization, five-factor : the diameter of the nozzle outlet , the distance between the nozzle outlet to the inlet of the mixing chamber and diameters of the contraction section of the mixing chamber and the diffuser chamber and four-level orthogonal tests to gain the sensitivity for every factor to performances of the ejector, indicating mainly that an optimized ejector has much better performances The effect of back pressure, the throat diameter and the NXP was studied using CFD simulation [10]. It was found that the back pressure should not exceed a critical value, a shock wave can prevent the disturbance caused by back pressure by propagating upstream.

Different ejector geometries are tested under different working conditions. A 1D analysis is presented [11] to evaluate ejector performance. The entrainment ratio at working conditions is investigated in order to validate analytically the experimental results of a steam ejector. Results show that the model predicts fairly the entrainment ratio of the ejector and the performances of many studied refrigerator machines. Experimental and theoretical studies [12] are investigated to study ejector working with various flow to establish its design and then optimize the chiller prototype. Experimental works are performed to study the effect of ejector geometries on the performances of a cooling system 13], Results showed the difficulty to reach the optimum of using one ejector under various operating conditions. A 3D ejector model [14] is developed using AutoCAD, meshed and simulated using Ansys CFX. for predefined inputs and boundary conditions, pressure, temperature, Mach number and velocity contours are analysed Parametric analysis was carried out to identify the convergence. A steam ejector [15] is investigated. Two theoretical approaches are discussed: ejector design for a fixed duty and performance ejector prediction for known geometry. Semi-empirical correlations are proposed for the design and performance prediction of steam ejectors. Investigations are carried out to design and optimize an ejector using ammonia [16] in order to find out the optimum operation conditions. A maximum entrainment ratio is found under various boundary conditions and for each value. An optimum area ratio is then concluded for each case. The purpose of the present work is to analyse theoretically the design under various operating conditions of steam ejector. Optimum operating conditions as function of thermodynamic and geometric parameters governing the ejector are discussed in order to optimize its performances and to evaluate its off design conditions.

ISSN 1737-9296

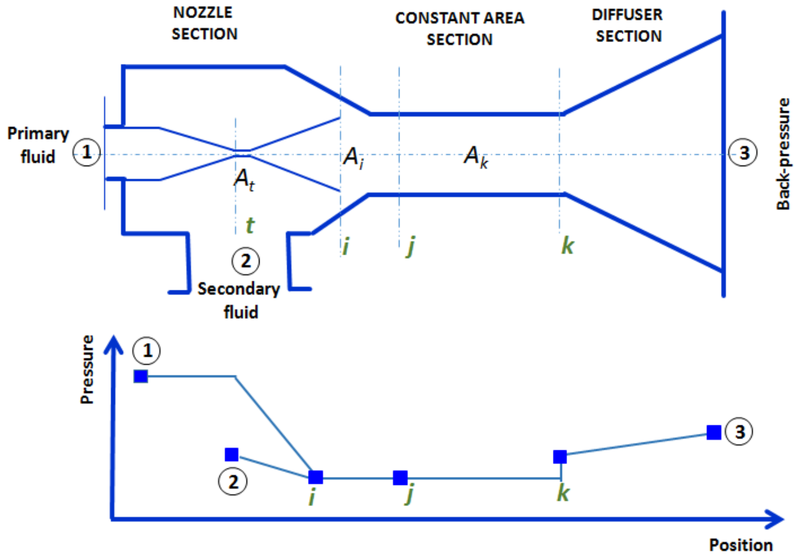

Fig. 1. Schematic Presentation of an Ejector.

II. EJECTOR DESCRIPTION

A typical ejector configuration is shown in figure1. A steam ejector is composed from four elements, a primary nozzle, a suction chamber, a mixing chamber (convergent-duct-constant section) and a subsonic diffuser. Where Secondary mass flow rate $\dot{m}_2$ is entrained by primary flow rate $\dot{m}_1$, defining ω the entrainment ratio.

Where ω stands for the entrainment ratio

$$\omega = \frac{\dot{m}_2}{\dot{m}_1} \qquad (1)$$

In the primary nozzle (convergent–divergent)the high pressure of the primary fluid P1expands and accelerates, creating a vacuum at the nozzle exit position (i) with very low pressure Pi in order to entrain the secondary flow inside the mixing chamber. At the exit of the mixing chamber j, the combined two streams are assumed to be completely mixed at a uniform pressure (Pj=Pi). Due to the existence of a high pressure area, the mixed stream undergoes normal shock wave within the constant section area Ak, so the pressure rises to Pk, and a compression effect is created. At the exit of the diffuser the pressure is compressed to the back pressure P3.

