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MIXING OF TWO SUPERSONIC PARALLEL FLOWS IN 2D CONFIGURATION

R. PRUD'HOMME, F. BAILLOT
Laboratoire d'Aérodynamique du CNRS
4ter route des Gardes
92190 Meudon
France

New possibilities for air breathing cycle engines are offered due to the recent progress in the field of high temperature materials and of cryogenic propulsion. That gives the possibility of new developments.

As the flight velocity increases, decreasing the flow velocity in the air intake leads to an increasing of the momentum losses and besides involves high static pressure and heat transfer in the combustion chamber, for classical propulsor devices where the combustion is subsonic [1]. Supersonic combustion is the only way to limit the momentum losses and to reduce the static pressure and the heat transfer in the combustion chamber, with a correlative increasing of the specific impulse [2].

The supersonic combustion involved in scramjet puts forward some technical and scientific questions which need experimental, theoretical and numerical studies. One of the fundamental problems is the mixing of fuel and air jet. The combustion efficiency will greatly depend on quality of the mixing, not only of the air flow with the flow of fuel but also of the fresh reactants with the combustion products.

In addition, some questions as flame anchorage and ignition must be solved. Vortices can be used to stabilize the subsonic combustion. This can be done in supersonic combustion using the instability coming from the mixing of the two boundary layers with different densities, which creates vortices.

The anchorage distance L is fluctuating and the phenomenon is not the same in supersonic as it is in subsonic regime. At last, although the heat flux is strongly reduced, it remains important at high velocities where the effects are increased [3].

Several studies upon mixing layers with or without combustion have been engaged.

Although combustion does alter the mixing processes, it is interesting to study them without any combustion. Not only it is easier but also it can reveal certain mechanisms, all the more so as an upstream zone of mixing layers is not reactive.

There are many sorts of geometrical configurations : plane streams parallel or over expanded, cylindrical coaxial stream, orthogonal ones ; there are several physical conditions : flows of different fluids to simulate fuel and oxydant, fluid streams with different speeds but with identical total temperatures, streams of the same fluid with different speeds and different total temperatures.

In a first part, we are going to make a synthesis of the main experimental, theoretical and numerical current research works.

In a second part, we are going to show the supersonic mixing layer facility, installed in the Laboratoire d'Aérodynamique.

A plane mixing layer, whatever the nature of the two parallel jets and their thermodynamic conditions, can be characterized, in first analysis, by its thickness and by its space-time evolution.

A universal representation of experimental results has been sought for. To find it, the notion of convective Mach number M_c , which characterizes the dynamics of the mixing layer and its large structures, has been introduced [4].

Assuming isentropic flows for the large structures, one determines a convective Mach number M^+ : the identity of the relative stagnation pressures is written at the center of the structure where the static pressures of the two flows are equal too [5].

An other convective Mach number is equal to the ratio of the velocity difference of both the flows divided by the sum of their sound celerities. This convective Mach number seems to be more suitable for studying developed mixing layers [6].

Zhuang et al. [7] associate convective Mach number to the relative phase velocity of the more instable wave : this Mach number becomes different from the precedent for M_c larger than unity. Finally Barre et al. [8] derive a convective Mach number from turbulent viscosity considerations.

The influence of the convective Mach number M_c is easily noticeable on the widening of the mixing layer thickness δ , when it is quantified by the ratio of its axial gradient $\delta' = d\delta/dx$ to the value $(\delta')_{inc}$ of the flow, assumed to be incompressible. The jet has a relative expansion $\delta'/(\delta')_{inc}$ linearly decreasing as soon as M_c is above a value of about 0.3 and while M_c is below a value of about 0.6, 0.7. Beyond these values, the layer thickness is stabilized.

Mixing layer thickness d is experimentally estimated either from total pressure P_t : $\delta_{pit} = y(0,95\Delta P_t) - y(0,05\Delta P_t)$ or from Schlieren visualization : δ_{vis} or from a vorticity thickness parameter : $\delta_\omega = \Delta U / (\partial U / \partial y)_{max}$ where $\Delta U = U_2 - U_1$ is the velocity jump of the two parallel flows and $\partial U / \partial y$ is the transverse velocity gradient of the flow in the mixing layer. Ref. [4] shows that :

$$\delta_{pit} = 1,6 \delta_\omega = 0,8 \delta_{vis}$$

The notion of similarity permits to distinguish several zones in the mixing layer. From δ_ω , the dimensionless transverse variable distance is defined by :

$$y^* = \left[y - y \left(\frac{U_1 + U_2}{2} \right) \right] / \delta_\omega$$

and we characterize the mean relative velocity

$$[U(y^*) - U_2(y^*)] / \Delta U$$

To consider a self-similar mixing layer it is required that (c criterion) both the mean and turbulent velocity profiles as functions of y^* do not depend on the convective Mach number [9].

