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# FUNDAMENTAL ASPECTS OF THE AERODYNAMICS OF TURBOJET ENGINE COMBUSTORS

M. Barrere

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## NOTATIONS

$A$ - Area of a chamber section

$A_b$ - Area of a section occupied by burnt gases

$A_{DO}$ - Dome area

$A_f$ - Area of a section defined by the flame front

$A_j$ - Area of a jet section

$A_m$ - Area wetted by flow per unit length

$A_M$ - Maximum chamber area

$A_o$ - Area occupied by flame at stabilization level

$A_{ODO}$ - Area of holes placed in the dome

$A_{OR}$ - Area of cooling slots

$A_{OTF}$ - Area of air-injection holes on the flame tube

$A_{TF}$ - Area of flame tube

$A_1$, $A_2$, $A_3$ - Constants involved in the combustion laws

$B$ - Spalding transfer function

$C_D$ - Coefficient of flow

$C_F$ - Coefficient of friction

$G$ - Coefficient of drag

$C_p$ - Specific heat at constant pressure

$d$ - Jet diameter

$f$ - Characteristic parameter of impact pressure in the chamber

$F$ - Transfer parameter in two-phase flows

$l_o$ - Turbulence scale

$\dot{m}$ - Mass flow

M - Mach number

$M$ - Molar mass

$P$ - Pressure

$P_r$ – Prandtl number

$r$ – Radius of curvature

$r$ – Mean radius of drops

$R_{eo}$ – Reynolds number relative to drops

$t$ – Time

$t_b$ – Combustion time in turbulent flow

$t_s$ – Dwell time

$T$ – Temperature

$T_o$ – Aerodynamic resistance

$u$ – Flow velocity

$u'$ – Eddy velocity

$u_{bL}$ – Laminar combustion rate

$v_{bT}$ – Turbulent combustion velocity

$v$ – Flow velocity

$v$ – Drop velocity

$X_L$ – Reduced length of chamber

$z$ – Degree of progress of the reaction

$\beta$ – Angle of jets

$\beta$ – Temperature ratio before and after combustion

$\gamma$ – Specific heat ratio

$\lambda_g$ – Coefficient of thermal conductivity of the gas

$\mu_g$ – Coefficient of viscosity of the gas

$\rho$ – Density

$\theta$ – Characteristic time of the vaporization of drops

Subscripts

$A$ – Air

$b$ – Burnt gases

$c$ – Burning gas

$e$ – Intake

$i$ – Arrest conditions

$j$ – Jet, chamber radius mark

| | | |
|---|---|---|
| K | - | Kerosene |
| $g$ | - | Gas |
| $f$ | - | Fresh gas |
| $f$ | - | End of vaporization |
| $m$ | - | Mixture |
| $o$ | - | Initial conditions |
| $s$ | - | Flow point in a flow line |

# FUNDAMENTAL ASPECTS OF THE AERODYNAMICS OF TURBOJET ENGINE COMBUSTORS

M. Barrere
Scientific Director of Energetics at O.N.E.R.A.

## 1. Introduction /55

The improvement in turbojet combustion chambers has become increasingly difficult as a result of the restrictions imposed on the builder; the latter must therefore seek a compromise among the different trends [1]. The purpose of this report is to give an account of certain basic studies that should help the builder to achieve this compromise leading to the optimal solution for a given application. These studies are limited here to the aerodynamics of the chamber and affects both the main chamber and the afterburner chamber.

Let us first examine the different qualities that modern combustion chambers must exhibit [2], [3].

- The first of these qualities is combustion efficiency, which must be as high as possible; excellent results have been obtained in the case of the main burner, but progress must still be made in afterburner chambers

- The main combustion chamber must be as short as possible, while retaining the highest fuel efficiency. This minimum length is basic, since it reduces the length of the shaft connecting the compressor and the turbine. For reasons of space, the length of the afterburner chambers must also be as short as possible.

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* Numbers in the margin indicate pagination in the foreign text.

- It is equally important to reduce the pressure loss in the chamber; it is certain that simplification in combustor design is a move in this direction, but one must not forget that this pressure loss is proportional to the square of the intake Mach number. A very careful aerodynamic analysis is necessary, however, if we wish to reduce pressure losses.

- It is also necessary to design a cooling system for the walls that is as effective as possible in reducing the flow of air required for the protection thereof. This limitation is difficult to comply with due to the increase in the richness of the chamber resulting from an increase in compression ratio, inlet and exhaust temperature of the main chamber.

- In order to limit the temperature at the turbine inlet, it is necessary to dilute the burnt gases with colder air. The problems that thus arise are linked to homogeneity of temperature and flow composition at the turbine inlet. As a result of the /56 intermittency in the structure of the flow, the turbine blades receive successively hot and cold bursts, but given the thermal inertia of the blades, the temperature of the material remains virtually constant; there is however a possibility of chemical reaction on the surface as a result of the variation in composition that might contribute to a faster destruction of the blade. It is therefore necessary, insofar as possible, to provide a flow as homogeneous as possible both in temperature and composition at the turbine inlet turbine.

- The builder is furthermore required to limit the emission of pollutants (solid particles and the production of nitrogen oxides). This emission is above all a function of temperature level and organization of combustion.

Though no attempt is made at a complete coverage of the subjects that serve as guidelines for the current research programs, we would like to underline in th course of this report the importance of aerodynamics in the different problems involved in the improvement of a combustion chamber.

The plan we have adopted is the following:

-The first part is devoted to the main combustor listing particularly the aerodynamic problems relating to the preparation of the mixture in the recirculation zone where primery combustion takes place, and in the secondary combustion zone followed by the dilution zone in order to limit the turbine inlet temperature; the chamber ensemble is [illegible] studied to determine the pressure drop between inlet and exhaust; this pressure drop depends not only on the velocity at the combustion chamber inlet but on the organization of the flow as well.

-The second part deals with the aerodynamics of the [illegible] chambers; a model providing for an evaluation of the development of pressure, temperature, velocity, and efficiency of combustion throughout the chamber has been developed.

## 2. Organization of Flow in the Main Chamber and Development of Combustion

Figure 1 is a diagram of a main annular chamber of a turbojet. The development of combustion can be set forth diagrammatically in four stages:

-Firstly, fuel injection: in the example selected, the injection device comprises an entire system whose role it is to introduce the fuel in the chamber in the form of the finest possible drops, previously mixed with air. The injection device used is, for example, the S.N.E.C.M.A. device consisting of a T-shaped tube through which fuel drops and air circulate at a high richness, of the order of 7 to 8, in order to avoid all combustion in th tube.

-We then observe a recirculating flow zone, the place of combustion at a virtually stoichiometric ratio; the fuel is injected by the T-shaped tube into this vortex.

-In order to complete combustion, the secondary combustion zone, which consists of the incompletely burned gases leaving the vortex region and of air injected through the wall, is situated downstream of the vortex.

-Lastly, the final stage is the zone of dilution of burnt gases with air so as to bring the flow at the combustion chamber exhaust to a temperature consistent with turbine blading behavior.

