Numerical study of the injection process in a transonic wind tunnel. Part II: The off-design points

João B.P. Falcão Filho, Marcos A. Ortega

Abstract

For many years now, injection has been of great utility in the wind tunnel activity. Sometimes injection is the sole source of power. Other times it is used in an auxiliary fashion in conjunction with the main compressor. This paper focuses on this last instance. In a transonic facility, some supersonic injectors are installed at the entrance of the transition section, with the ultimate aim of expanding the Reynolds number envelope without demanding extra power of the main compressor. The objective of this work is the numerical investigation of the mixing process between the supersonic streams coming out of the injectors, and the tunnel main subsonic current. In a first part of this reporting, the present authors have advanced the basic information, and discussed the results for the physical situation that was designated as “the design point”. This corresponds to a setting such that, exactly at the entrance of the mixing section — where the two flows start to interact —, the static pressures of the two mixing streams are equal. To obtain such state, one acts upon the stagnation pressure of the supersonic nozzles. The design point corresponds to a working condition, for which, in principle, losses are minimized. The aim of the present paper is to report upon a set of conditions that we refer to as the “off-design points”; here, the initial static pressures of the two currents are not equal. Besides investigating these new settings, many comparisons with the operation at the design point are also performed. Initially, an overview of the flow field for all cases is presented, and attention is called to the expansion and compression domes, that now, for the off-design points, are much more illustrative. After that, a thorough study is undertaken comprising the mixing layers growth behavior, and the performance of the mixing chamber in terms of pressure losses, overall gain and efficiency. As a consequence of these analyses, the nozzles stagnation pressure for a zero gain was obtained. This is an important result, because it represents the threshold for the efficient use of the injection process.

1. Introduction

During the second half of the last century, the transonic wind tunnel has evolved continuously and its usage today is basically common practice. On the other hand, a complete transonic facility is a very expensive installation, especially the element compressor. For this reason, an “injection capability” was incorporated into the conceptual design of the Brazilian transonic wind tunnel. The idea is to use it as an auxiliary source of power, in the sense that it would be activated either to “alleviate” the compressor in a normal run, or to be “called upon” in order to reach ranges of the Reynolds number that otherwise would not be reachable with the compressor only. Fig. 1 illustrates this by showing the industrial tunnel’s envelope. Because of its novelty, both in terms of concept and positioning inside the circuit, the injection system has to be tested beforehand, and then, a 1/8 scaled pilot facility is being designed and shall be constructed in order to support the development of the industrial installation. (From now on the pilot tunnel will be indicated by the nomenclature PTT.) The basic lay-out corresponds to ten nozzles, five at the floor and five at the ceiling, all of them mounted at the entrance of the transition section. This element of transition is the one that transforms the shape of the tunnel transversal sections from square at the entrance to circular at the exit. The exit of the transition chamber corresponds to the entrance of the first diffuser.

Now, let us consider that the tunnel is already running and the injection is turned on. The objective of this work is the numerical simulation of the mixing process that is set at the transition chamber, which, by the adopted design, happens to function also as the “mixing chamber”. In a former publication [1] the present authors discussed the basics of the formulation, the main simplifying assumptions, and the various difficulties that had to be faced to accomplish the initially proposed goal. The results reported in that paper referred to a specific physical situation, which was...
of the mixing chamber both width and height are equal to width of 30.0 cm and a height of 25.0 cm, while at the entrance chamber are given in Fig. 2(a). The test section of the PTT has a trial facility. Some geometrical details of the transition/injection herein are referred to the PTT configuration and not to the industrial transonic tunnel operation envelope. Test section conditions.

