SUPERSONIC/SUBSONIC MIXING CHAMBER EXPERIMENTAL ANALYSIS

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Abstract. *Concern about energy efficiency, the waste of natural resources and the desire for cost reduction, has lead to the use of innovative solutions. In this context, a mixing chamber driven by a supersonic injector inducing a main subsonic flow was built at the Aerodynamic Division (ALA) of the Institute of Aeronautics and Space (IAE) to assess the chamber's main physical phenomena and to obtain global characteristic parameters. The injection system discharges compressed air from high pressure reservoirs (through a control valve, and an injector nozzle which operates chocked at Mach number 1.9) in a mixing chamber. The high speed flow promotes the primary flow acceleration from atmospheric condition by momentum transfer. A diffuser sector follows the chamber and allows the flow velocity to decrease to ambient conditions, improving the global device performance. This work presents the theoretical principles that describe the operation and performance of a mixing chamber, and its application in many engineering areas like in the processing industry, natural gas extraction and wind tunnel operation. Each particular application has special geometric and operational characteristics. Subcritical and supercritical regimes that occur in convergent and convergent-divergent nozzles are discussed along with typical operational curves. Some of the theoretical characteristics related to the mixing chamber are demonstrated through experiments conducted at ALA, concerning the pressure distribution in the mixing chamber and in the diffuser, and the entrainment characteristic, which is evaluated by the flow Mach number increase at the mixing chamber entrance.*

Keywords*: Mixing Chamber, Supersonic Flow, Experimental Data*

1. INTRODUCTION

Contemporary society has shown increasing concern about environmental issues that has lead to a massive influx of investment in research into new methods and processes that both seek to optimize the energy issue (preserving the remaining natural resources and minimizing costs) as well as to minimize the impact on the environment (air pollution, noise, among others). The aerospace sector is no different (Jardine, 2005, POST, 2003).

Whether in search of innovative solutions with respect to the operation of wind tunnels through the use of injection systems (Falcão Filho, 2006) or in search for alternatives to reduce the noise of aircraft engines, the study and description of the phenomena involved in mixing high speed jets is of great scientific and technological importance. Despite of the widespread use of ejectors as the sole source of power for wind tunnels, especially in the Russians ones (Bedrzhitsky and Roukavets, 1997), their combined use with compressors still attracts great attention from the scientific community.

The main idea concerning a mixing chamber basically comes from the concept of ejector operation. Gas ejectors are devices used to increase total pressure of a flow current by the action of another flow current at a higher speed. The energy transferred from one current to the other is made up by a turbulent mixing process through the mixing layer developed between currents. The use of this technology is very common in many aeronautical applications, like wind tunnel powering, engine operation, etc., and since the simple extension of the phenomena of incompressible flow being applied to compressible problems is questionable, much theoretical and experimental research has been developed over many decades. Abramovich (1973) is one example of basic compressible flow literature upon which many studies for high speed flows are theoretically discussed. Carrière (1973) theoretically studies the induction phenomenon of mixture in gases. Goebel and Dutton (1991) describe experimental results carried out at the University of Illinois wind tunnel (USA) with seven case studies of compressible mixture of gases, and establish procedures to evaluate the similarity region and the growth ratio present in the turbulent mixing layer. Georgiadis *et al.* (2003) numerically simulate some of the Goebel and Dutton case studies. Many other significant works are worthy of note, however the basic idea here is to support the relevance of such investigations into high speed flow.

With this in mind, the TTP (Pilot Transonic Wind Tunnel) technical team from the Aerodynamic Division (ALA) of the Institute of Aeronautics and Space (IAE) has built a supersonic mixing chamber to support the studies for optimization of the TTP injection system and also to expand the knowledge in high speed flow experimentation.

The mixing chamber has a cross sectional area of 0.17 m x 0.23 m, with a length of 0.55 m, a diffuser section with variable wall angles, and it is driven by one supersonic injector beak which operates chocked at Mach number 1.9. The induced mass flow from the atmosphere is controlled by the injector stagnation pressure, varying from 2 to 10 bars. The mixing chamber is well documented in Silva *et al.* (2010a, 2010b, 2010c, 2010d).

This article focuses the mixing phenomenon comparing theoretical analysis with experimental results conducted in the TTP supersonic mixing chamber facility.

2. THEORETICAL ANALYSIS

In the scientific literature there are different definitions concerning the terms ejector and injector. Abramovich (1973) defines injector as a device which delivers high speed flow into a confined ambient while ejector is referred to as a device which uses an injector to expel or to accelerate a gas current. In this way, sometimes the definition of ejector is mixed up with the mixing chamber definition. Pope and Goin's (1978) definitions for injector and ejector are related with the relative positions into the high speed diffuser. In the present work the definitions found in Abramovich (1973) shall be adopted.

An ejector is of a simple construction and it can work in a wide range of gas parameters, making it possible to change from one operational regime to another. This way, ejectors have a wide range of uses in many engineering applications. Depending on their use ejectors may have different geometries. Some of these uses will be presented.

Figure 1 shows a common use of injectors in driving wind tunnels, like found in many Russian installations (Bedrzhitsky and Roukavets, 1997). In these installations normally the aim is the lower power consumption with the disadvantage of having intermittent operation. The injectors (2) play the role of a compressor, by delivering a relatively small amount of gas flow at high pressure to accelerate a relatively great amount of main flow at low pressure. The reservoir (1) holds compressed gas at a pressure higher than the necessary value in the wind tunnel operation. The relatively high pressure flow adjusted by a control valve (8) and delivered by the injectors (2) is sufficient to keep the wind tunnel operating during a quite long time interval. The high pressure flow induces the main stream admitted from the atmosphere (3), which travels through the wind tunnel test section equipped with an aerodynamic model (7), goes through the mixing chamber (4) and, finally is delivered back to the atmosphere (6). Normally a diffuser (5) is installed at the end to decelerate the flow to atmosphere conditions diminishing the global losses. In this installation, the greater the pressure used, the more mass flow is delivered by the injector and therefore more atmospheric air will be induced at a determined speed.

