CHARACTERISTICS OF FLOW IN GAS EJECTORS AND PRIMARY NOZZLE GEOMETRY EFFECTS

Bogdan Diaconu, *University "Constantin Brâncuși" of Tg-Jiu, ROMANIA*

ABSTRACT: *Steam and gas ejectors are static device used for pumping (increasing pressure) of a low pressure fluid by means of a high pressure fluid – motive fluid. Ejector technology is simple, low-cost and reliable. The main disatvantage is the low efficiency of the process. The geometry of the device, fluid thermo-physical properties and parameters influence the efficiency of the entrainment process. The efficiency is characterised by the entrainment ratio. Supersonic flow in ejectors resulting from expansion of the motive fluid in the nozzle creates the chocking condition that limits the maximum value of the entrained flow. Expansion of the supersonic motive fluid after the nozzle outlet creates an oscilatory phenomenon that develops in the mixing chamber and can extend as far as the difuser. This phenomenon contributes to a significant increase of the ejector losses. However, it can also promote turbulent mixing, which is beneficial when the purpose of the ejector is mixing of two fluids (combustion mixture). The paper investigates by means of CFD the oscilatory phenomenon developing after the expansion of the primary fluid and the influence of the ejector geometry on the magnitude of the phenomen.*

KEY WORDS: Ejector, Chocking, Oscilatory flow, Expansion, Nozzle

1. INTRODUCTION

Gas and steam ejector efficiency is expressed in terms of entrainment ratio, defined as the amount (flow rate) of motive fluid required to entrain and compress the low pressure fluid. Ejector operation is based on suction of the low pressure fluid caused by local pressure drop of the motive fluid when the last accelerates due to the expansion in the primary nozzle. The main components of any ejector are the primary nozzle, the suction chamber, the mixing chamber and the diffuser. The structure of the device is relatively simple but the flow structure is complex due to shock interactions, turbulent mixing and condensation in two-phase regime. The overall efficiency of the device depends on the characteristics of each process:

- Expansion of the motive fluid in the primary nozzle
- Mixing of the two fluids
- Compression of the mixture in the diffuser

Chen et al [1] reviewed the ejector efficiencies by component and fluid. The analysis shows that the primary nozzle has the highest efficiency and it depend on the fluid and geometric elements. The primary nozzle efficiency is given by the general equation (deviation of the real expansion process from the isentropic one):

$$\eta_{PN} = \frac{h_{inlet} - h_{outlet}}{h_{inlet} - h_{outlet,is}}$$

h_{inlet} - enthalpy at the primary nozzle inlet section

h_{outlet} - enthalpy at the primary nozzle outlet section

$h_{outlet,is}$ - enthalpy at the primary nozzle outlet section considering the isentropic expansion

Variable flow regimes for fixed geometry ejectors results in significant drop of the efficiency.

McGovern et al [2] defined the reversible entrainment ratio efficiency concept, which compares the entrainment ratio of a real ejector to a reversible process with the same inlet fluid states and the same discharged pressure. The flow regimes are as follows [3]:

Reversed flow region – p_D is to the right of point A on the x axis of Fig. 1 and the discharged pressure is too high to allow entrainment. Flow through the converging diverging nozzle is overexpanded, resulting in compression shocks. Motive fluid partially flows back through the entrained fluid inlet.

2. Unchoked entrainment – The discharged pressure drops to point A in Fig. 1, causing the compression shocks at the exit of the motive fluid nozzle to weaken, allowing the pressure at nozzle exit to drop and cause entrainment.

3. Critical operation – The discharged pressure reaches p_D^*, allowing a decrease in pressure upstream and causing the entrained flow to be accelerated to sonic speed within the mixing region.

4. Choked Flow – For values of p_D below p_D^* the entrainment ratio remains constant. The motive fluid is choked at the motive fluid nozzle throat and the entrained flow remains choked in the mixing region.