## 2.1. Injection Device

The injection device plays a dual role; it must not only ensure a suitable supply of fuel, but it must, above all, provide for an atomized structure which, when mixed with the air, is the most likely to burn with proper combustion efficiency for a minimum chamber length, thus producing a minimum of pollutants, the ideal solution being reached with a gaseous fuel previously mixed with a portion of the air.

In order to achieve this end, it is necessary to design a device that prevaporizes the fuel drops and produces a mixture with air while avoiding ignition of the medium.

Fron the aerodynamic standpoint, it is therefore necessary to determine fast atomizing and vaporization conditions of the drops.

The spray depends on the injection system used, and on flow conditions, especially on the difference in velocity between the jet and the air. In what follows, we assume the the structure of the atomized jet (mean diameter and distribution function of drops) is known. The study of the vaporization of fuel drops in a flow is made on a theoretical plane from equations of conservation of mass, of momentum and of energy established for the gas and the drops.

The reduction of the mean radius $r$ of the drop as a function of time is given by the $r^2$ relationship:

$$\frac{r^2}{r_0^2} = 1 - 2\frac{t}{\theta}$$

where $r_0$ is the initial radius of the drop and $\theta = \frac{\rho_l C_p}{\lambda_g} r_0^2 \frac{1}{ln(1+B)}$;

this time constant $\theta$ depends on the thermal conductivity of the gas ($\lambda_g$), of the density of the fuel $\rho_l$, of the specific heat of the gas $C_p$, and of the Spalding transfer function:

$$B = \frac{C_p(T_g - T_v)}{\Delta E_v}$$

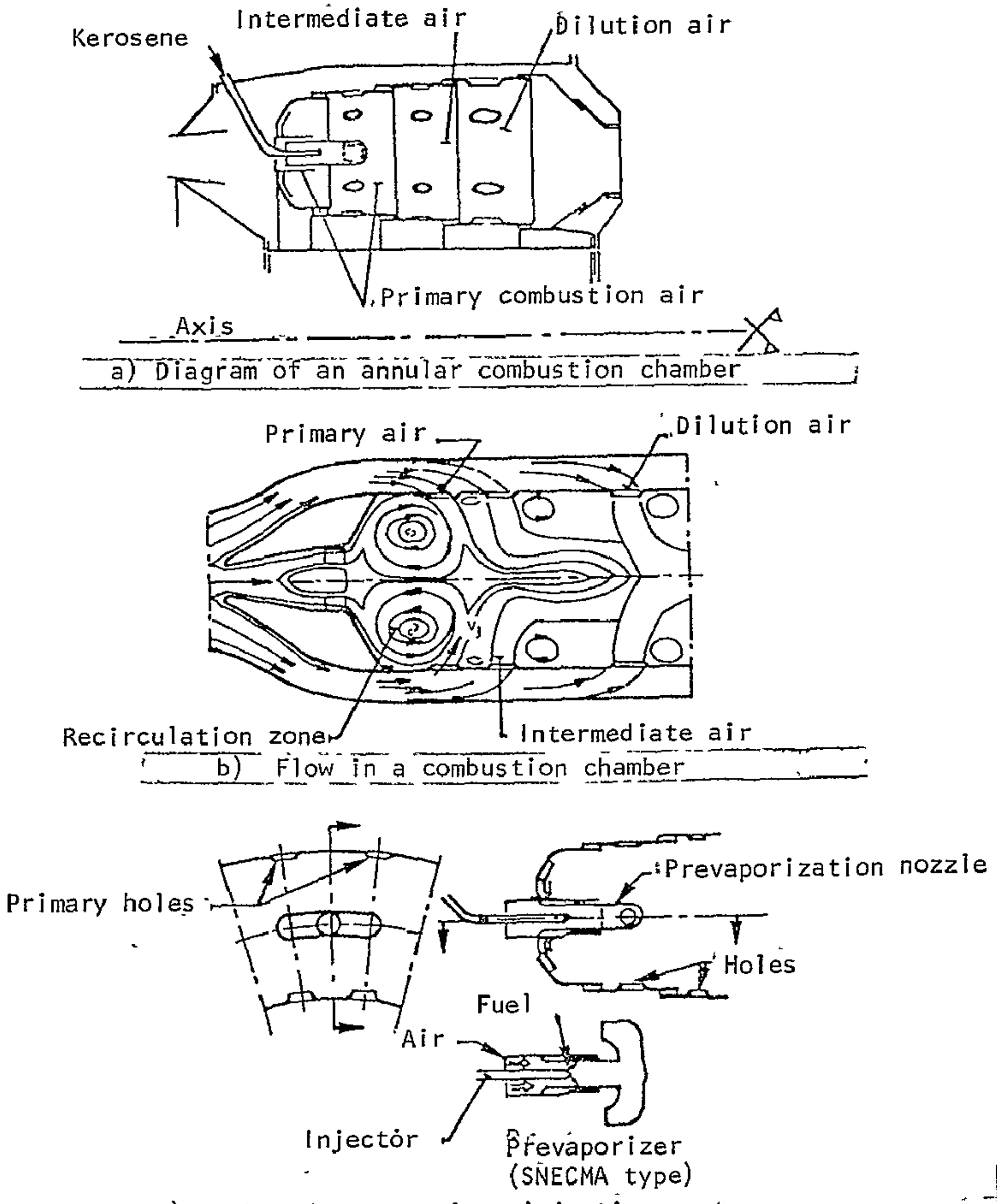
where $T_g$ is the temperature of the gas surrounding the drop, $T_v$ the vaporization temperature, $\Delta E_v$ the energy necessary to trans- from the fuel into gas. By introducing Prandtl number $P_r = \frac{\mu_g C_p}{\lambda_g}$, time constant $\theta$ is written:

$$\theta = \frac{\rho_l}{\mu_g} P_r r_0^2 \frac{1}{ln(1+B)}$$

The solution of the system formed by the equations of conser- tion leads to the appearance of non-dimensional parameters that are representative of the development of the drops, and thus of the length of vaporization: /57

-first, an overall transfer function

$$F = \frac{9}{2} \frac{Pr}{ln(1+B)} = \frac{9}{2} \frac{\mu_g \theta}{\rho_l r_0^2}$$




a) Diagram of an annular combustion chamber

b) Flow in a combustion chamber

c) T-shaped prevaporizer injection system

Fig. 1. Turbojet annular combustion chamber

in which the Prandtl number and the Spalding number are involved;

-then the initial Reynolds number

$$R_{eo} = \frac{\rho_g |u_o - v_o| r_o}{\mu_g}$$

where $u_o$ is the velocity of the gas and $v_o$ the velocity of the drops at the inlet plane;

-finally, the ratio $\phi = \frac{v_o}{u_f}$ of drop velocity at the inlet to gas velocity $u_f$ at the end of vaporization.

Length L of the combustion chamber is represented by the non-dimensional parameter /58

$$X_L = \frac{L}{\theta u_f}$$

The practical values of F range from 0.5 to 1, and for $\phi$ they range from 0.5 to 3.