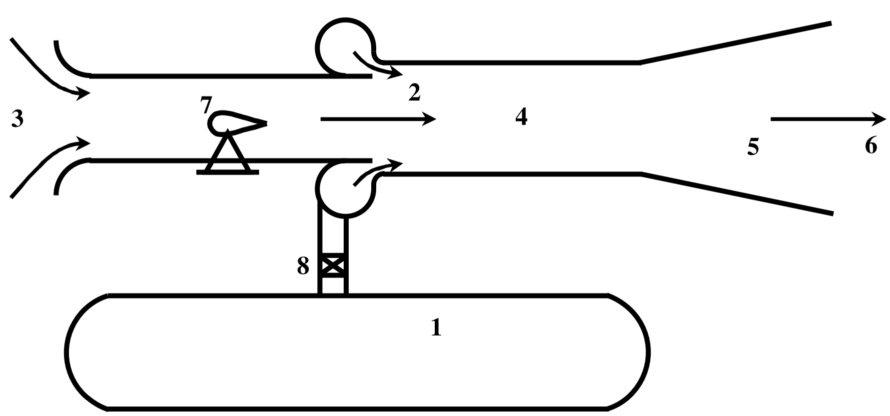


Figure 1. Scheme of a wind tunnel driven by ejectors.

Most ejectors are used to maintain a flow condition in a channel or a chamber, like those used for turbo-reactive motors simulation, as shown in Figure 2. The mass flow from the engine (which acts like an injector) draws the air contained in the chamber (1) through the action of the ejector (3). This way, the necessary ventilation is provided for engine cooling. Hot gas from an engine nozzle is mixed with the air from the chamber, lowering the gas temperature from the exit section (4), and improving the engine operation.

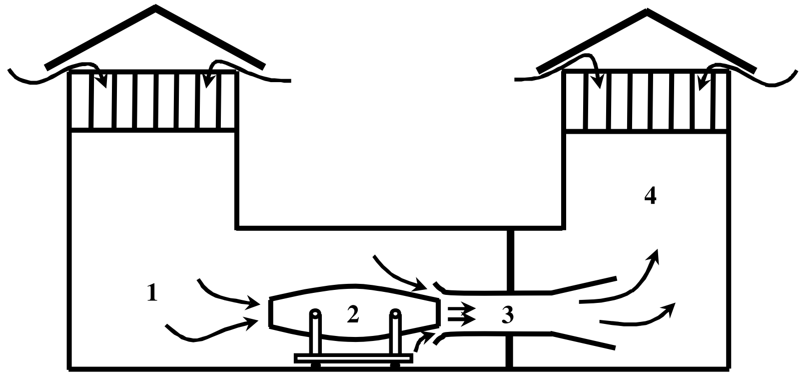


Figure 2. Scheme of a bench of tests for turbo-reactive engine.

Another example of ejectors use is as exhausters/pumps, diminishing pressure in certain compartments. The ejector shown in Fig. 3 normally works with water vapor, and creates an exhauster flow. The same arrangement is utilized in vacuum pumps. In these cases, when very low pressure is desired, the drive fluid used is mercury. Drive flow is injected (1) pumping a desirable fluid flow amount (2), through a mixing process in a mixing chamber (3) and then conducting the mixture through a diffuser (4) to a compartment at a low speed condition.

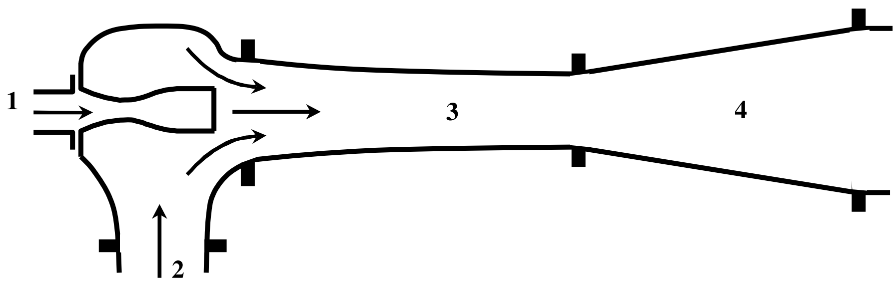


Figure 3. Scheme of ejector acting like a pump.

One successful application of such a device is found in gas extraction installations. Natural gas reserves localized in the same area can have different pressures. If the many supplies are simply jointed into a unique tubing, the low pressure sources would have problems during the extraction process. On the other hand, energy would be wasted from the high pressure sources. In a more efficient use, the high pressure sources may be used to pump flow from the low pressure sources, through the use of ejectors, optimizing the whole extraction process.

A brief operational description of an injector in a mixing chamber specifically concerning the mixing process and the mass flow gain will be presented. Independent of its use, according to Fig. 4, an ejector will always have the following constructive elements: (1) injector – a nozzle with higher pressure (inducer jet), (2) a nozzle with lower pressure (induced jet), (3) mixing chamber, (4) diffuser (sometimes absent). The two currents may differ in composition, speed, temperature and pressure. The aim of the nozzles is to establish the flow in the chamber with minimum possible loss. The disposition of the nozzle may vary: the inducer current may be in the center and the induced current annularly distributed, like in Fig. 4 or on the contrary way, like in Fig. 1. To shorten the whole length and still ensure a good mixture process, one or both currents may be divided in many branches, increasing the surface of contact between currents, and optimizing the mixture process. Although the layout and the shape of the nozzles' variation may change the optimal length of the mixing chamber, these characteristics do not much affect the global parameters of the mixing process. Other parameters are very important, like the cross section area ratio of the inducer and induced jets at the inlet section, *i.e.*, the injection area ratio.

Depending on the operational pressure range, above a critical value it will be important to consider the use of a supersonic (converging-divergent) nozzle in order to optimize the mixing process and the energetic operation of the installation. However, for high supercritical pressure relation the use of an injector with sonic nozzle (also called sonic ejector) is possible, frequently being used in a wide range of gas parameters.

Also in Fig. 4 the main flow parameters associated with the chamber operation is presented: static pressure (p), mass flow ($\dot{m}$), static temperature (T), and cross sectional area (A), related to four distinct sections: 1 – inducer gas inlet, 2 – induced gas inlet, 3 – mixing chamber outlet, and 4 – diffuser outlet.