2.1. Statement of the problem

It is important to stress that the simulations to be reported herein are referred to the PTT configuration and not to the industrial facility. Some geometrical details of the transition/injection chamber are given in Fig. 2(a). The test section of the PTT has a width of 30.0 cm and a height of 25.0 cm, while at the entrance of the mixing chamber both width and height are equal to 33.1 cm. There are five nozzles at the ceiling and five at the floor of the tunnel and their width and height are equal to 1.57 cm and 2.26 cm, respectively. Considering the ratio of widths between nozzle and tunnel (Fig. 2(b)), one immediately observes that the numerical treatment of the problem has to be necessarily three-dimensional. At the design condition, the test section Mach number, stagnation pressure, and temperature, are, respectively, 1, 110 kPa, and 313 K, while at the entrance plane of the mixing chamber the Mach numbers are 0.51 and 1.90, and the static pressures for both subsonic (coming from the tunnel) and supersonic (coming from the nozzles) streams must be equal. To guarantee that the static pressure of the supersonic flow at the exit of the nozzles matches the pressure of the main subsonic stream, one is able to set the nozzle’s stagnation pressure by means of a controlling valve, which is mounted between the high-pressure reservoirs and the supersonic feeding chamber. The nozzles’ stagnation pressure corresponding to the design condition will be indicated by $p_{0,\text{des}}$. The off-design cases to be studied are such that the ratio ($p_{0,\text{inj}}/p_{0,\text{des}}$) was assigned the values 1.30, 1.15, 0.85, and 0.70, where $p_{0,\text{inj}}$ stands for the nozzles stagnation pressure.

In the next section we shortly state the problem, and give, also very briefly, some details about the numerical tools. In the sequel we pass immediately to the discussion of the results. Initially, an overall view of the physical scenario that is established when the off-design points are set is shown and discussed. The analysis of the various layers and the performance of the mixing process are presented in the following. Finally, comparisons with the design point solution are duly discussed.

2. Basic formulation and solution strategy

### 2.1. Statement of the problem

Some simplifying assumptions were introduced; otherwise the problem would be almost intractable. The first was to consider the domain of solution — the volume between planes $S_1$ and $S_2$ in Fig. 2(a) — as having the same squared transversal section along all the longitudinal length. One should remember that the injection mixing is realized at the transition portion, the element of the tunnel that transforms the squared section at the inlet to a circular form at the exit — see Fig. 2(a). (It is important to have in mind that, the design of the transition chamber is such that the cross-sectional area is kept constant, in spite of the geometrical form variation.) Another simplification was applied to the flow about and inside the nozzles. This is important because regions of large viscous gradients emanate from those elements and cross the entrance plane of the calculation domain (plane $S_1$ in Fig. 2(a)). There are two planes of symmetry, one horizontal and one vertical that contain the central axis of the tunnel. This permits the adoption of only one quadrant as the calculation domain, and this is illustrated by the shaded area in Fig. 2(b).

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$a$</td>
<td>sound speed (m/s)</td>
</tr>
<tr>
<td>$\bar{a}$</td>
<td>average of “freestream” speeds of sound, $(a_1 + a_2)/2$ (m/s)</td>
</tr>
<tr>
<td>$R$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$M_r$</td>
<td>relative Mach number, $\Delta u / \bar{a}$</td>
</tr>
<tr>
<td>ml</td>
<td>mixing layer</td>
</tr>
<tr>
<td>PTT</td>
<td>pilot transonic tunnel</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure (Pa)</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>$u$</td>
<td>local mean streamwise velocity (m/s)</td>
</tr>
<tr>
<td>$\Delta u$</td>
<td>freestream velocity difference, $u_1 - u_2$ (m/s)</td>
</tr>
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<td>$x$</td>
<td>streamwise coordinate (m)</td>
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<td>$y$</td>
<td>vertical coordinate (m)</td>
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<td>$z$</td>
<td>lateral coordinate (m)</td>
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<td>$\lambda$</td>
<td>injection gain</td>
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<tr>
<td>$\eta$</td>
<td>injection efficiency</td>
</tr>
</tbody>
</table>

Subscripts

- $0$: stagnation condition
- $1, 2$: high and low speed, respectively
- $\text{des}$: design condition
- $\text{inj}$: injection
- $r$: relative
- $TS$: test section

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Fig. 1. Industrial transonic tunnel operation envelope. Test section conditions.
Notwithstanding this, the number of points in the grid was too high due to the many boundary layers and mixing layers that are present in the problem. To gain in efficiency we have then adopted a sequence of grids technique.