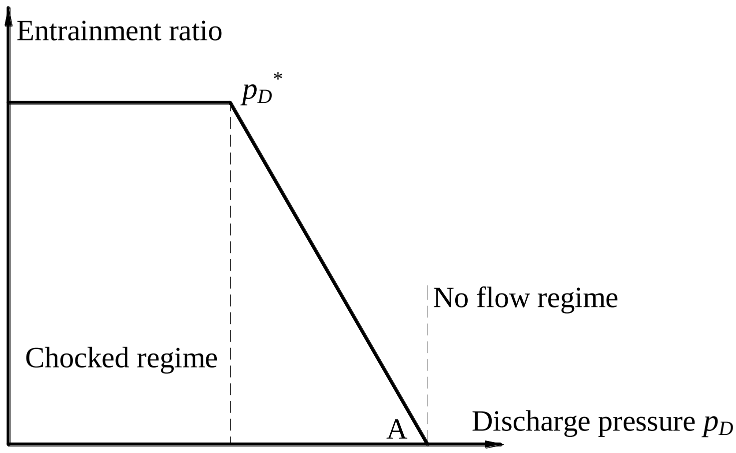
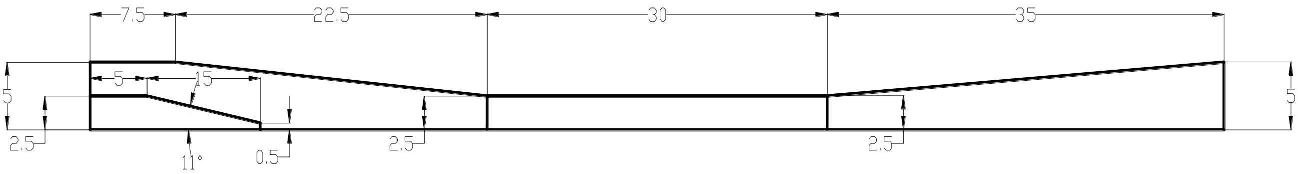


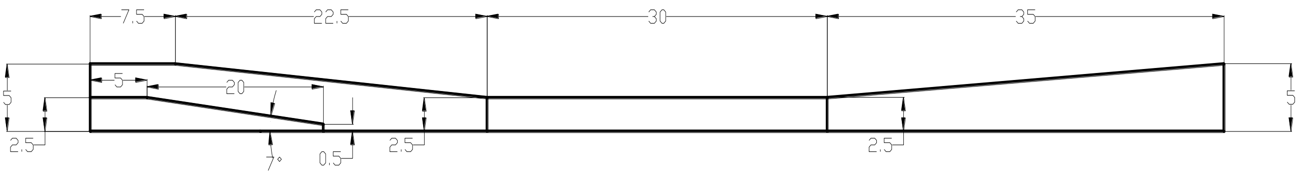
Figure 1. Entrainment ratio vs discharge pressure

2. PROBLEM FORMULATION

Ejector geometry and adaptation to the specific operating condition is a critical factor that influences the efficiency. An ejector with axial suction will be considered in this study since it is considered that the region where entrained fluid is accelerated is critical in the flow structure that develops in the mixing chamber and diffuser. Thus, an acceleration region that does not force the entrained fluid to change the flow direction is expected to improve the efficiency.



Geometry 1: Nozzle converging region 15 mm, angle 11 deg



Geometry 2: Nozzle converging region 20 mm, angle 7 deg

Figure 2. The two ejector geometry cases considered

The geometry of the ejector considered it shown in Figure 2. The objective of the study was to investigate the influence of the entrained fluid flow path on the flow structure and entrainment ratio. All dimensions are given in milimeters. It is considered that varying one geometrical parameter only will provide key information on the influence of that particular parameter. The parameter that was varied was the length of the converging region of the primary nozzle, from 15 mm in case 1 to 20 mm in case 2. This will change significantly the geometry of the flow channel for the entrained fluid and is expected to influence significantly the entrainment ratio. In case 1, the ejector has a relatively short acceleration path with a diverging profile while in case 2 the acceleration path is longer with approximately constant cross section.

The fluid considered was air for both motive and entrained fluids. The fluids parameters were considered the same in the two cases. The CFD modelling considered k-ε turbulence model (most frequently used turbulence model for CFD). Realisable k-ε is known to predict more accurately spreading of both planar and circular jet, therefore it was employed in this study.