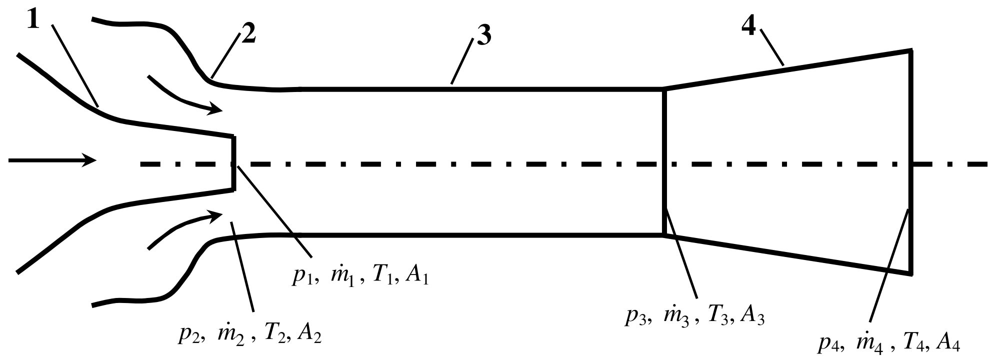


Figure 4. Scheme of the ejector operation principle: (1) nozzle of the inducer jet; (2) nozzle of the induced jet; (3) mixing chamber; (4) diffuser.

The mixing chamber (3 in Fig. 4) may have cylindrical, pyramidal or conical geometry. And this choice greatly influences the performance of mixing jets process. The present work will treat chambers with cylindrical section. The total mixing chamber length definition must be determined after a compromise analysis between a uniform flow at its exit and the pressure friction loss along the walls. The greater the mixing chamber length the more uniform the flow is at its end, but the pressure drop increases.

A diffuser must be installed at the end of the mixing chamber whenever a higher static pressure of the mixture of gases at its end or a lower static pressure in the mixing chamber inlet is desired. This is true for subsonic flow at the end of the mixing chamber. If the mixing flow is supersonic a second throat section will be necessary to de-accelerate the flow to subsonic condition before delivering it to the diffuser. It is worth noting that an ejector may operate without a diffuser. Sometimes the diffuser is replaced by a convergent-divergent nozzle when the aim is to maximize the mixture gas speed. This idea is common in aeronautical engines when the by-pass flow is mixed with hot gas from the engine in a common chamber to be accelerated up to supersonic regime, depending on the nozzle design.

The high speed inducer jet has its static pressure (p_1) below the stagnation pressure of the main current (p_{02}), promoting an acceleration of the main flow. The mass flow ratio between induced and inducer gas, called by ejection coefficient, is given by $n = \dot{m}_2/\dot{m}_1$, and it is a parameter of fundamental importance in understanding the ejector operation. Although the velocity of the induced gas at the inlet section u_2 is always lower than the velocity of the inducer gas u_1, the choice for the cross sectional areas A_1 and A_2 may result in values of n as high as needed.

In an approximate approach, the whole mixing process may be divided conventionally in two distinctive phases, as it can be seen in Fig. 5, and be well applied to subsonic mixture processes. Initially the flow behavior may be compared to a turbulent flow in the presence of a transverse speed discontinuity (the initial region up to section D in Fig. 5). Due to the turbulent speed pulsations the momentum diffusion is very high, gradually forming a so called mixing layer.

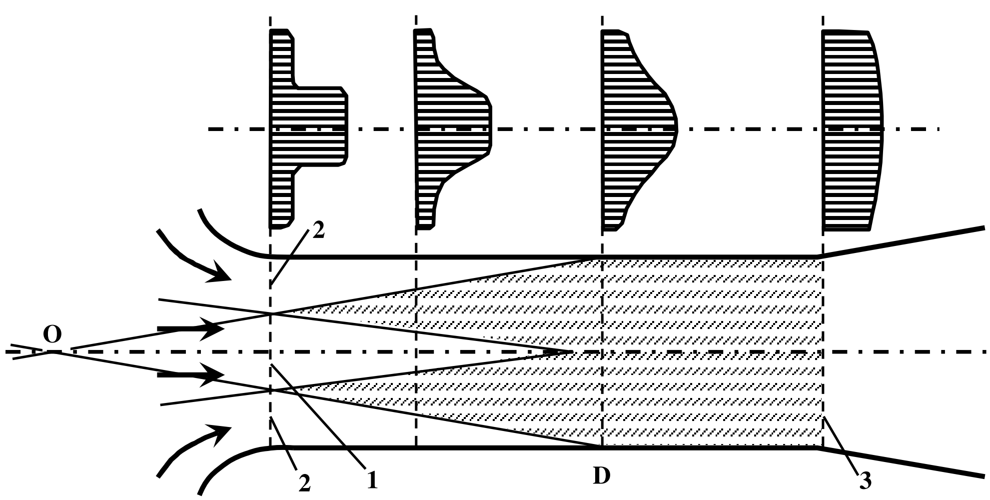


Figure 5. Development of the velocity profiles along the mixing chamber.

Within the mixing layer occurs continuous variation of the gases (1) and (2) parameters – from the inducer to the induced. Outside the mixing layer the flows remain undisturbed. In this first region the induced gas particles are continuously carried into the mixture zone by the higher speed jet. This physical phenomenon characterized by a gradual increase of the induced current mass flow is called "entrainment". Thanks to this phenomenon the static pressure is kept low at the mixing chamber entrance, ensuring the acceleration of the induced current. After some distance, the properties plateau of the inducer current is vanished.

If the mixing chamber is long enough a second region shall appear (after section D in Fig. 5) where there is no plateau of properties, and where there is continuous variation of properties across the field. The section D is called mixture limit section and it is located approximately 8 to 12 equivalent diameters from the mixing chamber entrance. In this region the mixture process is already well developed and the total pressure of the mixture (p_{03}) is as much higher than the induced current total pressure as is lower the ejection coefficient (n). A rational ejector design will choose its geometry to obtain the maximum use of the mixture total pressure with the same initial parameters and ejection coefficient, or to obtain the maximum ejection coefficient with the same initial parameters and the total pressure of the mixture. More detailed description can be found in Trentacoste and Sforza (1967).