III. EJECTOR SOLUTION PROCEDURE AND VALIDATION

A. Ejector solution procedure

Detailed mathematical 1-D model of the ejector is described by [4] based on mass, momentum and energy balances, in order to carry out the ejector entrainment ratio ω as defined in equation (1) and ejector area ratio AkAt=Ak/At., as defined in quation (2). In this work an algorithm chart based on iterations to calculate to optimize and design the ejector, is used.

First knowing the nozzle area ratio AiAt=Ai/At and the primary pressure, the pressure exiting the nozzle Pi can be calculated. Also, as it is an ejector with constant pressure, the mixing pressure before the shock wave is known (Pi=Pj). Also for a given back pressure P3 the pressure Pk is can be found. Once ω is deduced, it is injected in the equation expressing the area ratio AkAt and a new Pk and AkAt are calculated, from equation (2) .

The ejector area ratio $\left({}^{\mathrm{A_t}}/_{\mathrm{A_k}}\right)$, i.e. the ratio of nozzle throat area and diffuser constant area section writes

$$\frac{\mathrm{A_t}}{\mathrm{A_k}} = \frac{P_3}{P_1}\left(\frac{P_k}{P_3}\right)^{\frac{1}{\gamma}}\sqrt{1-\left(\frac{P_k}{P_3}\right)^{\frac{(\gamma-1)}{\gamma}}}\sqrt{\frac{1}{(1+\omega\tau)(1+\omega)}}\,\frac{\sqrt{\frac{\gamma+1}{\gamma-1}}}{\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}} \qquad (2)$$

With :

γ Ratio of steam specific heats,(C_p/C_v)

τ T_2/T_1

B. Ejector model validation

A computer program is developed using Engineering Equation Solver (EES) software [17] in order to validate the theoretical model of steam ejector. In the experimental work of T. Sriveerakul et al [7], various combination of ejector geometry was tested at different operating temperatures and pressures. The primary and secondary flows are at saturation conditions, so the pressures are identified from the saturation properties of every flow temperature. In the present program, the thermo-physical properties of steam are used as internal functions from the EES database for all temperature and pressure range. Results of simulations were compared with those reported by T.Sriveerakul et al [7]. Table 1 illustrates the comparison between 1-D analysis and the experimental results of the ejector performances at critical backpressure.

TABLE I: RESULTS OF VALIDATION WITH EXPERIMENTAL DATA

Back pressure (mbar)			**Entrainment ratio**			**Area ratio**		
Experiment	**Calculated**	**Error(%)**	**Experiment**	**Calculated**	**Error(%)**	**Experiment**	**Calculated**	**Error(%)**
Operationg conditions (°C): Tp=120, Ts=10								
0.53	0.48	-9.72	90.25	103	14.12	37	37	0
Tp=130, Ts=10								
0.4	0.39	-2.54	90.25	97.71	18.26	50	50	0
Tp=140, Ts=15								
0.28	0.33	18.38	90.25	96.02	6.397	65	65	0
Tp=130, Ts=5								
0.31	0.32	4.56	90.25	96.55	6.98	48	48	0
0.39	0.43	12.48	117.9	117.5	-0.30	41	37	10.81
0.47	0. 57	23.18	160.5	144.2	-10.14	35	31	12.9
0.31	0.32	4.56	90.25	96.55	6.98	48	48	0
0.31	0.36	18.83	90.25	104.6	15.86	45	43	4.65
0.3	0.35	17.64	90.25	101.7	12.74	46	46	0
0.31	0.32	4.56	90.25	96.55	6.98	48	48	0

Also errors $\%Error$ are calculated on entrainment, ejector area ratio and back pressure as the relation below :

$$\%\text{Error} = \frac{\text{calculated value} - \text{experimental value}}{\text{experimental value}}$$

The minimum absolute error on entrainment ratio is about 2.5% and the the maximum is about 20%. Also the minimum of error on area ratio is 0.3% and the maximum is about 18% beciedes error on back pressure is about 20%. Based on simulated results and errors, the present model and the used chart is describes fair the experimental data. Thus the methodology is used below to simulate, and design and optimize the ejector performance.

IV. RESULTS AND DISCUSSION

C. Effect of Nozzle design on Ejector Performances

Fig. 2 depicts the evolution of the entrainment ration with pressure at exit primary nozzle Pi for constant primary and secondary flow properties (T1=120, P1=1.98bar) and (T2=10°C, P2=12.3mbar) where each pressure is a saturation pressure. For four fixed values of back pressure P3 (30, 32, 34, 36mbar), curves of entrainment ratio have the same shape, it increases until reaching a maximum and later decreases with increasing Pi. For each of the four curves, calculations of ω is stopped with Pi=12mbar≈P2 which presents the limit of the nozzle exit pressure. Otherwise the ejector will be shocked by the value of Pi and the secondary flow could not be entrained into the mixing chamber.