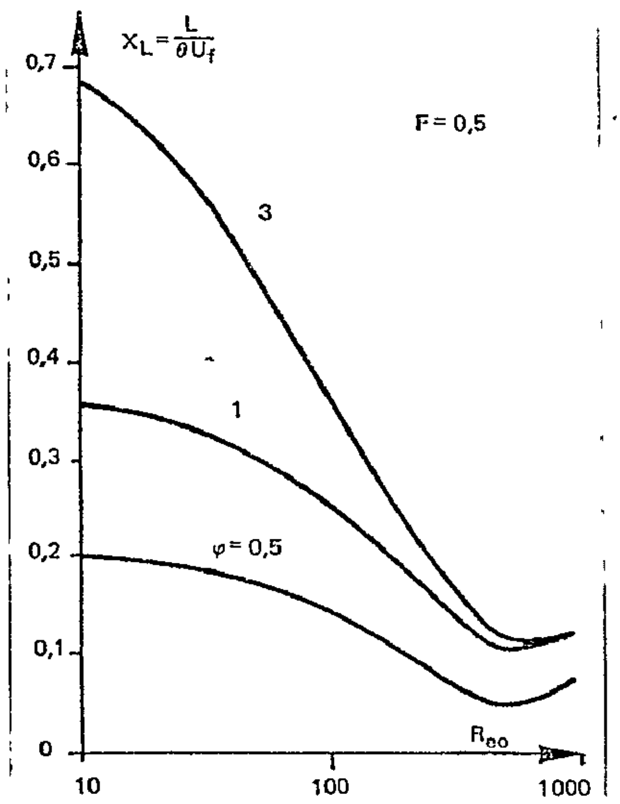



Fig. 2. Length of the vaporization tube. Effect of $R_{eo}$.

One example of the results obtained is given in figure 2 where $X_L$ is plotted as a function of the Reynolds number for different values of $\phi$ and for F = 0.5; it is noted, particularly, that an increase in the Reyholds number reduces the length of the tube, while the $\phi$ ratio is high. The effect of F about $\phi$ = 1 remains slight. This parameter study provides indications of the best definition of the vaporization device. It is specifically necessary to produce a homogeneous mixture of fuel and air, and to avoid the vortices that run the risk of becoming ignition zones. The problem of ignition has been approached experimentally heretofore in order to determine the richness limit beyond which there is no ignition; an accelerated vaporization of the fuel results in a drop in temperature of the flow and thus avoids ignition.

### 2.2. Recirculation Zone

Side injection of air produces a turbulence, and this recirculation zone is the site of a primary combustion with an air/fuel mixture in virtually stoichiometric proportions; the aerodymanic study of this zone is complex,the important thing is the determination of the air fraction entering the nucleus. In the present state of the art, this zone is likened to a Longwell homogeneous reaction engine, whose operation is given by the balance of species and the balance of energy.

Let us take a chemical equation of the second order to characterize combustion of the form:

$$\begin{array}{ccccc} K & + & A & \rightarrow & P \\ \text{Fuel} & + & \text{Air} & \rightarrow & \text{Combustion products} \end{array}$$

Continuity of species P in the recirculation zone is given, in the steady state, by: $\dot{m}_P = V\dot{W}_P$ where $\dot{m}_P$ is the burnt discharge leaving the turbulence, V the volume of the recirculation zone, and $\dot{W}_P$ the mass rate of production of P due to chemical reaction. The preceding reaction leads to a value of $\dot{W}_P$ of the form:

$$\dot{W}_P = \frac{M_P B e^{-T_A/T}}{M_K M_A} \rho_A \rho_K,$$

where $M_P$ is the molar mass of P, $M_K$ and $M_A$ those of K and A, B the frequency factor, $T_A$ the activation temperature, $\rho_A$ and $\rho_K$ the density of the species A and K. Flow $\dot{m}_P$ leaving the recirculation zone is equal to $\dot{m}_P = \frac{\rho_P}{\rho}\dot{m}$ where $\dot{m}$ is the outgoing overall flow (burnt products and diluent) and $\rho$ the mean density of the flow in the recirculation zone and at the outlet of this zone (perfectly mixed jet). By introducing gas dwell time $t_s$ in the recirculation zone defined by $t_s = \frac{\rho V}{\dot{m}}$ and defining the degree of advance of the reaction $z = \frac{\rho_P}{\rho} \frac{I}{M_B}$, the species P balance equation is written:

$$z = t_s B \rho e^{-T_A/T} (1 - z)^2$$

with stoichiometric mixture $\frac{\rho_L}{\rho_e \mathcal{M}_L} = \frac{\rho_K}{\rho_e \mathcal{M}_K} = (1 - z)$

The equation of conservation of energy ât steady speed is equal to:

$$\dot{m} C_p (T - T_e) = \Delta H_p V \dot{W}_p$$

Rise in temperature in the turbulent zone from $T_e$ to T is given by the input of energy by chemical reaction $\Delta H_p V W_p$, $\Delta H_p$ being per unit mass of P, the energy released by a complete combustion; we assume that there are no losses.

Assuming a maximum temperature $T_a$ released by combustion $\frac{\Delta H_p M_p}{C_p} = T_a - T_e$ so that:

$$T - T_e = (T_a - T_e)\, t_s B \rho e^{-T_A/T} (1 - z)^2;$$

or yet:

$$T - T_e = (T_a - T_e) z$$

we thus obtain a linear relationship between T and $z$.

Let us introduce the production rate in the form: /59

$$\dot{C} = B \rho e^{-\frac{T_A}{T_e + (T_a - T_e) z}} (1 - z)^2 = \frac{1}{t_{ch}} z^m (1 - z)^2$$

replacing the exponent of $z$ by a power of $m$ degree of $z$, this approximation is valid for high values of the activation temperature ($T_A$ > 12,000 K), $t_{ch}$ being a characteristic time of the chemical reaction.

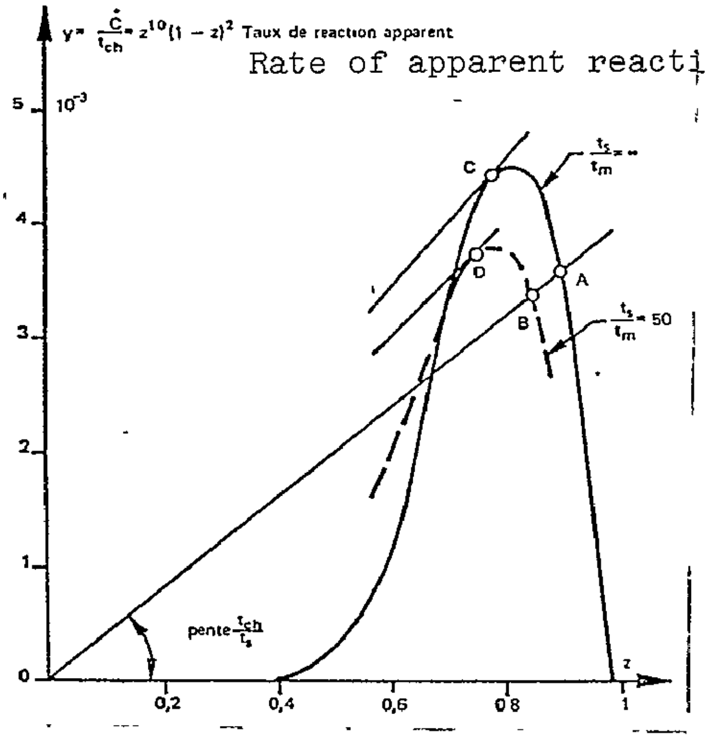



Fig. 3. Effect of the imperfection of the mixture.