The above description is essentially valid for subsonic mixture processes, and it is similar to the mixture processes with incompressible fluids. However, new characteristics are observed in the presence of supercritical regimes, as the pressure of the inducer current in most cases differ greatly from the pressure of the induced current.

If the inducer jet nozzle has sonic geometry (convergent-only shape) at supercritical condition, its static pressure at the initial section A (1 in Fig. 6) is greater than the static pressure in the induced jet (2). The jet progresses expanding and reaching supersonic regime with the formation of expansion waves, as the flow current sees a virtual divergent contour.

The same behavior is observed with supersonic geometry nozzles (convergent-divergent shape). In this case the jet speed at the section A reaches a supersonic well defined Mach number value according to the nozzle design. If the total pressure in the injector is greater than its design value, the supersonic inducer jet further expands with the formation of expanding waves – the jet is said to be at under-expanded condition. The induced flow feels a decrease in cross section area, and it is accelerated, since it is subsonic, with static pressure drop, as it can be seen in Fig. 6.

If the inducer flow is subsonic, the maximum velocity is observed at the inlet section A, while when supersonic, the maximum velocity value and consequently the lower static pressure occurs at the cross section A´ located some distance from the nozzle outlet, and where the cross section area of the supersonic expanded current is maximum, and commonly called the chocking section.

For a given set of boundary conditions and each value of the stagnation pressure ratio p_{01}/p_{02}, one can observe a large variation in the performance parameter of the ejector, namely the ejection coefficient ($n = \dot{m}_2/\dot{m}_1$) and the maximum values of induced gas speed (u_2), corresponding to the various operation regimes of the ejector.

The operation regime for the ejector in which the coefficient of ejection does not depend on pressure at the diffuser outlet is called critical. The particularities of the operation of the ejector system are linked with the critical flow characteristics in the early portion of the mixing chamber – between the input section A and the critical section A' (Fig. 6). As previously mentioned, the subsonic induced flow, while entering the mixing chamber, finds a channel with decreasing cross-sectional area bounded by the chamber walls and the boundary of the supersonic inducer flow. The speed of the induced flow in the minimum section is limited to the speed of sound – the minimum section is the chocking section. This fact determines the limit speed in the entrance section and the maximum mass flow of gas induced.

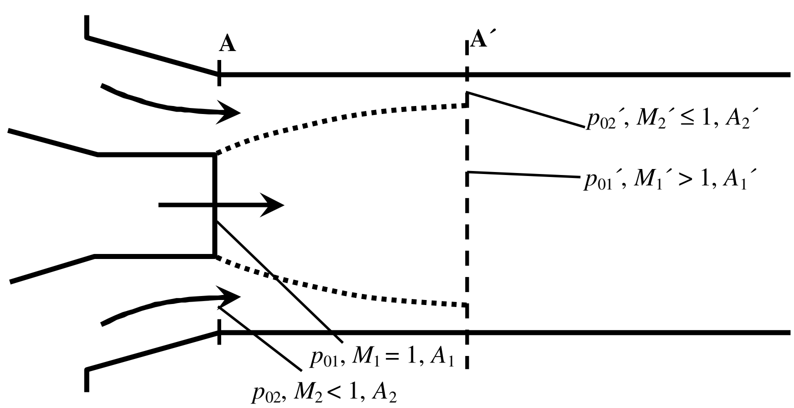


Figure 6. Flow scheme at the beginning of the mixing chamber in a supercritical pressure ratio.

One can realize an important feature present in supersonic flow mixing process: the interaction of a supersonic jet with its surroundings is significantly less intense than that observed between two subsonic jets. Supersonic jets are more stable than subsonic because its frontiers are less susceptible to disturbances. These ideas are more easily understood by observing two situations in presented in Fig. 7. In both situations the reaching flow (represented by 1) undergoes a pressure disturbance in a determined region (represented by 2). In case (a), if for any reason a subsonic jet is subjected to a disturbance, for example by the action of an external pressure p_d over the border, there will be an area decrease of the stream, and consequently an acceleration of the flow and a decrease of pressure. This pressure decrease tends to increase the distortion of the border caused by the pressure p_d reaching another balance situation. The vertical arrow in the figure shows the direction of the differential pressure action ($\Delta p = p_1 - p_2$). In other words, when a subsonic flow interacts with the surroundings it draws back part of the external current and the frontier is quickly distorted – an instable frontier.

On the other hand, in case (b), when a supersonic flow frontier is distorted, the area decrease will result in a pressure rise due to the area decrease, tending to move the frontier back to its original location – a stable frontier. In this case the differential pressure acts in the opposite ($\Delta p = p_2 - p_1$), as shown by the vertical arrow.

So, subsonic current draws mass flow and, on the contrary, supersonic current has rigid frontier resisting to external disturbances.

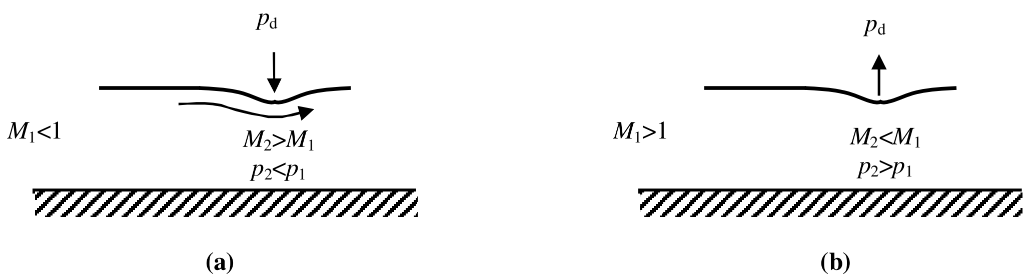
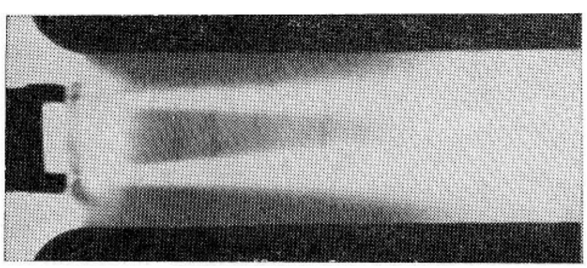
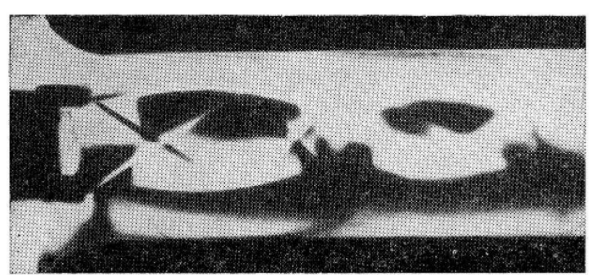


Figure 7. Scheme of the forced action against any current causing frontier curvature in presence of subsonic (a) and supersonic (b) flow.