An optimum point is find equal to 1.2, 1, 0.8 and 0.75 for respectively P3 set as (30, 32, 34, 36mbar), when Pi is almost equal to 9mbar. The maximum values decrease with increase of back pressure.

These result indicates the entrainment ratio depends of Pi while it is maximum was found almost for an identical Pi.

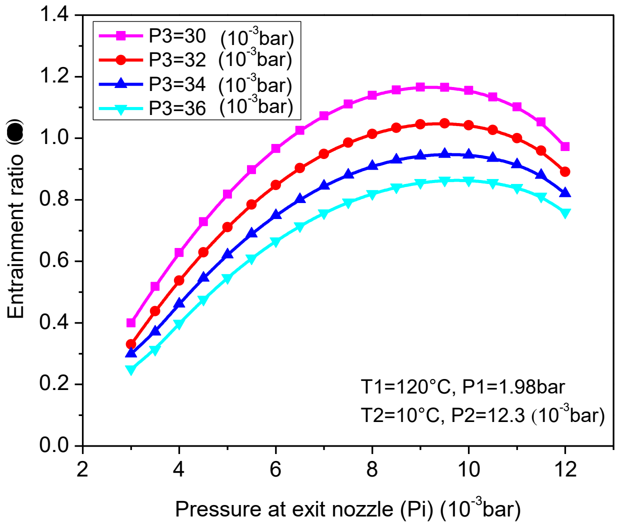

Fig. 2. Effect of pressure at exit nozzle (Pi) on entrainment ratio.

D. Effect of Ejector Design (Area Ratio) on Ejector Performances

Fig. 3 presents the relationship between the pressure at exit the nozzle and the ejector area ratio. For fixed primary and secondary conditions, curves of ejector area ratio have an optimum value corresponding to its maximum. The optimum values decrease with increase of back pressure. As Fig 2, results from fig 3 indicate that the maximum value of the ejector area ratio is reached for an identical Pi regarding to different P3.

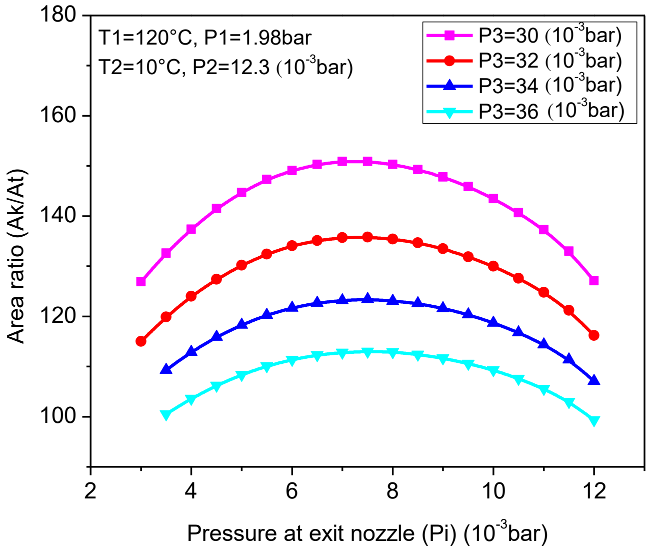

Fig. 3. Effect of Pressure at Exit Nozzle (Pi) on Ejector Area Ratio

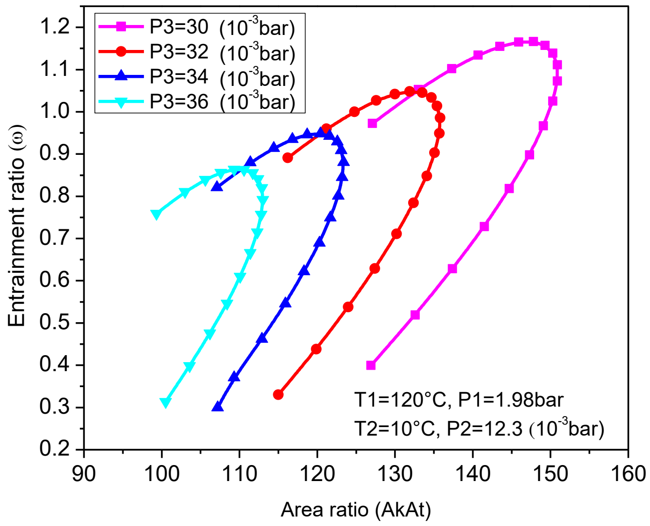

Fig. 4. Effect of Ejector Area Ratio on Entrainment Ratio.