The continuity, momentum and energy equations were solved by means of a standard CFD software. The fluid parameters are listed in Table 1. Both cases employed the same values of the fluid parameters in order to discriminate the effect of geometry.

Table 1. Fluid parameters and entrainment ratio achieved for the two geometry cases

Parameter	Flow rate		Temperature		Pressure		Entrainment ratio	
	1	2	1	2	1	2	1	2
Motive fluid	0.601	0.474	300	300	3.0e5	3.0e5		
Entrained fluid	0.317	0.319	400	400	1.7e4	1.7e4	1.89	1.485
Outlet	0.919	0.794	324.9	333.6	4.5e4	4.5e4		

The flow structure presents an oscillatory behavior after the exit of the primary nozzle. Such behavior has been observed in many CFD studies and it cannot be predicted by 1-D ejector models. It is believed that it occurs due to intense momentum exchange between the high-speed motive fluid and the entrained fluid. As the motive fluid jet is decelerated by momentum exchange at the outer regions, the central region will undergo less momentum loss and friction. The main variables studied were velocity, pressure, temperature and density.

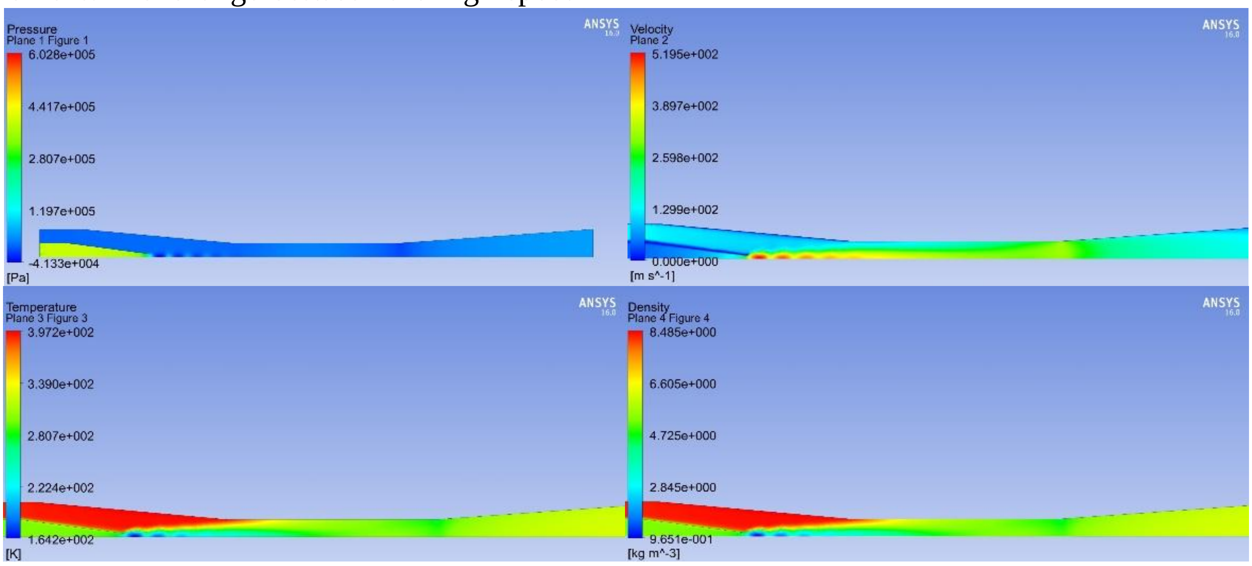


Figure 2. The 2-D profile of the variables studied: velocity, temperature, pressure, density (Geometry case #1)

Velocity, temperature, pressure and density exhibit a similar damped oscilatory profile following the expansion of the motive fluid in the primary nozzle. A number of five oscillations was identified with a maximum velocity value of approximately 1.5 Ma. The oscillatory behavior can be better observed if parameters are plotted along ejector axis, as shown in Figure 3.