Figure 8 shows very illustrative examples of *schlieren* photographs of flow developed in mixing chamber of plane ejector working at subsonic (a) and supersonic (b) regimes, with total pressure ratio of 1.5 and 3.4, respectively. In both cases the area ratio is approximately A_1/A_2=1, and the ambient pressure of induced gas and mixture gas are kept constant. Note that in subsonic case (a), as the flow develops downstream the frontier between the currents it thickens and gradual gases parameters variation occurs until reaching a uniform condition. Because the flow is subsonic the frontiers between the currents are not so evident – no shock waves. The same is not observed in supersonic case (b), but the flow development occurs with strong shock-expansion waves structures resembling domes, well captured by the *schlieren* photograph. It can be seen how the supersonic jet core is more persistent in interacting with the surroundings.



(a)



(b)

Figure 8. *Schlieren* photographs of flows in a mixing chamber of a plane ejector working at (a) subsonic regime (p_{01}/p_{02} = 1.5) and (b) supersonic regime (p_{01}/p_{02} = 3.4) (Abramovich, 1973).

To theoretically analyze the mixing process in a first approach, it is considered that both currents have equal static pressure, and there are no hydraulic losses. In this special case study the momentum is conserved along the mixing chamber, and the flow velocity at the chamber outlet section may be expressed in terms of mass flow and velocity for the streams at the chamber inlet by

$$u_3 = \frac{\dot{m}_1 u_1 + \dot{m}_2 u_2}{\dot{m}_1 + \dot{m}_2}. \tag{1}$$

The difference between the kinetic energy at the inlet and the kinetic energy at the outlet section may finally be expressed after substitution of u_3 from Eq. (1) by

$$\Delta e = (e_1 + e_2) - (e_3) = \frac{1}{2}\left(\dot{m}_1 u_1^2 + \dot{m}_2 u_2^2\right) - \frac{\dot{m}_1 + \dot{m}_2}{2} u_3^2 = \frac{\dot{m}_1 \dot{m}_2}{\dot{m}_1 + \dot{m}_2} \frac{(u_1 - u_2)^2}{2}. \tag{2}$$

This expression indicates that the loss of kinetic energy comes only from the kinetic energy involved during the mixing process. The last expression in Eq. (2) shows that the loss is as high as is the velocity difference between the two mixing streams. It is interesting to observe that the global loss, which comes from viscous process, is represented in Eq. (2) without being directly expressed by terms with fluid viscosity. In other words, for determined u_1 and n in order to obtain the minimum kinetic energy loss it is necessary increase u_2 to the nearest of u_1. On the other hand the momentum transfer occurs by the mixing layer between two currents and different speeds. Then, to diminish pressure loss and still have efficiency in the ejector one can think to increase the contact area as much as possible. In principle, supersonic/subsonic mixing chamber does not seem to have good performance.

However, frequently the static pressure is not constant along the mixing chamber. So, a second hypothesis will be assumed to analyze the mixing process. In this case the flow density will be considered constant along the mixing chamber – this is clearly right for ejectors working at low speeds. Figure 9 shows a typical result of pressure distribution along a mixing process.

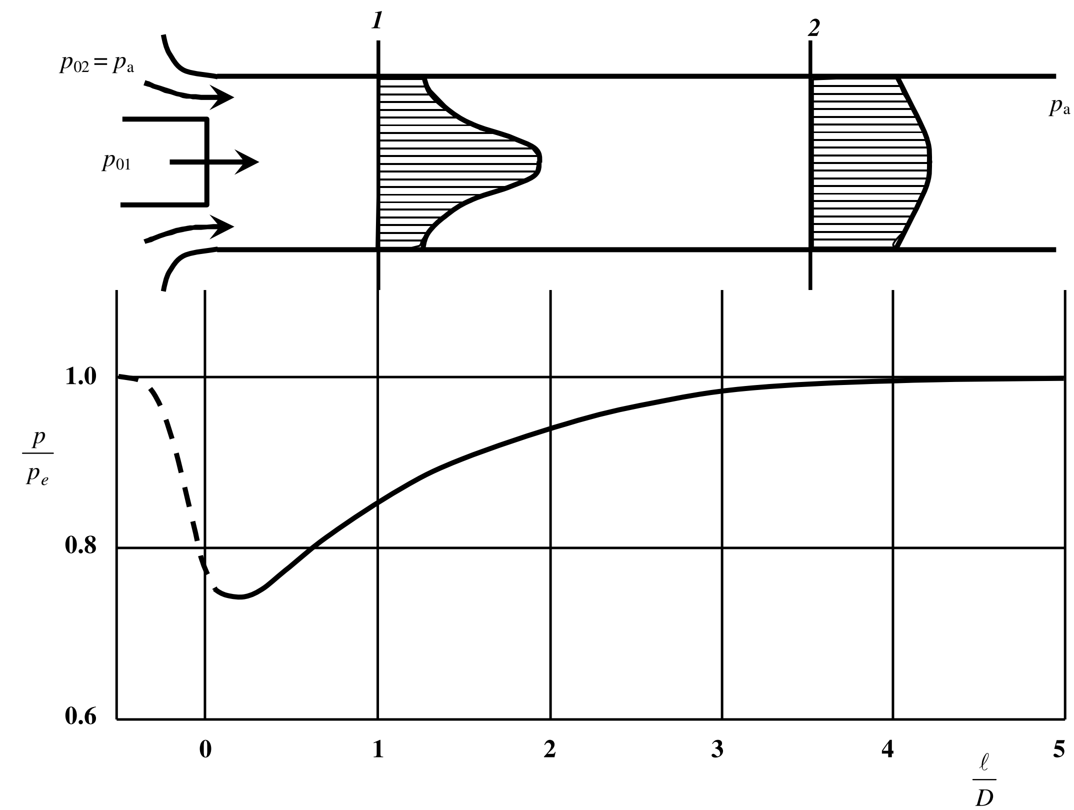


Figure 9. Static pressure variation along the mixing chamber in subsonic mixture of jets.