On the same graph (Fig. 3) let us plot the variations of the line $y = z\frac{t_{ch}}{t_s}$ and of the curve $y = z^m(1-z)^2$; the solutions yielding the operation of the nucleus correspond to the intersection of the straight line and of the curve (point A, for example). This simple theory enables us to explain the operation of the recirculation zone. If dwell time $t_s$ is reduced, we arrive at point C that determines the blast conditions of flame; improvements have been made taking into account mixing time $t_m$ compared to dwell time $t_s$. For a mixing time $t_m = \frac{t_s}{50}$, for example, we observe a deformation of the curve, the degree of progress of reaction is less, point A shifts to B for the same ratio of $t_{ch}/t_s$.

The aerodynamic study of this zone still has to be made, it should determine, specifically, the distribution of mass flow, momentum, and energy; certain attempts have been made by Spalding and Anasoulis using techniques of integration by finite differences [5].

## 2.3. Secondary Combustion Zone

Combustion efficiency in the recirculation zone remains low and ranges between 0.6 and 0.8; it is therefore necessary to complete combustion mixing the hot gases leaving the recirculation zone with secondary air. This part of the combustor resembles a more or less stratified tubular reaction engine. In order to define this zone on an aerodynamic plane, we use the equation of one-dimensional balance in a manner similar to what would be done in the case of afterburner chambers, and this will be dealt with in greater detail. In a simple model, these two parts of the combustion chamber: recirculation zone and secondary combustion, zone may be likened to the juxtaposition of a homogeneous reaction engine and a tubular reaction engine. This coupling leads to a minimum dwell time, i.e., for a minimum combustor length if the homogeneous reaction engine is adjusted to the mâximum rate of chemical production [2].

The flow diagram is generally the following: since the combustor is assumed to be annular, the $j^{th}$ flow tube situated between radii $R_j$ and $R_{j-1}$ is considered; at a steady velocity, the balances os mass, momentum and energy are written on the $x$ abscissa:

$$\frac{d\dot{m}_j}{dx} = \frac{d\dot{m}_c}{dx} \quad (\dot{m}_j = \rho_j u_j A_j)$$

$$\frac{d}{dx}(\dot{m}_j u_j) = \frac{d}{dx}(p_j A_j) + 2\pi p_{j+1} R \frac{dR_j}{dx} - 2\pi p_{j-1} \frac{dR_{j-1}}{dx} + \left.\frac{d\dot{m}_t}{dx}\right|_{j-1,j}(u_{j-1} - u_j) + \left.\frac{d\dot{m}_t}{dx}\right|_{j,j+1}(u_{j+1} - u_j)$$

$$\frac{d}{dx}(m_j C_{pj} T_{ij}) = \dot{m}_j \dot{Q}_j + \left.\frac{d\dot{m}_t}{dx}\right|_{j-1,j}(C_{pj-1} T_{ij-1} - (p_j T_{ij}) + \left.\frac{d\dot{m}_t}{dx}\right|_{j,j+1}(C_{pj+1} T_{ij+1} - C_{pj} T_{ij})$$

where $\dot{m}_j$ is the flow tube rate, $\dot{m}_c$ the external excess flow, $\dot{m}_t$ the turbulent exchange rate between two neighboring flow tubes, $p$ static pressure, $T_i$ arrest temperature and $u$ axial velocity; Q is the rate of energy released by combustion [6].

## 2.4. Dilution Zone

The role of the dilution zone is to raise the temperature at the turbine inlet to an acceptable level for blade protection.

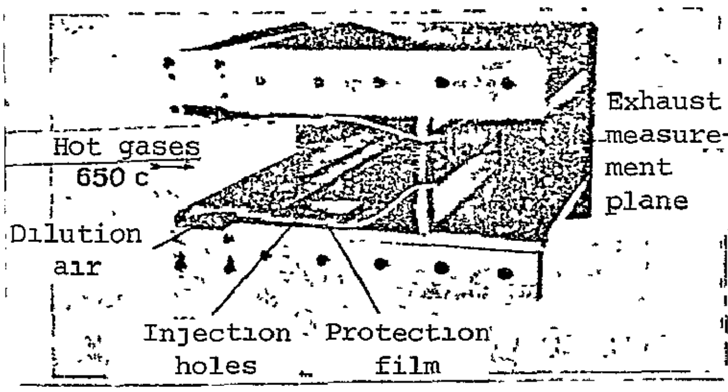



Fig. 4. Organization of combustion in the dilution zone.

It is therefore necessary to produce in the shortest possible distance a homogeneous flow both in temperature and composition. The assembly used for this purpose is shown in figure 4; dilution air circulates throughout the combustor, it is used to cool the wall providing a protective film close to the surface; dilution air is injected into the hot flow through large-sized holes. From the aerodynamic standpoint, it is important to know, on the one hand, the mean line of the jet entering the combustor and, on the other hand, from this mean line, the diffusion of cold air in the hot /60
gases, so as to be able to predict the degree of homogeneity of flow in the exhaust plane of the combustor.

### 2.4.1. Jet Penetration [7]

The jet forms an angle $\beta_0$ with the main stream; it is subjected to forces that impose the curvature: according to the perpendicular $n$ to the mean line, the centrifugal force applied to the mean line by an element having a length $ds$ and a cross section $A_j$ expressed as

$$\frac{\rho_j v_j^2}{r} A_j ds$$

is equalized by the aerodynamic resistance $T_n$.

Along the tangent, the inertial force.

$$\rho_j v_j \frac{dv_j}{ds} A_j ds$$

is equalized by the longitudinal component of drag.

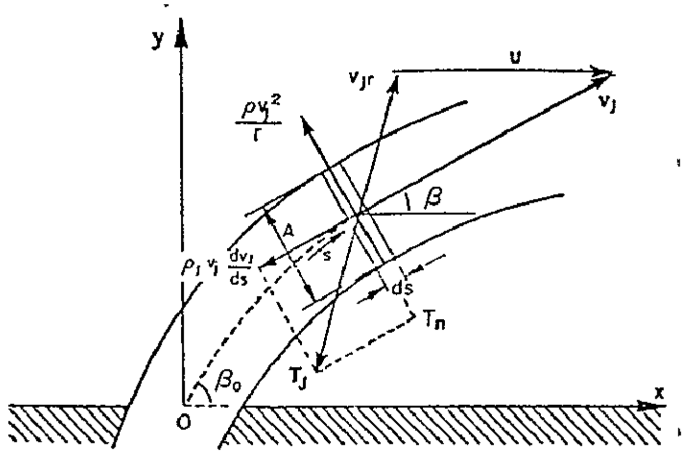



Fig. 5. Diagram of the dynamic equilibrium of the jet.