According to Goebel and Dutton [6] these requirement is expressed by the necessity to impose the following criterion to the relative Reynolds number, built with the characteristic parameters of the mixing layer :

$$Re = \rho (U_1 - U_2) b / \mu = 10^5$$

with :

$$b = y(U_1 - 0,1 \Delta U) - y(U_2 + 0,1 \Delta U)$$

where b is shown to be equal to $1,02 \delta_\omega$.

For Metha and Westphal [9] and in addition to the c criterion, it is necessary that :

- 1) The mixing layer thickness grows linearly with the streamwise distance.
- 2) The profiles of all turbulence quantities are independent of streamwise location when scaled by mixing layer thickness. But the last point is not easy to satisfy in experimental measurements contrary to the Goebel and Dutton proposal.

In the fully developed region one observes similar trend of mean flow and turbulence fluctuation profiles as seen in incompressible shear layers.

Otherwise, as M_c is increased, one observes :

- a diminution of level and lateral extent of turbulence fluctuations σ_u , σ_v , uv , of skewness u^3 , v^3 and of flatness u^4 ,
- an increase of turbulence anisotropy σ_u/σ_v [10, 11].

An evolution of the morphology of the structures, which are becoming 3D, is observed experimentally as M_c is increased [4, 11, 12].

It is one of the possible explanations for the stabilization of δ which can be favoured by the presence of walls.

Experiments, wrongly considered as being executed in free flow conditions, are in fact realized in test chambers whose rigid walls reflect pressure waves ; these reflections lead to a 3-dimensionalization of the mixing layer, as supposed in theoretical and numerical studies, at $M_c > 0.6$ [13].

The appearance of 3D structures can also come from a change in the turbulent nature of the flow. The existence of two convective Mach numbers, strongly different in both the flows, suggests the appearance of shocks attached to the structures, changing the isentropic nature of these structures [4, 11, 12].

The theoretical studies treat the mixing layer problem as the deformation of a reference configuration by mean of small perturbations whose space amplitude is considered like the layer thickness. This shape of reference is considered either as an interface (slip surface, vortex sheet) or as a thick layer (shear layer). The computations are 2D or 3D and permit the study, for example, of the influence of the Reynolds number, of the convective Mach number, of the influence of the jets' temperature and of the one of the rigid walls upon the perturbation amplitude ratio $\alpha_i/(\alpha_i)_{inc}$.

The nature of the layer instability changes with the value of M_c . For small values of M_c , Kelvin-Helmholtz instability is the greatest, whereas for $M_c > 1$ Liepman and Roshko instability prevails [14, 15].

Free jets results [16] show that :

- 1) viscosity is a stabilizing factor,
- 2) a temperature jump ΔT between the two jets is a stabilizing factor for Mach numbers M_1 of the faster flow below 1.5 (the slower flow being at rest). For $M_1 > 1.5$ the amplification rate of the perturbations is increasing with ΔT but is very small.

The results obtained in the case of a confined jet show the interaction of reflected pressure waves with the mixing layer. Tam and Hu [15] have proved the existence of one instable mode whatever the frequency in 2D or 3D, the predominant modes depending on the ratio δ_ω/h with h -distance between the walls-.

Taking into account these wave reflections leads to a better agreement between experiment and theory as can be seen on the curve giving the normalized growth rate versus theoretical Mach number M_{c1} (fig. 1) [7].

Numerical simulations show the large eddy structures [17] and the difference of behaviour in 2D and 3D [18] as well as the time evolution of turbulence with the structure motion [19].

There are three steps in the mixing procedure : an initial growth step where the laminar large structures are growing, a convective mixing step where the vortices begin to interact, with generation of sketched interfaces and sharp growth in the intensity of the scalar dissipation, and a final stage where the small scales of turbulence are reached and the interfaces are destroyed by molecular diffusion.