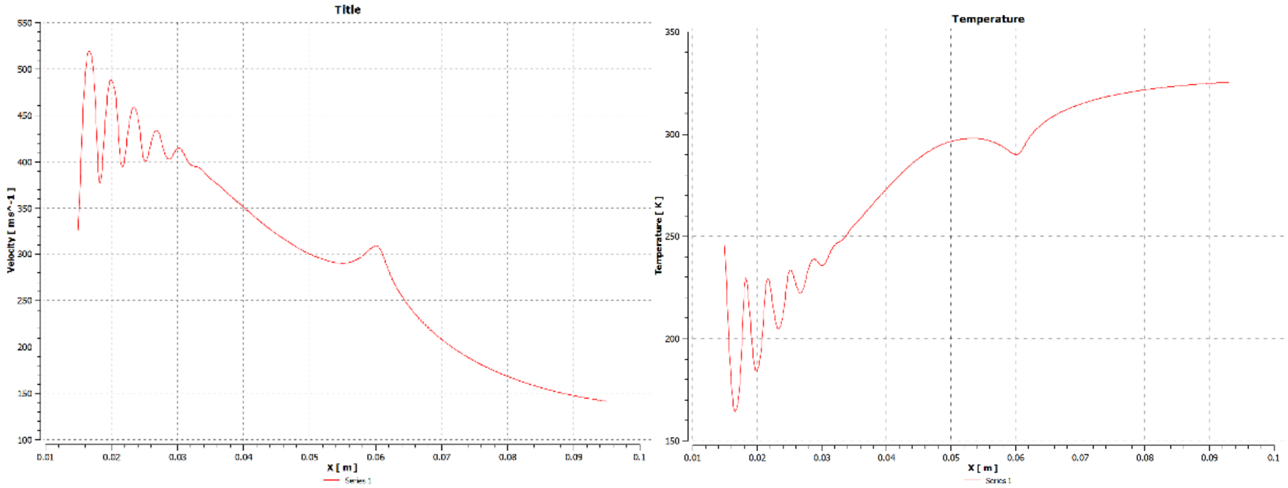


Figure 3. Velocity and temperature profile in the ejector axis. Geometry case 1

Mixing of the fluids is a matter of concern especially for applications in which species transport is the objective. Since the present study does not consider species transport (both fluids are air) the mixing can be assessed by means of the final temperature profile (at the outlet of the diffuser) since the fluids have different initial temperatures.

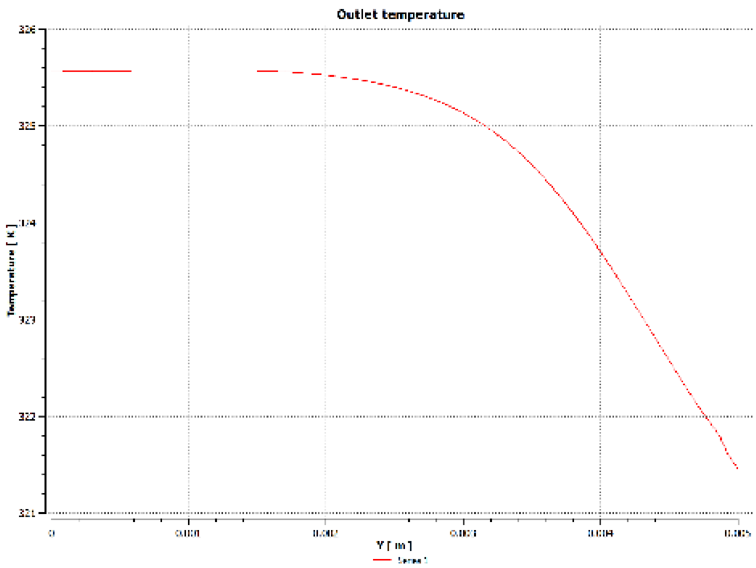


Figure 4. Temperature profile at the diffuser nozzle

The temperature profile at the diffuser outlet offers an image of the mixing degree achieved. The temperature profile in the jet at the diffuser outlet is presented in Figure 4. It can be observed that the central region of the jet has a uniform temperature with a total gradient of approximately 4.5 deg.

The effect of primary nozzle geometry is further investigated by maintaining all ejector dimensions except converging region of the primary nozzle. The primary nozzle geometry is modified by extending the converging region from 15 mm to 20 mm, as shown in Figure 1. The same oscilatory behavior of the flow in the ejector axis is observed, as shown in Figure 5.