The equations of the equalization of forces and the equation of continuity yield the development of the mean line; the system is written:

$$\begin{cases} \frac{d\beta}{ds} = \frac{1}{r} = -2\frac{\rho u^2}{\rho_j v_j^2} \cdot \frac{C_T}{\pi d} \sin^2\beta \\ \frac{dv_j}{ds} = -2\frac{\rho u^2}{\rho_j v_j^2} \cdot \frac{C_T}{\pi d} v_j \left(\frac{v_j}{u} - \cos\beta\right) \sin\beta \\ v_j d^2 = v_{j0} d_0^2. \end{cases}$$

The notations used are derived from figure 5.

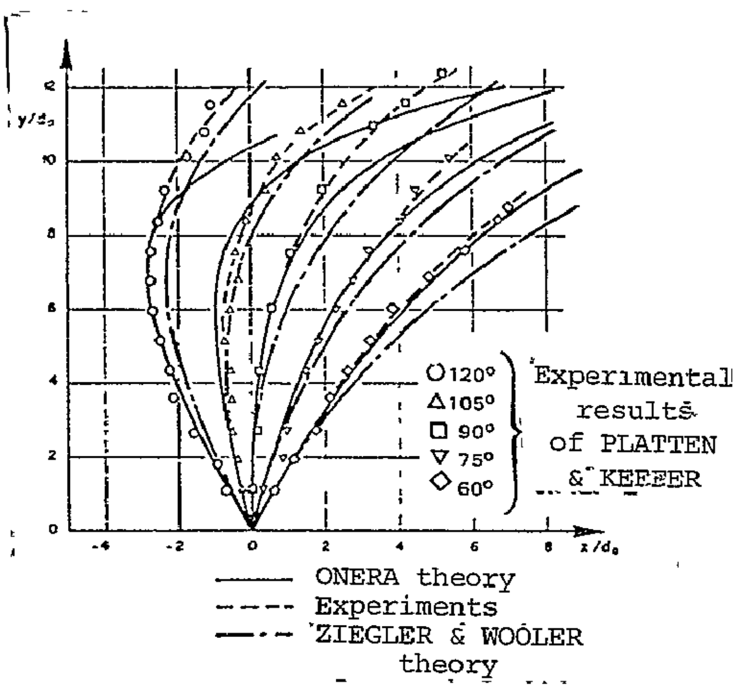



Fig. 6. Penetration compared according to the initial orientation of the jet, (mean line) — ($v_{jo}/u$ = 8.32)

The solution of this system leads to the determination of the mean line. These results are compared with the experimental results for different values of $\beta_0$ as well as with Ziegler's calculation (fig. 6), the agreement between theory and experiment is satisfactory.

It is therefore possible in the case of a wide range of injection angles, flow velocity and injection velocity to have an idea of the mean line.

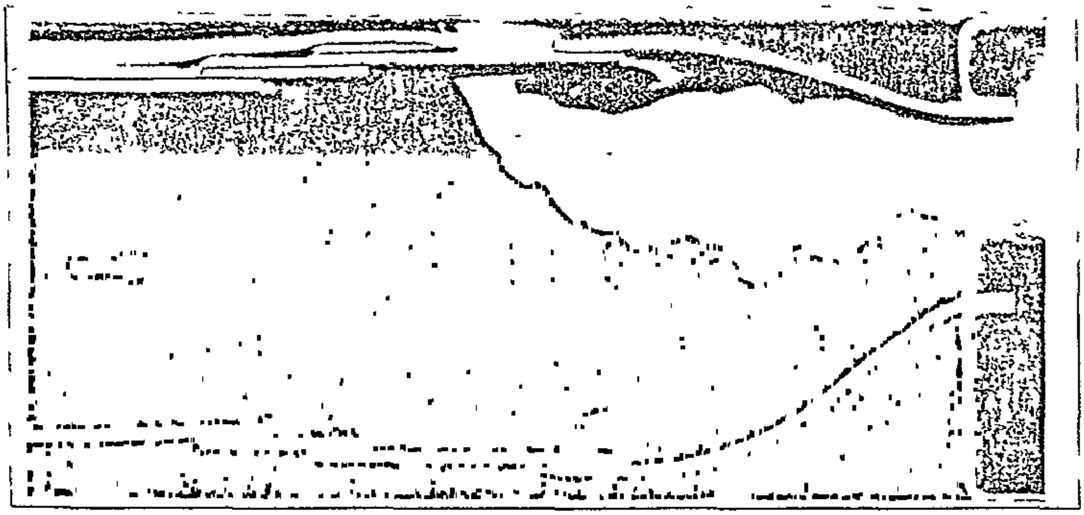


Fig. 7a. Overall appearance of a dilution jet and wall film.

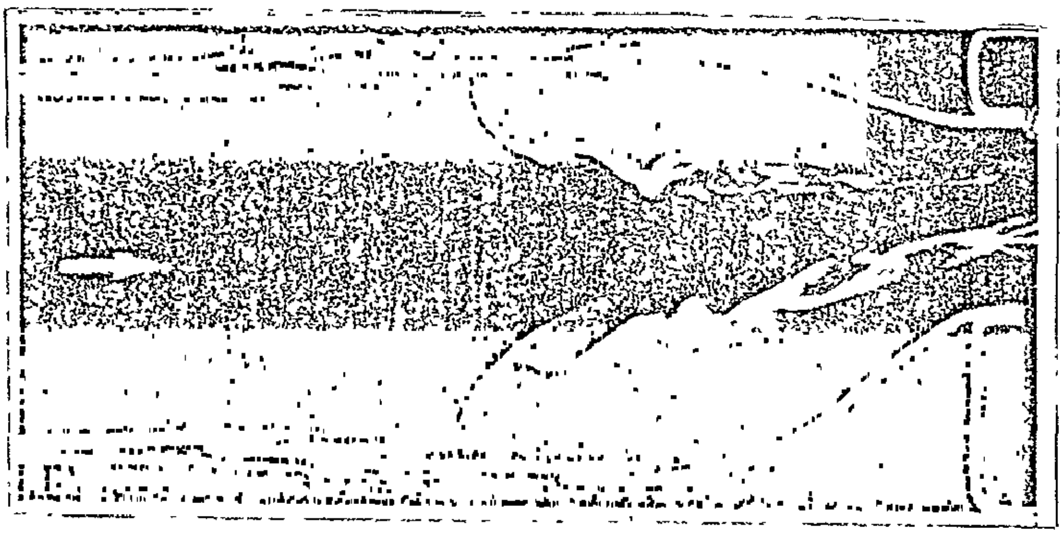


Fig. 7b. Study of flow lines.