The experimental facility built at the Laboratoire d'Aérothermique du CNRS (fig. 2) permits to study the evolution of two parallel supersonic plane flows with different stagnation temperatures. The chosen Mach numbers are equal to 3 for the hot stream and 1.5 for the cold one. In these conditions, the static temperature ratio t defines the convective Mach number $M_c = [\sqrt{t} M_2 - M_1] / [\sqrt{t} + 1]$.

- The choice of two different total temperatures in each stream can be justified by :
- a "simple" way to make M_c vary,

- certain interest in thermic effects acting eventually on the behavior of the mixing layer in the transition zone, $M_c \sim 0.6, 0.7$.

The total temperatures have been chosen respectively equal to 520K and 300K in order to get M_c equal to 0.7. A future facility, with a more powerful and warmer air-stream should permit to get M_c numbers close to or even higher than 1, without changing the Mach number values cited above. (Another simpler way to obtain these supersonic M_c numbers would consist of reducing M_1 without changing the total temperatures, nor the static pressure ; but the M_1 flow would become subsonic which is not desired for the reasons mentioned above).

The static pressure is equal to 0.2 atmosphere. The flow is confined. The two half nozzles (fig. 3) are realized such that most important dilatations are avoided. First results concern Schlieren and laser tomography, mean pressure and temperature measurements by Pitot probes and thermocouples. The boundaries' effects and the effects of superimposed acoustic field will be studied and LDA velocity measurements will be performed.

The authors wish to mention that the nozzles calculations have been performed by G.B. Diep and that execution of blue prints have been realized by M. Police.

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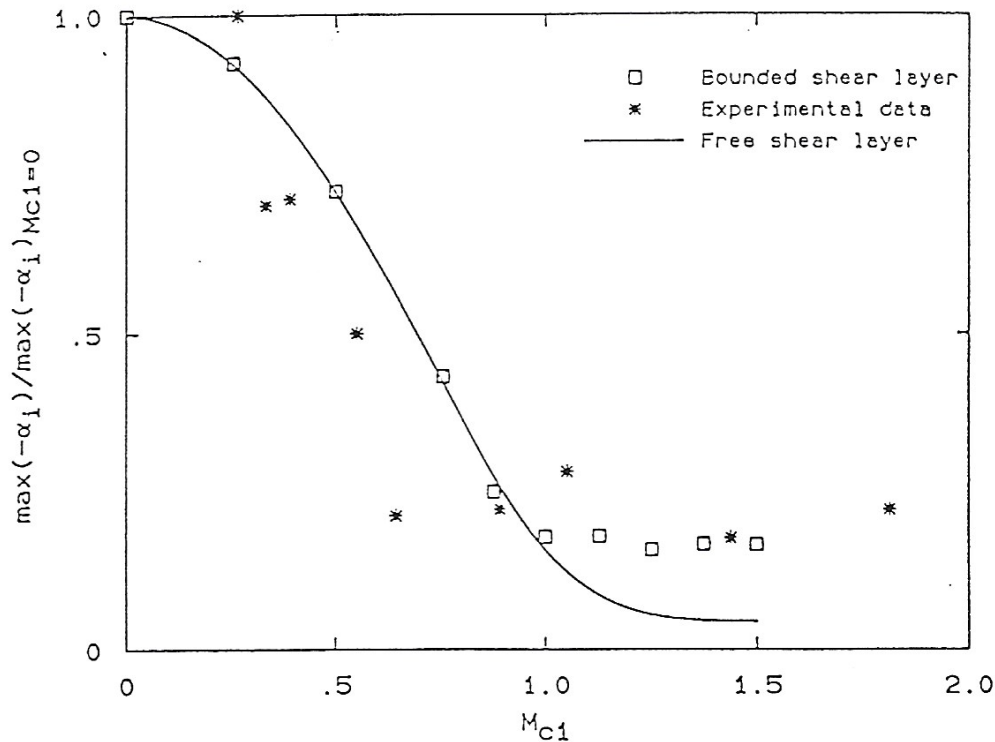


Fig. 1 - A comparison of data [7] for a 2D bounded shear layer with the experimental data of Papamoschou and Roshko as a function of M_{c1} .