To reflect the level of uniformity in the velocity profile a new important parameter may be determined based on the relation between two evaluations of the transversal velocity distribution, as can be expressed by the parameter τ, called field coefficient, in Eq. (3), given in terms of area elements in cross section and the related velocity. It is easy to note that for uniform velocity profile the value of τ is 1 and for all other cases greater than unity. The parameter τ represents the level of uniformity of the velocity field in a certain cross section, and so, it is expected that $\tau_1 > \tau_2$.

$$\tau = \frac{A\int u^2\, dA}{\left(\int u\, dA\right)^2}. \tag{3}$$

It is easy to demonstrate that the momentum at a determined cross section may be given by

$$\dot{m}\, u \;=\; \tau\frac{\dot{m}^2}{\rho^2 A}, \tag{4}$$

where ρ is density. Writing the momentum equation applied to the control volume between sections 1 and 2, one can obtain

$$\rho\int_1 u_1^{\,2} dA - \rho\int_2 u_2^{\,2} dA = -\left(p_1 - p_2\right) A\,. \tag{5}$$

Since $\tau_1 > \tau_2$, the left hand side of Eq. (5) is always positive along a mixing layer development, it results that $p_2 > p_1$, and this fact can be realized in the graphic of Fig. 9 by the branch with a continuous line, *i.e.*, the pressure rises in the velocity development in the mixing chamber. However the sudden pressure decay close to the entrance, shown by the dashed line in Fig. 9, is caused by another physical phenomenon: the entrainment caused by the low static pressure of the inducer, which causes the acceleration of the induced flow from far away upstream to the mixing chamber entrance.

From the lowest static pressure value further, the induced flow continues to be accelerated but not for pressure action, since the pressure gradient is negative, but due to momentum diffusion through shear forces in the mixing layer.

3. EXPERIMENTAL METHODOLOGY

Figure 10 shows a scheme of the mixing chamber installation, pointing out the inlet from atmosphere section (2), the injector outlet section (1), the mixing chamber outlet section (3), and the diffuser outlet section (4). The injector was designed to operate chocked at Mach number 1.9, and it is supplied by compressed air from reservoirs through a pressure control valve.

Much experimental data was collected with the installation at various stagnation pressure conditions (4 bar, 5 bar, 6 bar, 7 bar, 8 bar, 9 bar and 10 bar), different diffuser opening angles (0.36°, 3.8° and 7° combined with upper and lower walls) and injector angles related to mixing chamber wall (0°, 2.5°, 5°, 7.5° and 10°). These experiences are fully documented in Silva (2010d). The present work will depict some of those results, related more with the mixing process between the supersonic jet and the atmospheric flow stream entraining the mixing chamber.

The various openings of the diffuser are represented by the distance between the edges of the upper and lower walls in the output section of the diffuser and the horizontal plane of symmetry of the diffuser. The designation 180u125d corresponds to the configuration of the diffuser in which the upper edge is 180 mm above the horizontal plane of symmetry and the lower edge, 125 mm. The configuration 180both, which stands for 180u180d, corresponds to an opening ratio equivalent to that found in the diffuser of the mixing chamber of TTP.

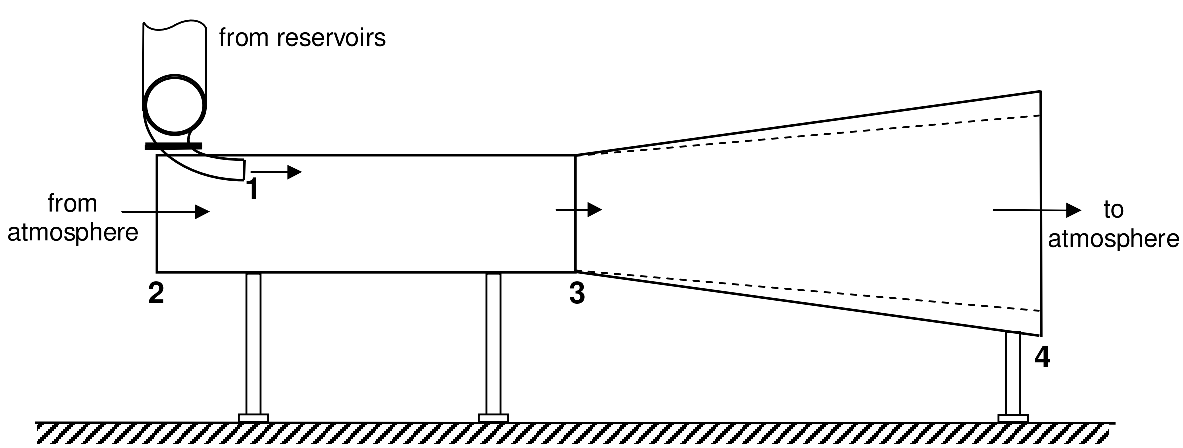


Figure 10. Scheme of the mixing chamber.

The mixing chamber configurations selected to show herein were: the injector stagnation pressures of 4 bar and 5 bar, the injector at an angle of 0^o, and the upper and lower diffuser walls of 0.38^o and 2.36^o, corresponding to 125 mm and 180 mm of opening from the horizontal plane of symmetry, respectively.

The velocity at the mixing chamber entrance (2) was measured using Pitot tubes – the velocity profile was verified to be very uniform. To map the velocity at the mixing chamber exit (3) a hot-fiber device was used, and to map the velocity profile at the diffuser exit (4) nine Pitot tubes arranged in a rake were used. The Pitot tubes ports were connected to differential pressure scanner sensors from PSI™ (PSI, 2000). The conditions at the injector exit (1) are determined by the control system parameters and the assumption of chocking condition of the flow at the injector throat section.