## 2.4.2. Effect of Dilution

The problem of the effect of dilution is more complex because it is difficult to describe; experiments conducted in a tub of water have made it possible to show this complexity: thanks to a process of visualization, let us examine the structure of the jet; figure 7a shows the overall appearance of the dilution jet

underscoring the structure by bursts of the stream. A study of the flow lines is made possible by a materialization thereof with a very localized injection; the helical structure of the fluid thread surrounding the main jet (fig. 7b) is seen. In order to show the incidence of the dilution jet on the cooling of the walls, the visualization of the wall injection, downstream of the jet, shows (fig. 7a) a return of the flow towards the dilution /61
jet. These visualization processes thus make it possible to describe the flow better

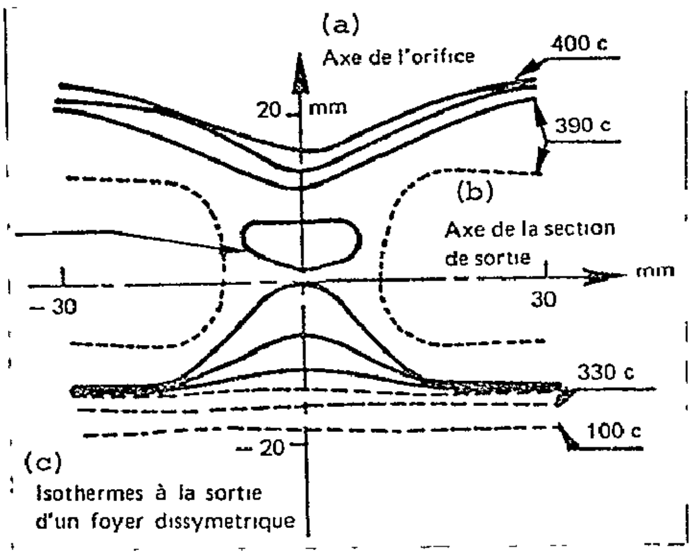



Fig. 8. Study of dilution

Key: (a) Axis of the hole
(b) Axis of the exhaust section
(c) Isotherms at exhaust of a dissymmetrical combustor

A study of dilution by a distribution of temperature in the exhaust section of dilution has made it possible to determine the structure of this zone. Figure 8 shows the isotherms at the exhaust of a dissymetrical combustor, thus showing the efficiency of the cooling film (lower part of the figure [100 and 300°C isotherms]) and the efficiency of dilution with the isotherm at 400°C along the axis of the two-dimensional combustor.

## 2.5. Evolution of Pressure All Along the Combustor

An important optimization relating to the aerodynamics of the combustor deals with the evaluation of pressure loss. In effect, the performances of the turbojet are affected by pressure loss in the combustor. These losses are due to three main causes:

the supply of energy in a subsonic stream, the losses due to friction and separation, the losses due to jet mixing. If we designate the impact pressure at the compressor exhaust as $p_{isc}$ and the impact pressure at the turbine inlet as $p_{iET}$, we define, generally two criteria that characterize this loss in pressure:

$$f_1 = \frac{p_{isc} - p_{iET}}{p_{isc}}, \quad f_2 = \frac{p_{isc} - p_{iET}}{q_r}$$

the dynamic reference pressure being equal to

$$q_r = \frac{1}{2} \frac{\dot{m}^2_T}{\rho_{sc} A^2_M}$$

where $\dot{m}_T$ is the total rate of flow passing through the combustion chamber, $\rho_{sc}$ density at the compressor exhaust, and $A_M$ the maximum annular cross section of the combustion chamber. $q_r$ thus /62
refers to a fictitious flow where the steady state of the fluid is the one corresponding to conditions at the end of compression $p_{sc}$ and $T_{sc}$ for static pressure and temperature, and $a^2_{sc} = \gamma_{sc} nRT_{sc}$ for the speed of sound. We define a reference Mach number $M_r$ such as

$$M_r = \frac{\dot{m}_T}{A_M} \cdot \frac{a_{sc}}{\gamma_{sc} p_{sc}}$$

so that:

$$q_r = \frac{\gamma_{sc}}{2} p_{sc} M_r^2$$

The study of an optimum combustion chamber leads to a maximum reduction of $f_1$ or $f_2$.

The strategy to be followed is thus the following:

Since the conditions defining the upstream flow are given, i.e., $p_{sc}$, $T_{sc}$, $M_r$, $\dot{m}_T$, and since the energy involved in the combustor is defined by the arrest temperature ratio $T_{iET}/T_{isc}$, it is a matter of determining the geometry of the combustion chamber leading to the minimum value of $f_2$ (or $f_2$). This geometry must also respond to the principles of combustion organization discussed in preceding paragraphs.

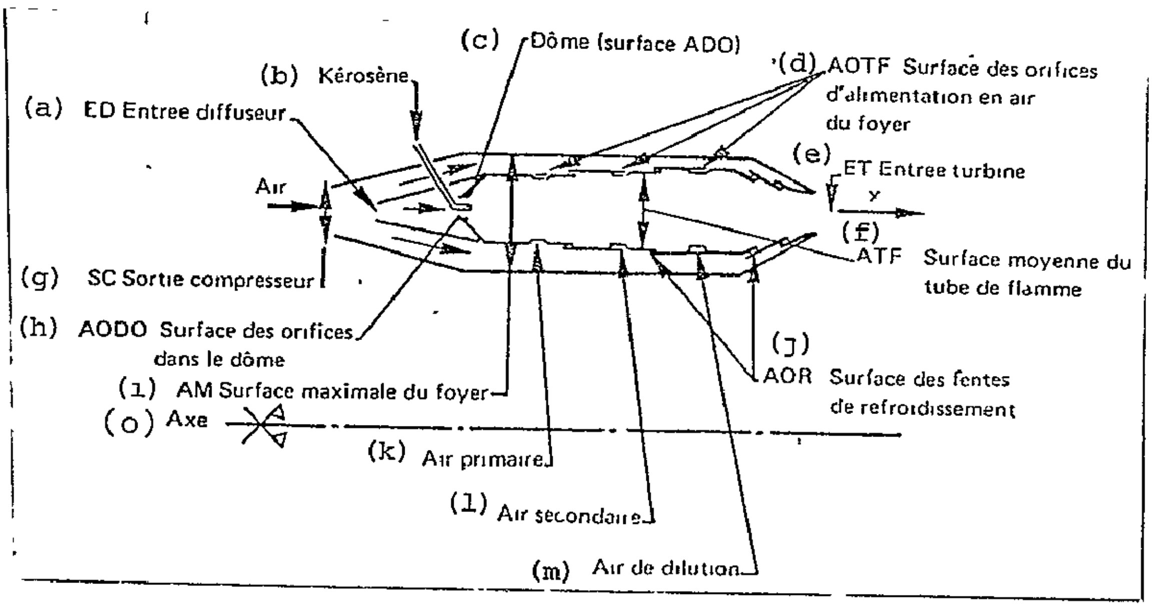



Fig. 9. Conventional annular combustion chamber - Notations

Key: (a) ED Diffuser inlet; (b) Kerosene; (c) Dome (ADO area); (d) AOTF Combustion chamber air-supply hole area; (e) ET Turbine inlet; (f) ATF mean flame-tube area; (g) SC Compressor exhaust; (h) AODO Area of holes in dome; (i) AM Maximum area of combustion chamber; (j) AOR Area of cooling slots; (k) Primary air; (l) Secondary air; (m) Dilution air; (o) Axis.