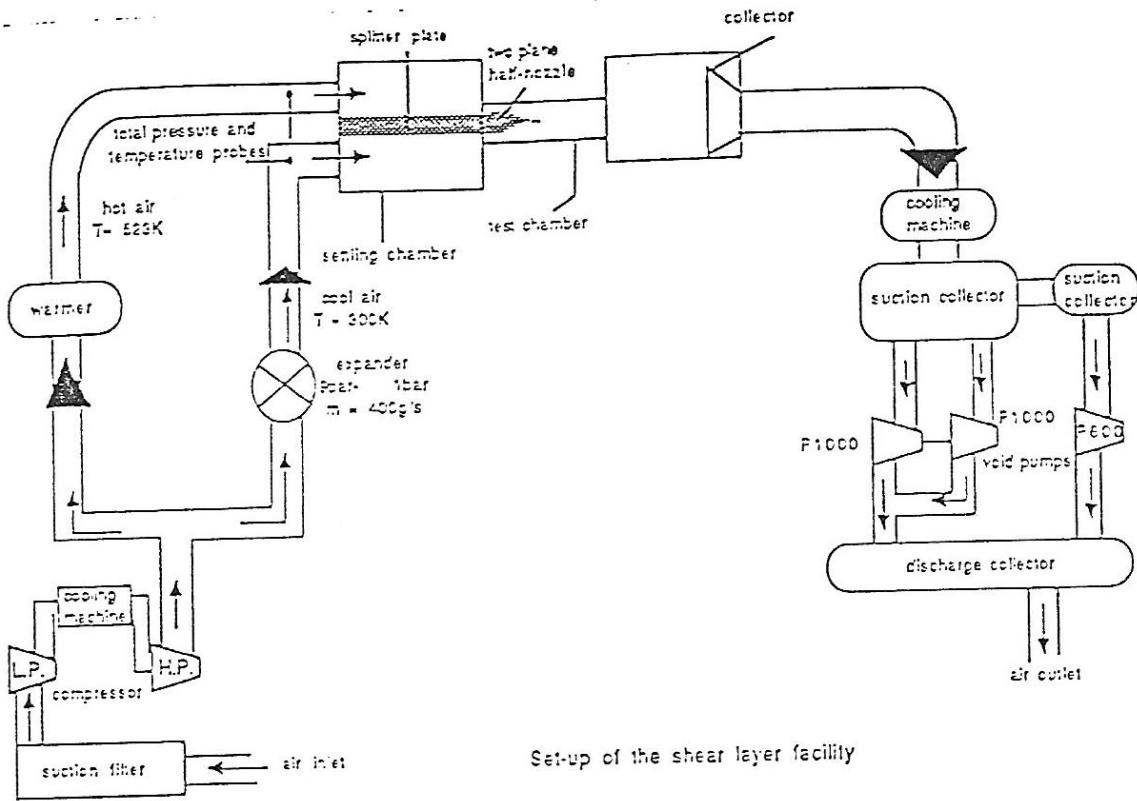


Fig. 2 - Set-up of the shear layer facility.

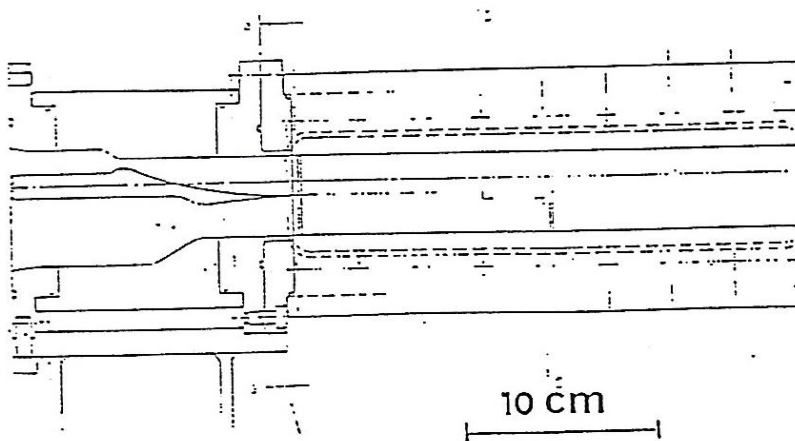


Fig. 3 - Nozzles and test chamber

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