The code was developed by the authors, and consists of an implicit, finite-difference, three-dimensional computing tool, corresponding, in general terms, to the diagonal algorithm of Pulliam and Chaussee [2]. The mathematical model corresponds to the Reynolds-Averaged Navier–Stokes equations. Turbulence modeling is accomplished by the use of the one-equation scheme as proposed by Spalart and Allmaras [3].

For the sake of completeness in informing the reader, we have advanced the above general overview of the problem, and how we coped with some points of the respective solution techniques. But the complete explanation of all the aspects that had to be tackled (including here the validation and verification of the code) in order to reach to final solutions is too lengthy. There is no room here for this and therefore we refer the reader to Falcão and Ortega [1,4], and Falcão [5], where the pertinent details are discussed.

3. Results and discussion

3.1. Introductory remarks

Before going into the final solution analysis, an important observation is due. When injection is activated and the two streams begin to mix, the tunnel “responds” as a unique system, in the sense that all elements work in a coupled fashion. In other words, the injection process does not affect only the mixing chamber, but, on the contrary, all elements that constitute the whole circuit are going to “feel” and “respond” in some way to this input. As a consequence of this “reaction” of the complete circuit, a new equilibrium condition will be reached after the compressed air valves are opened for a period of time. This condition will be sustained for some time, concerning that the capacity of the high-pressure reservoirs is finite. For example, at the design condition, a new set of properties is maintained by about 45 s — see Fig. 3. Some time ago, an analysis of this dynamic process was undertaken by the present authors [6,7]. A lumped parameters technique [8] was used and the reactions of the tunnel circuit to a series of inputs were estimated, and among these, the injection process. One of the most important results of this simulation is represented in Fig. 3. This figure depicts the establishment of an upper level of stagnation pressure at the tunnel’s test section as a result of the supersonic mixing. Following the test section, the stagnation pressure at the entrance of the mixing chamber also raises and behaves in a similar plateau-like fashion. This rising of the stagnation pressure at the entrance section of the mixing chamber has to be informed to the numerical code; otherwise, the simulation will not succeed in reproducing the proper physics of the process.

This is done by means of an extrapolation procedure based on the concept of the Euler characteristic equations. For the complete details, the reader should refer to Falcão and Ortega [4] or Falcão [5]. At the beginning of the calculation, the static pressure at the supersonic part of the inlet section is kept fixed and the stagnation pressure is allowed to vary. (It is evident that the static pressure at the supersonic nozzles exit, which constitutes part of the calculation domain inlet section — see Fig. 2 — is always fixed, as long as the nozzles stagnation pressure is not varied.) As a consequence of the mixing procedure, the Mach number at the supersonic entrance tends to increase. The stagnation pressure follows, because the static pressure is kept constant at this position. The supersonic stagnation pressure is allowed to increase until it reaches a value that corresponds to the plateau given in Fig. 3. After that, the inlet boundary conditions are interchanged, that is, the stagnation pressure is kept constant and the static pressure is allowed to vary. Then, the code is “run” until final convergence. The point of concern here is the fate of the static pressure of the supersonic stream at the entrance plane, especially at the design condition. In the sequel, the behavior of the inlet static pressure will be discussed in detail.

The plateau values of Fig. 3, which constitute the equilibrium values defined by the mass injection, were used to derive the following approximate correlation:

$$\left( \frac{\Delta p_{0,TS}}{p_{0,TS}} \right) = 0.03042 \left( \frac{p_{0,inj}}{p_{0,TS}} \right)^2 + 0.6800 \left( \frac{p_{0,inj}}{p_{0,TS}} \right) - 0.003727.$$  

(1)

where $p_{0,TS}$ is a reference test section stagnation pressure (equal to 100 kPa). This equation was very useful in the calculation of a new level of stagnation pressure at the entrance of the mixing chamber, for every new value of $p_{0,inj}$. It is important to point out that an
approximation was introduced here, and we considered that the increasing of $p_0$ at the entrance of the mixing chamber was equal, in each case, to the increasing of $p_{0,TS}$.