It is therefore necessary to anticipate the effect on $f$: of the geometry of the diffuser (fig. 9) linking the compressor exhaust to the combustion chamber, the geometry of the nozzle directing the flow to the right of the flame tube, the cross section of the holes $A_{ODO}$ arranged on the dome, the straight portion of the dome $A_{DO}$, the mean straight cross section of the flame tube $A_{TF}$ and the geometry of the flame tube, the cross section of the holed situated on the wall of the flame tube $A_{OTF}$ ensuring the supply of air to the primary and secondary combustion zones, and to the dilution zone, and the cross sections of the cooling slots $A_{OR}$.

The value of $f_1$ or $f_2$ is derived from the equations of conservation of flow velocity of momentum and energy. We are not listing these classic equations, rather we shall list the hypotheses one is lead to formulate, and the important terms involved in these relationships.

There is not much difficulty in writing the equations that define flow in the diffuser or the variable-geometry annular flame tube; it is enough to take into account a term of the type:

$$\int_{x_1}^{x_2} p \frac{dA}{dx} dx$$

between abscissas $x_1$ and $x_2$ to evaluate the variation in cross section and of a friction term:

$$\int_{x_1}^{x_2} \frac{1}{2} C_r \rho A_m u^2 dx$$

where $C_r$ is the coefficient of friction equal in the case of combustion chambers to $C_r = 0.0035 + 0.264\ R_e^{-0.422}$ and $A_m$ the surface per unit length wet by the fluid. Likewise, in the equation /63 of conservation of energy, we can take into account the energy released by the combustion reaction assuming a composition in equilibrium at the end of combustion.

These difficulties in the evaluation of $f_1$ and $f_2$ are derived particularly from the holes arranged on the flame tube that distribute air in the combustion chamber. Let us examine the effect of a hole. Flow in the annular space is divided into two parts, one relating to tracking the flow in the annular space, and the other to the flow velocity through the holes:

(a) Flow of the first part, which develops in the annular space, suffers an abrupt arrest due to the deviation of the flow in the hole, the loss of impact pressure on either side of the annular space is equal to:

$$p_{t_1} - p_{t_2} = a\frac{\rho_1 u_1^2}{2}\left(b\frac{\dot{m}_0}{\dot{m}_1}\right)^{\alpha}$$

1 and 2 are the conditions in the annular flow before and after the hole, i.e., after deviation of the flow, $\dot{m}_0$ is the deviated flow passing through the hole $\dot{m}_1 = \dot{m}_0 + \dot{m}_2$, $a$ and $b$ are two constants, and $\alpha$ a function of the downstream Mach number.

$$\alpha = \left(\frac{1}{2} + 0{,}242\ M_1^{2,21}\right)^{-1}$$

(b) Flow $\dot{m}_0$ passing through the hole can only be linked to the drop in pressure through the hole if flow coefficient $C_D$ is known; this coefficient depends not only on the velocity through the hole, but also on the pressure level in the flame tube; value of $C_D$ for holes of various shapes are currently available [8].

(c) The jet enters the flow that occupies the flame tube; it is then necessary to know the angle of the jet with respect to the mean flow in the flame tube, jet penetration and diffusion thereof, and its mixing with the main flow; as stated, the laws of penetration are starting to be well known, but they are not so well known in the case of the mixture; the results obtained with $f_1$ and $f_2$, assuming a perfect mixture or a stratified flow, are actually only slightly different, so that a quasi-instantaneous mixture can be assumed for this calculation without any major error.

The minimum values of $f_1$ and $f_2$ are obtained by a parametric sweep. The main results are the following:

-The diffuser inlet Mach number $M_{ED}$ and the reference Mach number $M_r$, which is proportional thereto, have a substantial effect on the overall pressure drop in the combustion chamber,

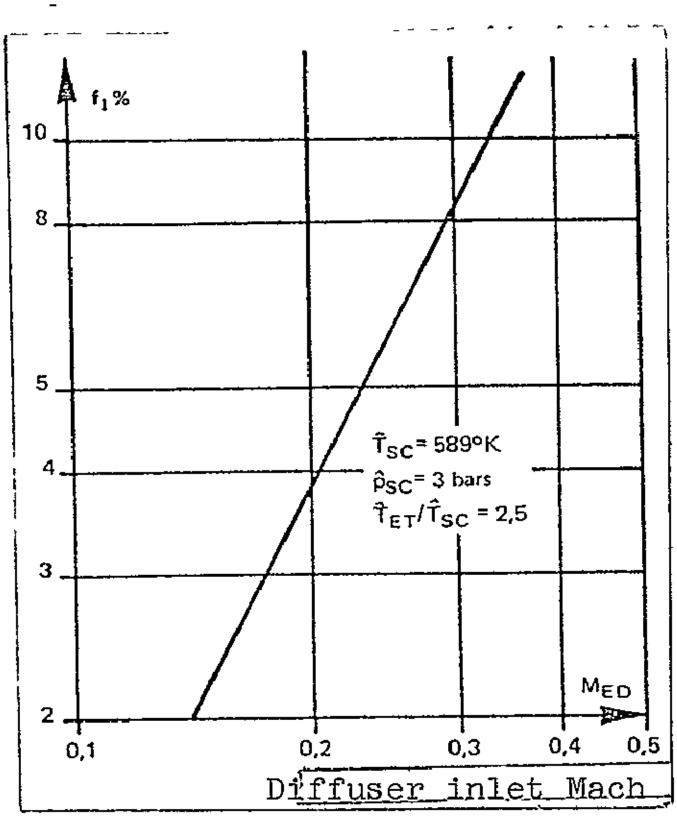



Fig. 10. Overall pressure drop in the combustion chamber.

as shown in figure 10 (the coefficient of proportionalty between $M_{ED}$ and $M_r$ being the ratio of the maximum chamber area to the diffuser inlet area).

Since the angle of the diffuser is determined by the separation, it is not possible to reduce the $M_r$ and thus increase the maximum area $A_M$ of the chamber without a prohibitive lenghtening of the diffuser. $M_r$ is therefore fixed by the length of the diffuser selected. Different expedients are currently used in order to increase the angle, the solution that appears to be the most promising consists in sucking the boundary layer in the diffuser, the suctioned flow is of the order to 3 to 4%; this suction also has the effect of standardizing the velocity.

It is then a matter of selecting the geometry of the flame tube that will lead to a minimum value of $f_2$. This geometry can be determined by two coaxial cylinders or by a divergent annular tube. In each of these cases (fig. 11), we have an optimum value for the straight portion of dome $A_{DO}$, this optiumum value depending on the arrest temperature ratio between the combustion chamber exhaust and inlet. The lowest pressure loss is obtained with the divergent flame tube. $f_2$ increases when the arrest temperature ratio increases.