4. PRACTICAL RESULTS

A better way to represent the performance of an ejector is through its characteristic curves. The characteristic curves are defined as the relation between some of the ejector parameters, such as the ejection coefficient, and the operational conditions. An example of how one can build these kinds of curves is shown in Figure 11. The Experimental Mixing Chamber is opened to the ambient: at the entrance of the mixing chamber and at the exit of the diffuser. Then, it can be considered that the static pressure at the diffuser exit p_4 and the stagnation pressure at the mixing chamber entrance p_{02} are equal to the atmosphere pressure. This last assumption is based on the fact that the air is adiabatically accelerated from rest to the inlet velocity u_2.

During the experiment, the stagnation pressure of the inducer flow (injector) was set higher than 10 bar and then the reservoirs were continuously discharged whilst the control valve opening was kept constant. The induced flow velocity could be obtained by placing a Pitot probe in the inlet section, and the ejection coefficient was determined. It is important to note that the injector works chocked at Mach number 1.9. The whole experience is represented by the curve in Fig. 11 from the left to the right (decreasing the injector stagnation pressure).

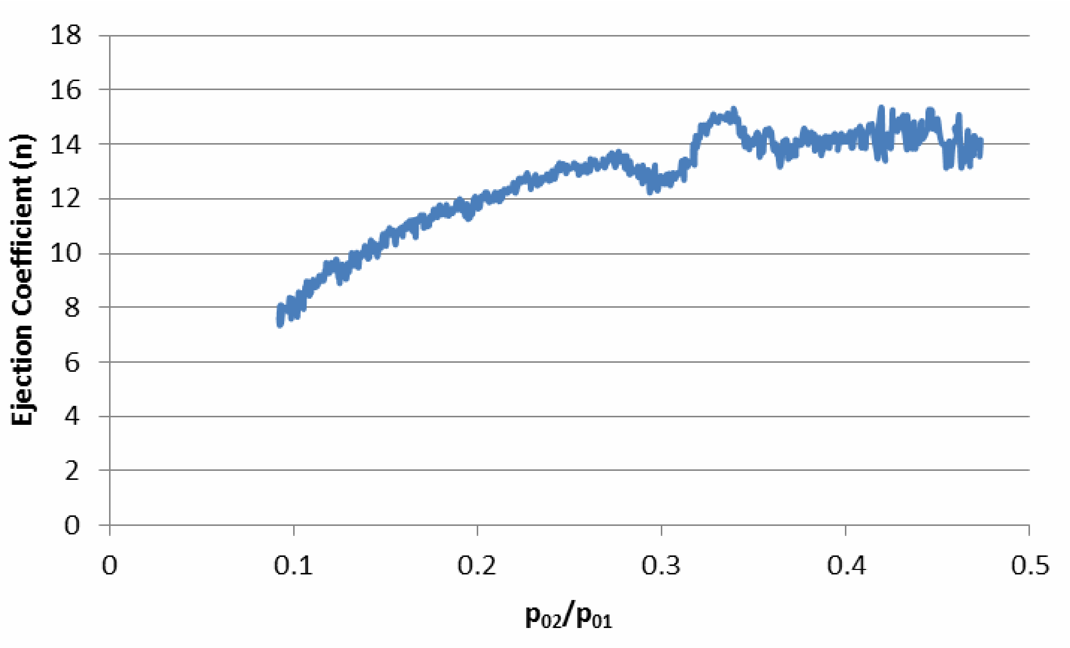


Figure 11. Characteristic curve determination for an ejector opened to the ambient.

Note that, for a given injection area ratio ($\alpha = A_1/A_2$), the ejection coefficient n decreases with an increasing injection pressure ratio $\Pi_0 = p_{01}/p_{02}$. The reason for this is the fact that the inducer gas mass flow increases with increasing p_{01} with much more intensity than the increase of the mass flow of the induced gas. The trend to decrease is accentuated when the ejector reaches the critical regime (high values of Π_0) culminating with the blockage of the ejector (when n becomes null). Abramovich (1973) has shown many other ways to represent the characteristics curves, depending on the particular details of construction and operation of each ejector.

In order to verify if the mixing process along the mixing chamber is occurring satisfactorily, it is desirable to obtain the velocity distribution at the exit section of the mixing chamber and evaluate the field coefficient as a measure of the uniformity of the flow. A hot-fiber anemometer was placed in the exit section of the mixing chamber by an orifice in the lower wall that allowed the free movement of the probe by a coordinated table placed under the experimental facility in such a way that a measurement mesh could be covered. A mesh of 70 measuring points with a refinement in the upper half section was adopted to allow a better characterization of the inducer jet from the injector. An example of the velocity profile for a given diffuser configuration is presented in Figure 12.

Each set of data, obtained for a different flow condition, were interpolated by cubic polynomials and, then, the expression given by Eq. (3) could be numerically evaluated to provide the corresponding field coefficient at the mixing chamber exit. The resulting values are presented at Table 1.