3.2. The physical scenario

In the first part of this section some pressure data will be plotted along special lines of the computational domain. In Fig. 4 we define those straight lines. Line 1 belongs to the mixing chamber entrance section and is the result of the intersection by the horizontal plane that contains the geometrical centers of the nozzles exit sections (let us remind the reader that the inlet plane of the computational domain contains the exit sections of the nozzles — see Fig. 2(a)). Line 2 is defined by the intersection of the entrance plane and a longitudinal vertical plane that contains the geometrical center of injector 2. Line 3 corresponds to the intersection of two planes: one is vertical and longitudinal (that is, parallel to the lateral walls of the tunnel), and contains the geometrical center of nozzle 1, while the other is horizontal and also contains the geometrical center of nozzle 1. Line 4 is the intersection of the same vertical plane that defines line 2 and a horizontal plane whose distance to the floor of the tunnel is equal to 0.10 m.

Distributions of static pressure (converged values) along line 1 are shown in Fig. 5 for the five cases that were studied. The values in the figure are made dimensionless by the static pressure of the main stream at the entrance plane and at the start of the injection process. Horizontal coordinate in meters. Dashed lines mark injectors’ walls positions.

Fig. 4. Special lines definition for the plotting of static pressure distributions.

Figs. 5 and 6 are indicative that the shock/expansion systems at the nozzles exit are going to be much stronger for the off-design points when compared to the design condition. This is corroborated by Fig. 7. This figure shows “cuts” of the complete three-
dimensional static pressure field by a longitudinal vertical plane containing the geometrical center of injector 2 — Fig. 7(a), (b), (c) corresponds to cases \( p_{0,\text{inj}} = 0.7 p_{0,\text{des}} \), \( p_{0,\text{inj}} = p_{0,\text{des}} \), \( p_{0,\text{inj}} = 1.3 p_{0,\text{des}} \), respectively. Fig. 7(d) corresponds to a cut by a horizontal plane that contains line 1, and for the case \( p_{0,\text{inj}} = 1.3 p_{0,\text{des}} \). Values in this figure are made non-dimensional in reference to the static pressure at the subsonic entrance, for the design condition, and at the start of the injection process. At the design point the pressure field is basically uniform (Fig. 7(b)), while for the off-design settings it is not, and shock and expansion “domes” are present and very well defined. When \( p_{0,\text{inj}} = 1.3 p_{0,\text{des}} \), the supersonic exiting static pressure is larger when compared to the subsonic pressure, what provokes the appearance of a strong expansion dome in front of the nozzles exit. See Fig. 7(c) and (d). This first expansion is too strong, and a shock appears in the sequel, followed by another expansion, and so on, until a downstream equilibrium is reached — see also Fig. 8(c). For the case when \( p_{0,\text{inj}} = 0.7 p_{0,\text{des}} \) the effects appear in reverse order, as shown in Fig. 7(a).

For the sake of a better understanding we have introduced Fig. 8. In this figure, plots of static pressures along lines 3 and 4 (see Fig. 4) are presented. The reader should be aware that the distributions are “put” together, just because they are to be compared, but, what is called “supersonic” refers to static pressures along line 3, which is positioned inside the supersonic stream, while by “subsonic” we mean the static pressure along line 4, and this line is completely immersed in the subsonic stream. The plotting is done until the intermediate cross-section \( (x = 0.30 \text{ m}) \), for which equilibrium is basically recovered in all three situations. The results here are very illustrative of the code’s ability in representing the physics of the mixing process. Fig. 8(b) shows results for the design point, and the reader can observe only very mild oscillations in both distributions. Values are basically coincident along all length of the lines. On the other hand, there are large pressure oscillations when \( p_{0,\text{inj}} = 1.3 p_{0,\text{des}} \) and this is shown in Fig. 8(c). After exiting the nozzles, the supersonic stream exhibits a large pressure drop, an expansion towards the ambient equilibrium pressure, which happens to be much lower. What happens is that this initial expansion is too large, and then a compression dome appears in order to recover a possible equilibrium state. But this compression is also too
words, 30% more (pressure and under-pressure are 1.34 and 0.68, respectively. In other the static pressures at the exit of the nozzles for the cases of over-