Fig. 4 shows that for every back pressure, there are optimum values of entrainment ratio. For constant primary and secondary operating condition, the optimum values of the entrainment ratio decrease with increasing of the back pressure. While it is possible to have the same entrainment ratio for different value of area ratio and back pressure , i.e to get ω = 0.4, the area ratio of the ejector should be 107,110,120, 125 for back pressure 36, 34, 32, 30 mbar respectively.

Fig. 5 shows the evolution of ejector area ratio with the back pressure, secondary pressure 8, 12, 17, 23 mbar and for primary pressure is constant and equal to 1.98bar. It can be seen that area ratio AkAt increases with increasing the secondary pressure and decrease with increasing the back pressure.

Fig. 6 presents the evolution of ejector area ratio with the primary pressure, secondary pressure 8, 12, 17, 23 mbar and for constant back pressure equal to 36mbar. It can be seen that area ratio AkAt increases with increasing the secondary pressure and the primary pressure.

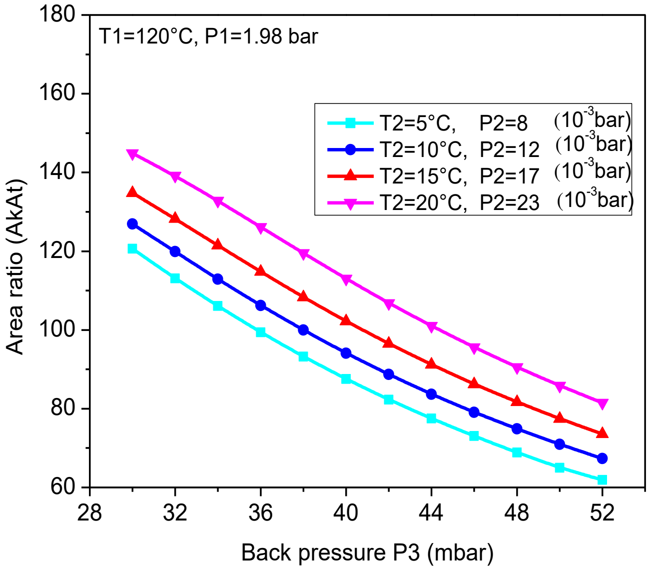

Fig. 5. Effect of back Pressure on Ejector Area Ratio.

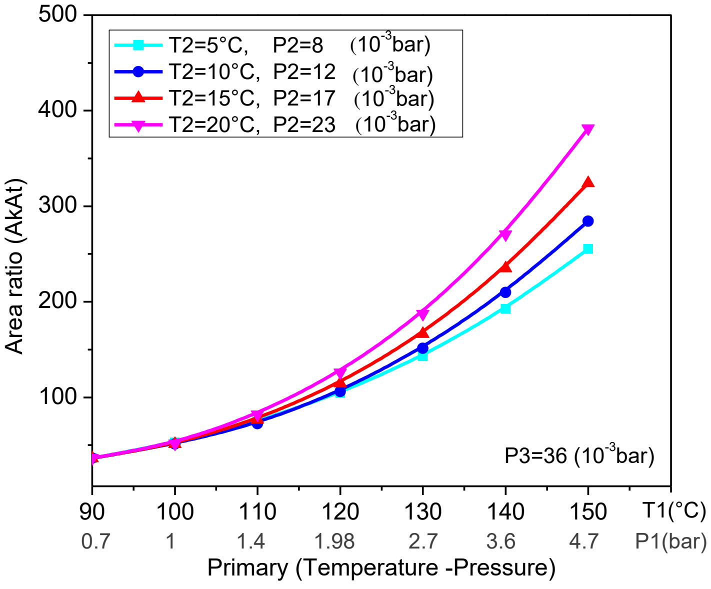

Fig. 6. Primary Pressure on Ejector Area Ratio.

V. CONCLUSION

In this paper, a theoretical investigation is carried to evaluate the performance and limits of design of steam ejector. A simplified ejector 1D–model, taking account of the irreversibility in nozzle, diffuser and mixing chamber is used and a specific chart algorithm is applied to solve it. The model is first validated based on data from literature and then performance of the ejector for varying operating conditions and ejector geometry was studied via the behavior of parameters inside the ejector. It was found that

For constant primary and secondary flow properties (P1,T1, T2, P2), the entrainment ratio increases with increasing pressure at nozzle exit Pi reaches a maximum, and then decreases, when the back pressure P3 is constant. Two borders (starting and ending points) was found limiting the design of the ejector: the ending point is limited when Pi ≈ P2 which chock the secondary flow and disable it to entrained into the mixing chamber. Also Pi related to primary pressure and primary nozzle area ratio. Thus the limit on it is characterized by the nozzle geometry design.