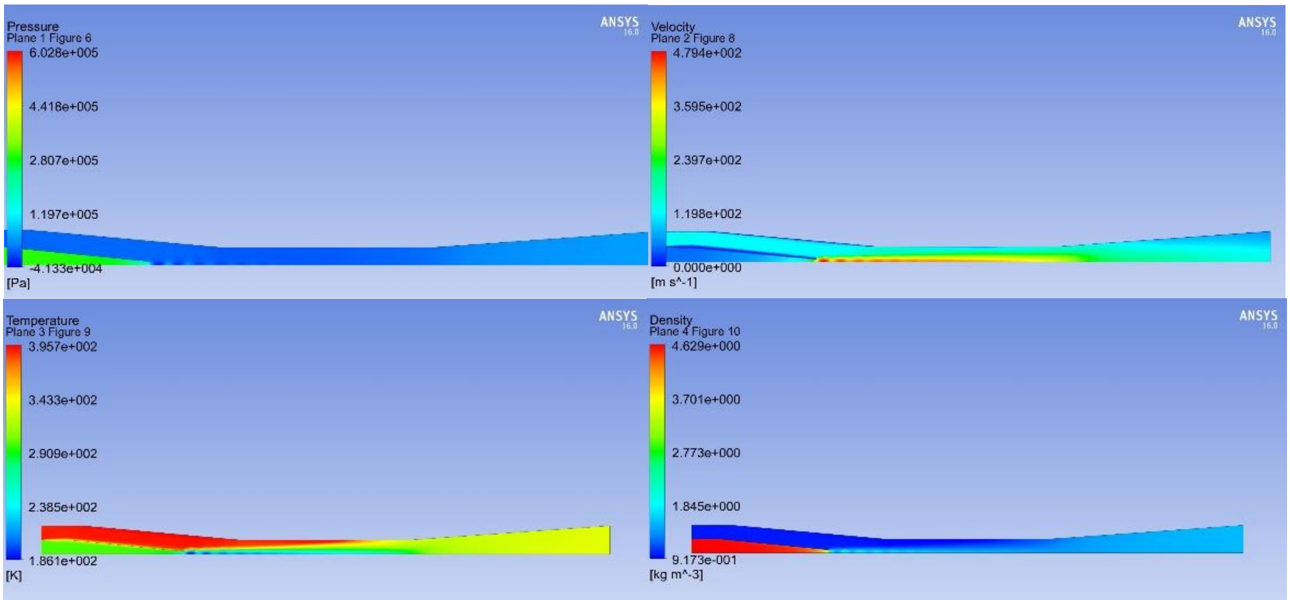


Figure 5. The 2-D profile of the variables studied: velocity, temperature, pressure, density (Geometry case #2)

The first observation is that the maximum velocity reached in the second case is lower than in case 1 (480 m/s as opposed to 520 m/s). This finding is expected as a longer converging region of the primary nozzle will induce supplementary friction losses (given the constant nozzle outlet section). The velocity and temperature profile in the ejector axis is shown in Figure 6.