Another very interesting effect can be observed in Fig. 8(c). The over-pressure at the nozzles exit dictates a higher final equilibrium level, when compared to the inlet subsonic pressure — the final value is about 7.5% in excess. This, in fact, contributes to a relative deeper initial dip of the supersonic expansion, and, consequently, contributes to the existence of a larger number of oscillation cycles. The under-pressure case, $p_{\text{inj}} = 0.7p_{\text{des}}$, is shown in Fig. 8(a). Oscillations here are not as strong as for the over-pressure situation, and the equilibrium is reached practically at $x = 0.10$ m. The reason for this, most probably, is related to the total pressure differential at the end of the first sweep. To better put this point, let us firstly observe that the static pressures at the exit of the nozzles for the cases of over-pressure and under-pressure are 1.34 and 0.68, respectively. In other words, 30% more ($p_{\text{inj}} = 1.3p_{\text{des}}$) and 30% less ($p_{\text{inj}} = 0.7p_{\text{des}}$) in stagnation pressure do not correspond to the same amount of variations in the nozzles exit static pressures. We then learn that, 30% more in stagnation over-pressure corresponded to 34% more is static pressure at the exit, while, in the under-pressure case the static pressure is only 32% lower than the static pressure of the main current. But, now, observing Fig. 8(c), we see that the value of the static pressure that corresponds to the bottom of the first dip is approximately 0.95, while the final equilibrium level is 1.075. The difference between these two important values is, therefore, $\Delta p = 0.125$. From Fig. 8(a), the maximum pressure that is attained by the supersonic stream is about 0.96 and the equilibrium value is 0.93, and the resulting difference is $\Delta p = 0.03$. We do believe that this is the main reason why the supersonic stream in the case of the over-pressure presents more oscillations, and, consequently, requires "more space" until a final equilibrium state is reached. For the other tests, i.e., $p_{\text{inj}} = 1.15p_{\text{des}}$ and $p_{\text{inj}} = 0.85p_{\text{des}}$, the results are intermediate to the ones already shown, therefore, there is no need to discuss them here.

One of the most interesting results of this work is the confirmation that in this three-dimensional flow, the supersonic pressure "adaptation" is realized by means of expansion and compression domes. This is especially apparent from Fig. 7(c) and (d) for the over-pressure injection case. Also shown in Fig. 9 is a perspective view of this case. In order to better visualize the domes topology, the generation of Fig. 9 required some rotation of axes. The basic dimensions of these domes are on the same order of magnitude of the injectors exit sections. This result was to be expected because as already stated in Part I [11] of this research work: ‘the supersonic jets coming out of the nozzles have to develop between the floor of the tunnel and a conical subsonic envelope" that limits them'.

Other important conclusions can be drawn by observing the behavior of other kinds of parameters. For example, in Fig. 10, we present maps of the Mach number. These correspond to a cut of the flow domain by a longitudinal vertical plane that contains the geometrical center of injector 1. The results are exactly as physically expected, that is, for the case with over-pressure, the strong expansion at the start accelerates the flow even further when compared to the design condition, while, in the case of un-
der-pressure, the initial strong compression decelerates the flow. It is important to have in mind that the Mach number at the nozzles exit was always fixed as $M = 1.9$, irrespective of the conditions in focus.

Fig. 11 shows maps of eddy viscosity, for a cut by a longitudinal vertical plane that contains the geometrical center of nozzle 3, the one closest to the lateral wall (see Fig. 12). The reader can perceive that raising the injectors stagnation pressure, while maintaining other conditions fixed, corresponds to augmenting the level of turbulence in the mixing chamber (much probably, due to the acceleration of the supersonic stream).