Ejector area ratio has maximum corresponding to an optimum Pi value. While The optimum values decrease with increase of back pressure. For every back pressure there are an optimum value of entrainment ratio that decrease with increasing of the back pressure, for constant primary and secondary operating condition, Area ratio AkAt increases with increasing the secondary pressure and decrease with increasing the back pressure, for constant primary and secondary operating condition.

ACKNOWLEDGMENT

Acknowledgements Doniazed Sioud gratefully acknowledges the Tunisian Ministry of Higher Education and Scientific Research for funding her internships at Rovira i Virgili University of Tarragona (Spain).

REFERENCES

[1] Xiangjie Chen, Siddig Omer, MarkWorall, Saffa Riffat. (2013).“*Recent developments in ejector refrigeration technologies*”. Renewable and Sustainable Energy Reviews, vol.19, pp. 629-651.

[2] Farshi, L. G., Mosaffa, A.H., Ferreira, C.A.I., Rosen, M.A., 2014. Thermodynamic analysis and comparison of combined ejector–absorption and single-effect absorption refrigeration systems, Applied Energy, 133, 335–346.

[3] D. Sioud, R. Garma, and A. Bellagi, “*Thermodynamic Analysis of a Solar Combined Ejector Absorption Cooling System*”, Journal of Engineering Vol. 2018, Article ID 7090524, 12 pages https://doi.org/10.1155/2018/7090524

[4] D. Sioud, M. Bourouis and A. Bellagi, “Investigation of an ejector powered double-effect absorption/recompression refrigeration cycle”, International Journal of Refrigeration, Vol. 99, pp. 453-468 March 2019.

[5] D. Sioud, R. Garma, and A. Bellagi, “*Analysis of Hybrid Ejector Absorption Cooling System*”, Journal of Engineering

[6] M. Elakhdar, E. Nehdi. (2011). *“Simulation of an ejector used in refrigeration systems”*. Int. J. refrigeration, vol. 34, pp.1657-1667.

[7] T. Sriveerakul, S. Aphornratana , K. Chunnanond. (2007).*“Performance prediction of steam ejector using computational fluid dynamics: Part 1. Validation of the CFD results*”.International Journal of Thermal Sciences, vol. 46, pp.812–822.

[8] Hailun Zhang, Lei Wang, Lei Jia, Hongxia Zhao, Chen Wang , Influence investigation of friction on supersonic ejector performance, International Journal of Refrigeration, Volume 85, January 2018, Pages 229-239

[9] Yifei Wu, Hongxia Zhao, Cunquan Zhang, Lei Wang, Jitian Han, Optimization analysis of structure parameters of steam ejector based on CFD and orthogonal test, Volume 151, 15 May 2018, Pages 79-93

[10] Yu Han, Xiaodong Wang, Hao Sun, Guangli Zhang, Lixin Guo, Jiyuan Tu, CFD simulation on the boundary layer separation in the steam ejector and its influence on the pumping performance, Energy, Volume 167, 15 January 2019, Pages 469-483

[11] Satha Aphornatana. (June 1996). “*Theoretical study of a steam-Ejector Refrigerator*”. International Energy Journal, vol. 18 no.1, pp.61-73.

[12] A. Milazzo, A. Rocchetti, Ian W. Eames,.“Theoretical and experimental activity on Ejector Refrigeration”. Energy Procedia vol. 45, pp. 1245- 1254, 2014.

[13] Da Wen Sun. “Variable geometry ejectors and their applications in ejector refrigeration systems”. Energy, vol. 21, pp. 919-929, 1996).

[14] C. Moorthy, V Srinivas, V. Prasad, T Vanaja, *“Computational analysis of a cd nozzle with ‘sed’ for a Rocket air ejector in space applications*”. International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) Vol. 7, Issue 1,pp. 53-60, Feb 2017.

[15] H. El-Dessouky, H. Ettouney, I. Alatiqi, G. Al-Nuwaibit. (2002). “*Evaluation of steam jet ejectors*”. Chemical Engineering and Processing, vol.41, n°6,pp. 551–561.

[16] E.D. Rogdakis, G.K .Alexis, “*investigation of ejector design at optimum operating condition*”, Energy conversion & management, vol. 41, pp. 1841-1849, 2000 .

[17] S. A. Klein, F. Alvarado. Engineering equation solver. Middleton, WI: F–chart software, 2003.