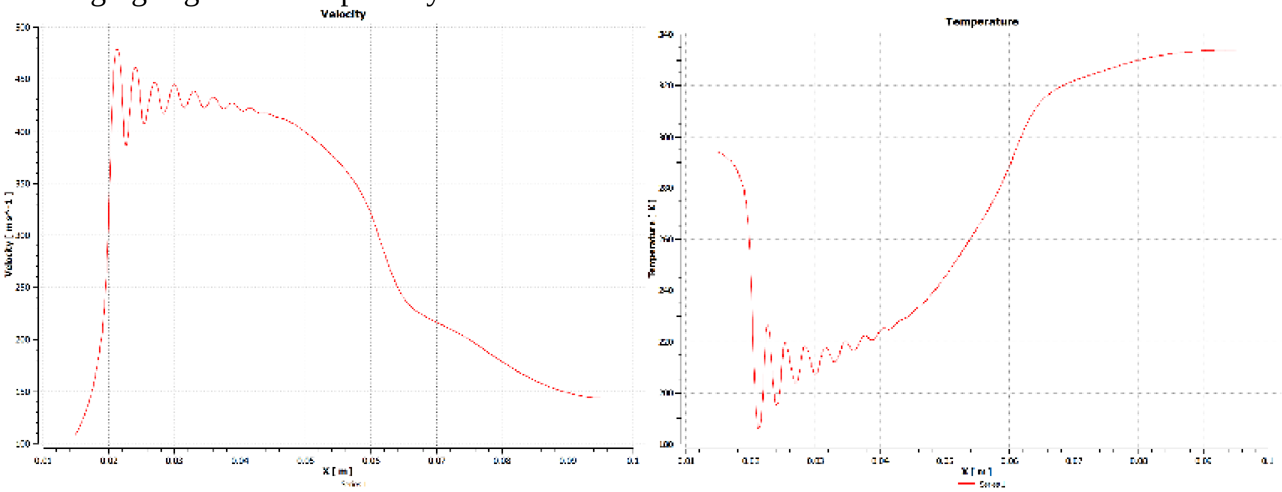


Figure 6. Velocity and temperature profile in the ejector axis. Geometry case 2

CONCLUSIONS

Flow profile and ejector performance – described in terms of entrainment ratio – were investigated by means of CFD for two gas ejector geometry cases. The main objective of the study was to establish the influence of the primary nozzle geometry on the flow profile and ejector performance. In the first geometry case the acceleration path for the entrained fluid consists of a short channel slightly diverging. The flow profile exhibits a number of five damped oscillations (which are in fact shock waves [4-7]). The motive fluid temperature after the expansion in the primary nozzle drops at approximately 165 K. The temperature difference between motive and entrained fluids is expected to promote heat and mass transfer in the first section of the mixing chamber. The density profile in the ejector section can be regarded as an indication of the mixing degree. Another parameter that provide information on the mixing efficiency is the temperature profile in the outlet section of the diffuser.

The second geometry case has a longer accelaration path for the secondary fluid with approximately constant section. This is created by extending the length of the primary nozzle and maintaining all other ejector dimensional paramter identical. With a longer converging region of the primary nozzle and constant outlet section, the motive fluid reaches a lower exit velocity. However, a number of seven damped oscillations of the velocity can be observed. The modifications affecting the motive fluid expansion in the primary nozzle do not affect significantly the entrained fluid flow rate. It can be observed that the flow rate of the primary fluid drops significantly when the length of the primary nozzle converging region increases with 5 mm only. The better entrainment ratio observed in the second case is actually caused by the drop of the primary fluid flow rate. That is to say, a better entrainment ratio has been achieved at the expense of the motive fluid flow rate drop. This is not necessarily a positive effect and it has to be considered in the context of the ejector application.

REFERENCES

[1] Jianyong Chen, Yunhai L., Weixiong Chen, Xianglong Luo, Ying Chen, Zhi Yang, Ian W. Eames, Investigation of the ejector nozzle in refrigeration system, Energy 157 (2018) 571-587

[2] McGovern R.K., Narayan G.P., Zubair S.M., Lienhard V J. H., Analysis of reversible ejectors and definition of an ejector efficiency. International Journal of Thermal Sciences 2012; 54:153- 166

[3] Ronan K. McGovern, Kartik V. Bulusu, Mohammed A. Antar and John H. Lienhard V, One-dimensional Model of an Optimal Ejector and Parametric Study of Ejector Efficiency, ASME International, 2012-06

[4] Zuozhou Chen, Chaobin Dang, Eiji Hihara, Investigations on driving flow expansion characteristics inside ejectors, International Journal of Heat and Mass Transfer 108 (2017) 490–500

[5] Cagri Metin, Okan Geok, Ugurcan Atmaca, Aytunç Erek, Numerical investigation of the flow structures inside mixing section of the ejector, Energy 166 (2019) 1216-1228

[6] Jiapeng Liu, Lei Wang, Lei Jia, Xinli Wang, Thermodynamic model for all modes performance analysis of supersonic ejector considering non-uniform distribution of flow field, International Journal of Refrigeration 96 (2018) 17–24

[7] Jiapeng Liu, Lei Wang, Lei Jia, Xinli Wang, Thermodynamic modeling and sensitivity analysis of ejector in refrigeration system, International Journal of Heat and Mass Transfer 126 (2018) 485–492