### 3.3. Analysis of the mixing layers

Some attention will be dedicated to the mixing layers, insofar as their influence in the process as a whole is absolutely instrumental. On the other hand, this is a very involved matter, considering the many influences that a specific layer receives as it grows in the environment of the present problem. In the quadrant that forms the computational domain — see Fig. 2(b) — one can recognize, at least in the initial stretch of the chamber, eight mixing layers, each of which issuing from a specific wall of the nozzles. This is sketched in Fig. 12. Later on, in general terms, and considering all cases (design and off-design points), for $x$ approximately equal to 0.30 m, these layers merge, and, from this point on, the representative topology should be viewed as closer to that of a jet (in this instance, one jet corresponding to each nozzle). We concentrate, then, our attention on the initial longitudinal stretch of the chamber.

One of the most important and representative parameters in the theory of mixing layers is the growth rate, denoted by $db/dx$, where $b$ is the mixing-layer thickness. Following Goebel and Dutton [9], the mixing-layer thickness is defined as the distance between two transversal positions for which the mean streamwise velocity is equal to $(\bar{u}_1 - 0.1 \Delta u)$ and $(\bar{u}_2 + 0.1 \Delta u)$. $\bar{u}_1$ and $\bar{u}_2$ are the local mean streamwise velocities at a certain transverse section. It is important to realize that the (at least, partial) cross-sectional uniformity of $\bar{u}_1$ and $\bar{u}_2$ characterizes in the two-dimensional theory what we shall understand as the “core” of the two streams that are in contact and being mixed. The existence of these two cores at a cross-section is a necessary condition for the present definition of the mixing-layer thickness. If, for some reason, at least one of the cores ceased to exist it would not be possible to define $\bar{u}_1$ and/or $\bar{u}_2$ anymore. The evolution of the mixing-layers thicknesses for the cases investigated is plotted in Fig. 13. The longitudinal segments marked between vertical dashed lines are the approximate “growth regions” for each of the cases. At the beginning of the mixing process the layer evolves, until it gets fully developed. After this, comes the growth region, at which the velocity profiles can be expressed in self-similar form. A well-known characteristic of the similarity region is the linearity of $b$ in terms of $x$ (see Goebel and Dutton [9], and also White [10]). We have applied this concept, at least approximately, to this case, and arrived at the growth regions that appear in the figures. The reader should be aware that most of these concepts and ideas come in general from two-dimensional theories applied to “well-behaved” two-dimensional mixing processes. In the present problem, we have compressible turbulent
mixing layers evolving in a three-dimensional space, in the presence of other layers and walls. This is why we have cared in focusing the analysis at the initial longitudinal stretch of the chamber, because, in this region, the evolution is more likely to have an approximate two-dimensional character and the influences are not yet too strong.

To support further the above arguments, we have included in the analysis the evolution of the cores. This is an attempt at discussing the point, based on the idea that while the core exists it is still possible to “measure” the mixing layer thickness (in a two-dimensional sense). Figs. 14–16 are cut views, vertical and horizontal, of the velocity fields in front of nozzle 3, for the initial part of the mixing chamber. Both cuts pass by the geometrical center of the nozzle’s exit section. As one can visually check, the longitudinal lengths of the horizontal and vertical layers, along which there is still a uniform core of velocities at the supersonic nucleus, are, respectively, 0.08 m and 0.10 m; 0.16 m and 0.16 m; 0.22 m and 0.20 m, for the under-pressure, design and over-pressure points, respectively. We focused on the injector 3, because this is the one that is subjected to more influences, considering the proximity of the tunnel lateral wall. Two points are worth noting. The first is the fact that the lengths increase corresponding to an increase in the nozzles’ stagnation pressure, what is an expected effect. The second is the realization that the lengths of the horizontal and vertical cores’ stretches are approximately the same. If one considers that the horizontal “opening” that is “offered” to the lateral layers is 8 mm (half of the nozzle width), and that 22 mm (the height of the nozzle) is “offered” to the vertical layer, the fact that the lengths of the potential cores are basically the same in both directions is an intriguing result. But one should keep in mind that the supersonic jets exit the nozzles flushing with the floor, and then, the high amount of momentum exchange with the solid wall is sufficient to decelerate that much the vertical “potential” core. On the other hand, because of the three-dimensionality of the situation, the growing of the horizontal layers on the supersonic side interferes directly with the growing of the supersonic vertical layer (and this happens since their very start at the tip of the nozzle wall). Most probably, it is the simultaneous influence of all these effects that dictates the final result.