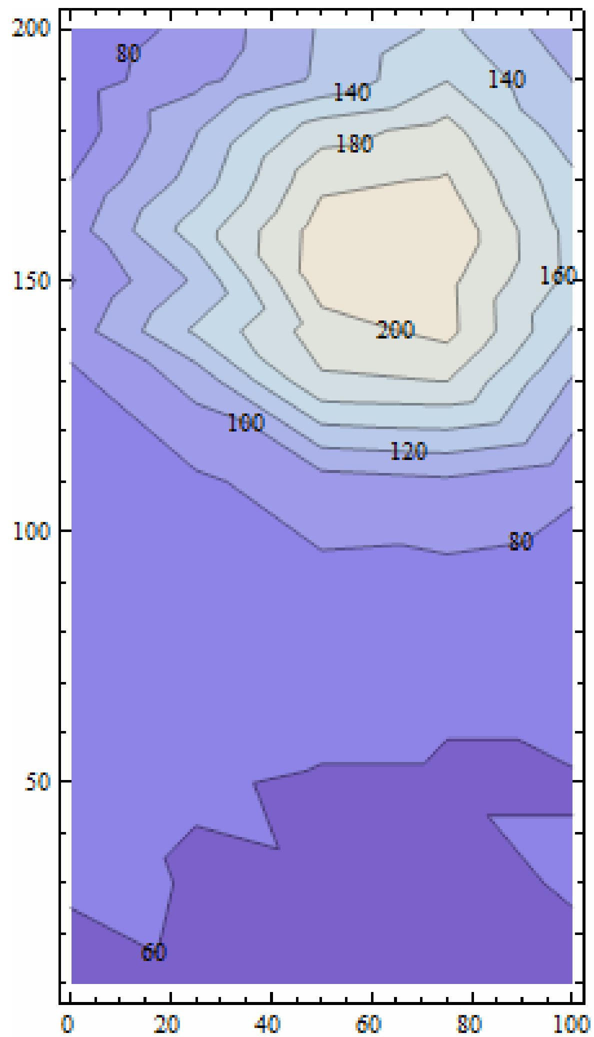


Figure 12: Velocity distribution profile along the exit section of the mixing chamber (p_{01} = 4 bar, diffuser at configuration 125u125d) – Mean velocity contour plot. The axes represent distances in data acquisition frame in mm.

Although there were small differences in the field coefficient values, it is remarkable that, for a given injector stagnation pressure, the smallest value is achieved when the diffuser has an asymmetric opening. This can be explained by the fact that, due to the asymmetric design of the mixing chamber (with just one injector placed in the upper wall) and the observed trend of the high speed jet to follow the upper wall of the diffuser, the flow along the diffuser lower wall experiences a strong decrease in its speed in such a way that it can even detach. The asymmetric configuration of the diffuser is an attempt to avoid this low energy region and improve diffuser efficiency (see Silva *et al.*, 2010b). The results have shown that by doing so the performance of the mixing process is also improved. For both pressures the field coefficient was also determined at diffuser exit with the diffuser in the opening configuration 180 both. It is interesting to observe that at the diffuser exit the field coefficient was greater than at the mixing chamber exit, denouncing that the diffuser did not work properly. This indicates a possible recirculation of the flow and, since the velocity profile was obtained with Pitot tubes, it was not possible to measure negative velocity at diffuser exit.

Table 1: Field coefficient at the exit section of the mixing chamber.

Injector Stagnation Pressure (p_{01})	Diffuser Configuration	Field Coefficient τ	
		at mixing chamber exit	at diffuser exit
4 bar	180 both	1.280	1.584
	180u 125d	1.238	-
	125 both	1.242	-
5 bar	125 both	1.229	-
	180 both	1.310	1.416

To perform a further characterization of the mixing process, the growth rate of the shear layer thickness between the inducer and the induced flow, denoted by *db/dx*, was calculated considering that at the exit section of the injector nozzle the shear layer thickness is null. Following Goebel and Dutton (1991), the mixing-layer thickness is defined as the distance between two transversal positions for which the mean streamwise velocity is equal to ($u_1 - 0.1\ \Delta u$) and ($u_2 + 0.1\ \Delta u$), being u_1 and u_2 the local mean streamwise velocities ($u_1 > u_2$) at a certain transverse section – as called here potential-like region or core region. Mapping the flow speed in the exit sections of the mixing chamber and diffuser, one can determine the average growth rate over these two basic components of the ejector and compare the resulting values with those presented in literature (Goebel and Dutton, 1991) and with those previously calculated numerically (Silva *et al.*, 2010b). The results of this analysis are presented in the Table 2. The calculated values considered two orthogonal planes of development of the jet: the vertical plane (y-direction) and the horizontal plane (z-direction), both planes passing through the point of highest velocity at the considered velocity profile and the center of the injector exit. The growth rate was calculated always considering two longitudinal stations. In a first determination, the jet development from the ejector exit to the mixing chamber exit was considered. It is remarkable that the jet had a development in the vertical direction ten times greater than that in the horizontal direction. It is even more impressive when taking into consideration the distance until the end of diffuser, the growth rate was lower, *i.e.*, the diffuser contributes negatively in the mixing layer growth process, as first observed in the determination of the field coefficient. This is a clear indication of flow detachment into the diffuser.

Table 2: Shear layer growth rate variation for diffuser opening of 180 both.

	4 bar		**5 bar**	
	$\Delta b/\Delta x\|_z$	$\Delta b/\Delta x\|_y$	$\Delta b/\Delta x\|_z$	$\Delta b/\Delta x\|_y$
from ejector exit to mixing chamber exit	0.0079219	0.0838614	0.0079342	0.0830922
from mixing chamber exit to diffuser exit	0.0049087	0.0231048	0.0040401	0.021191
from ejector exit to diffuser exit	0.0056364	0.0027305	0.0049806	0.0039963

Goebel and Dutton (1990), in their experimental study on the two-dimensional turbulent mixing of jets, mentioned that for the case referred to as 3 (mixture of two jets with Mach number of 1.96 and 0.27, similar to the present experimental condition), the growth rate of the layer mixing was about 0.059. Thus, the results obtained here into the mixing chamber only, although of the same order of magnitude, show a stronger growth of the mixed layer. This phenomenon seems to be invariant with increasing Mach number (related to the stagnation pressure of the injector) and with the configuration of the diffuser, at least in the investigated range. The probable reason for the higher growth rate of the shear layer into the mixing chamber may be addressed by the fact that the study carried by Goebel and Dutton (1990) reflect a two-dimensional physics whereas, in the current study, the phenomena involved are essentially three-dimensional.

5. CONCLUDING REMARKS

The theoretical basis for the analysis of an ejector was presented, giving special attention to the mixing process and its contribution to the overall performance of the mixing chamber and, consequently, the ejector itself. The physical phenomenon present in the momentum transfer across the shear layer is addressed and a practical parameter to allow the mixing process efficiency quantification is defined, namely the field coefficient.

The major experimental results concerning the mixing chamber overall performance and the mixing process itself are also presented and compared with similar results found in the literature. These results are part of an optimization study for the TTP injection system, whose initial steps are documented in Silva *et al.* (2010d) and remains in course.

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