Just to draw a broader perspective of the situation, the calculation of “pretense” layers’ thicknesses was realized along all the chamber length, and using, for each transversal section, the largest supersonic velocity available (as the value of \( u_1 \)). The results are shown in Figs. 17–19. The lines in these figures simply mark the positions at which \( (u_1 - \Delta u) \) and \( (u_2 - \Delta u) \) for each transversal...
section. It is instructive to observe that the lengths of the initial linear growing of the layers correspond exactly to the stretches for which the cores still exist. These correspond to the lengths for which the influences are still small and an approximate two-dimensional structure can still be referred to. From those positions on, one cannot speak of mixing layers anymore, even in approximate terms. The reader should be aware that there is still a supersonic flow in the inside of the jet. But this part of the flow cannot be considered a "potential core" in the context of a mixing layer concept. The topology of the mixing region corresponds to that of a jet instead of a collection of mixing layers. And, very interestingly, the jet tends, as it grows along the chamber, to an axisymmetric shape (see also Trentacoste and Sforza [11]). Axisymmetry is not completely attained (until the exit of the chamber) due to the presence of the tunnel floor. This can also be appreciated by inspecting Fig. 20, where a tridimensional perspective of the jets evolution is shown. Fig. 21 is a different version of Fig. 20(b), for the design case, where more details are shown, plane by plane. It is interesting to observe that the sonic line maintains, approximately, the same position, despite the severe change of form of the jets. The jet corresponding to injector 3 (see Fig. 12) is also deformed at its right side due to the presence of the tunnel lateral wall.

At the growth region a line was least-squares fit to the mixing layers distributions and the growth rates were determined. These values are summarized in Table 1. Two facts seem to be evident. The length of the growth region increases with the increasing of the injectors' stagnation pressure (Fig. 13). Most probably, this is so because the length of the supersonic cores also grows (see Figs. 14–16), and then the similarity regions have a chance to stretch further. The other important result is the verification that layers 1, 4, and 7, have larger growth rates. This is a result to be expected, by the simple fact that these layers are not bounded from above. And the calculation confirms this expectation. Besides, the relative Mach number of those layers is larger, and this is more so for layer 7, the one that is closer to the lateral wall of the tunnel. The reason for this, i.e., for $M_r$ being larger, is the realization that the Mach number of the subsonic field above the layers is in general less than the values between the layers. This is evidence that the subsonic
flow that runs above the layers are less accelerated and, in this situation, the upper layers are bound to grow more when compared to their counterparts in other positions.

3.4. Performance of the mixing process

In this subsection we concentrate on the comparison of the many cases in terms of the mixing processes' performance. In fact the comparison is “more” referred to the mixing chamber than to the mixing process, considering that the state of the flow at the exit section is, evidently, a function of the nozzles' stagnation pressure (see Fig. 10). The parameters of interest are shown in Table 2. The methodology to calculate the injection process pressure loss coefficient, gain, and efficiency has been already introduced in Part I [1], so there is no reason to repeat the details here.

From Table 2 one can immediately observe that the gain is basically proportional to $p_{\text{inj}}$. Therefore, one could argue: why not use a value such that $p_{\text{inj}} > p_{\text{des}}$? There are two main problems. The first is the raising of the total pressure loss, and the second is relative to the total injection time that can be maintained, considering section is, evidently, a function of the nozzles' stagnation pressure (see Fig. 10). The parameters of interest are shown in Table 2. The methodology to calculate the injection process pressure loss coefficient, gain, and efficiency has been already introduced in Part I [1], so there is no reason to repeat the details here.

Table 2
Injection process parameters.

<table>
<thead>
<tr>
<th>Injection stagnation pressure (kPa)</th>
<th>0.70 $p_{\text{inj}}$</th>
<th>0.85 $p_{\text{inj}}$</th>
<th>$p_{\text{inj}}$</th>
<th>1.15 $p_{\text{inj}}$</th>
<th>1.30 $p_{\text{inj}}$</th>
</tr>
</thead>
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<tr>
<td>Mixing chamber exit stagnation pressure (kPa)</td>
<td>101</td>
<td>105</td>
<td>113</td>
<td>118</td>
<td>124</td>
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<td>Mixing chamber stagnation pressure loss (kPa)</td>
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<td>6.72</td>
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<td>Injection chamber pressure loss coefficient, $k$</td>
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</tr>
<tr>
<td>Injection gain, $\lambda$</td>
<td>0.97</td>
<td>1.01</td>
<td>1.08</td>
<td>1.13</td>
<td>1.17</td>
</tr>
<tr>
<td>Injection chamber efficiency, $\eta$</td>
<td>0.59</td>
<td>0.64</td>
<td>0.67</td>
<td>0.69</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 1
db/dx in the growth region.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Mixing layers (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$p_{\text{inj}} = 0.70 p_{\text{des}}$</td>
<td>0.075</td>
</tr>
<tr>
<td>$p_{\text{inj}} = p_{\text{des}}$</td>
<td>0.061</td>
</tr>
<tr>
<td>$p_{\text{inj}} = 1.30 p_{\text{des}}$</td>
<td>0.053</td>
</tr>
</tbody>
</table>

Fig. 21. The design point: transversal “cuts” of the Mach number field showing the development of the jets. Coordinates are given in meters.
that the capacity of the reservoirs is fixed. For example, at the design condition, the available time is 45 s, while for $p_{0,\text{inj}} = 1.3 p_{0,\text{des}}$ this interval would fall to 25 s. (The available time was calculated considering a projected reservoir capacity of 20 m$^3$.) Taking into account the initial stabilization phase, one can perceive that there is a great loss in available time. Another very important conclusion can be drawn by observing that, for $p_{0,\text{inj}} = 0.85 p_{0,\text{des}}$, the gain is equal to 1.01, and for $p_{0,\text{inj}} = 0.7 p_{0,\text{des}}$, the value is 0.97, that is, a gain less than 1. In other words, for $p_{0,\text{inj}}$ less than 0.85 $p_{0,\text{des}}$, injection is, in practice, no longer effective. This means that, at these conditions, all the “new energy” introduced in the process is being “consumed” by the tunnel losses.

4. Conclusion

The numerical simulation of the injection process in a transonic wind tunnel was successfully simulated for off-design cases. In total, five situations were studied, including the design point. These applications have served as definite tests for the code, which showed in all instances both distinguished robustness and accuracy. Many points, results and conclusions are worth mentioning. First, the numerical maneuvering effect, including the dealing with entrance boundary conditions together with dynamical information, that was introduced in order to mimic the real functioning of the complete tunnel circuit. Secondly, we have succeeded in representing the physics of the mixing process, what can be attested by the many important results; the pressure adaptation domes, the faithful representation of the many mixing layers with their growth-rate calculations, and the proper prediction of general maps of the principal parameters. Finally, we have calculated the “engineering” parameters, so important to the tunnel engineer, namely, the pressure loss, gain, and efficiency of the whole process. As a very important result we have obtained the threshold point of the injection, which is basically $p_{0,\text{inj}} = 0.85 p_{0,\text{des}}$. For stagnations pressures less than this limit, there is no point in making use of the process.

Acknowledgments

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References