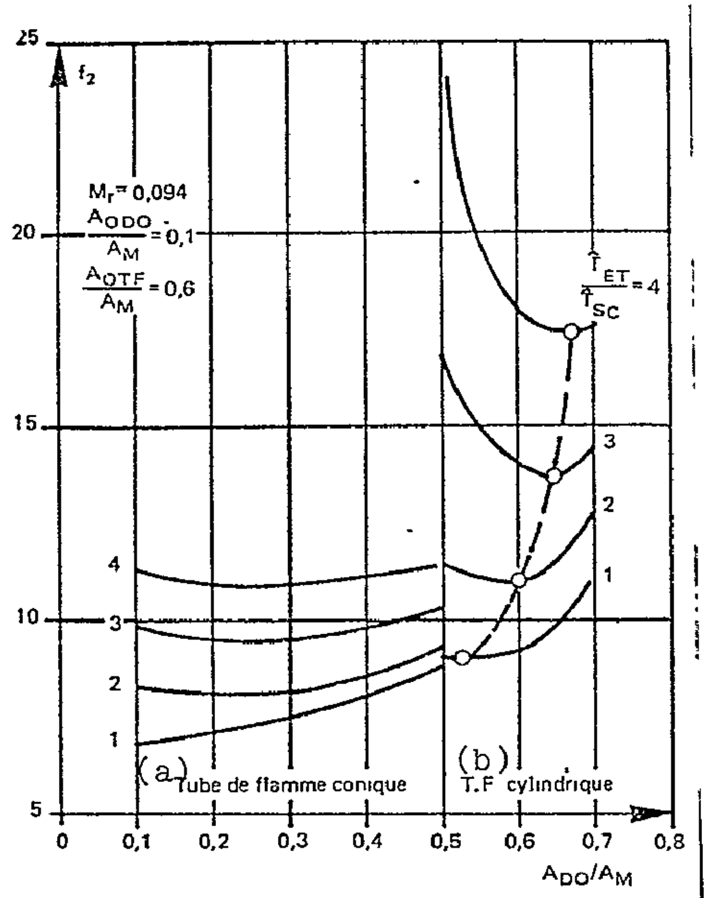



Fig. 11. Pressure drop as a function of the straight portion of the dome in the case of a flame tube consisting of two coaxial cylinders and of a divergent annular one [8].

The optimum value of $A_{DO}$ or, more generally, that of $A_{TF}$ the characterizes the area of a mean straight portion of the flame tube also depends upon the distribution of the openings in the dome ($A_{ODO}/A_M$). An increase of $A_{ODO}/A_M$ increases the value of $A_{TF}/A_M$ corresponding to the minimum of $f_2$. In order to fix concepts, and for an arrest temperature ratio of 2, $A_{TF}/A_M$ is equal to 0.55 for $A_{ODO}$/AM = 0, $A_{TF}/A_M$ = 0.6 for $A_{ODO}/A_M$ = 0.1, and 0.64 for 0.2.

Likewise, the ratio $A_{OTF}/A_M$ that characterizes the flame openings changes the optimum value of $A_{TF}/A_M$; this effect is generally slight; the increase of $A_{OTF}/A_M$, however, reduces the value of $f_2$ considerable; $f_2$ going from 18 for $A_{OTF}/A_M$ = 0.4 to 11 for $A_{OTF}/A_M$ = 0.6; in this case $M_r$ = 0.63, $A_{ODO}/A_M$ = 0.1, and $T_{ET}/T_{sc}$ = 2.

The increase in the number of holes, for a constant value of $A_{OTF}/A_M$ reduces this criterion slightly.

The cooling holes, characterized by their $A_{OR}$ area are also /64
involved in the calculation of $f_2$; we note, generally, that $f_2$ decreases linearly when the ratio $A_{OR}/A_{OTF}$ increases.

The study of the overall aerodynamics of the combustion chamber is therefore very important; specifically, it permits, in the case of given inlet conditions, to determine the optimum geometry of the combustion chamber.

## 3. Aerodynamics of Afterburners

This burner is situated at the exhaust of the turbine, inlet flow is therefore rapid (at a velocity of the order of 100 $m.sec^{-1}$; the static temperature is high (of the order of 1000°K), and its composition is that of a combustion (kerosene-air) with a richness of the order of 0.2, i.e., with a substantial excess of air. The kerosene is injected upstream of the afterburner and, due to the temperature level encountered and to the velocity, it is possible to assume that the kerosene is premixed with the gas emitted by the turbine (homogeneous-type flame) downstream of the stabilization zone. Actually, there is a stratification of the mixture ratio at the level of the injection system that modifies the composition of flow, but this stratification is neglected in the aerodynamic study.

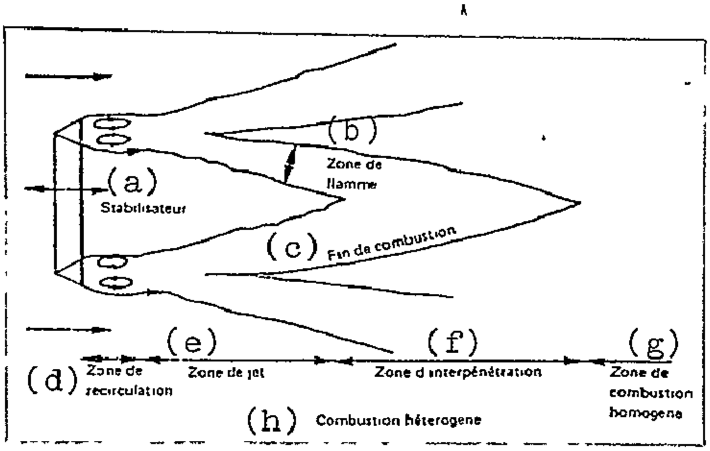



Fig. 12. Organization of combustion in an afterburner.

Key: (a) Stabilizer; (b) Flame zone; (c) End of combustion; (d) Recirculation zone; (e) jet zone; (f) Interpenetration zone; (g) Homogeneous combustion zone; (h) Heterogeneous combustion.

The flame is stabilized by annular and radial obstacles, generally in the form of a trough as shown in figure 12. Combustion takes place as follows:

(a) Near the stabilizers we observe a recirculation zone that acts as a homogeneous reaction engine, the length of this zone depends on the velocity of the gas at the stabilizer level and on a chemical time that is a function of the mixture ratio.

(b) The turbulent propagation of combustion, with stratified flow of fresh gases and burnt gases is located after this recirculation zone, it is the jet zone.

(c) Farther downstream, the fresh gas zone disappears and the flames that propagate after the stabilizers are mixed, it is the interpenetration zone.

(d) Farther downstream combustion continues in a homogeneous combustion zone; generally, and so as not to lengthen the combustion chamber, the homogeneous combustion zone is restricted to a value of an efficiency value of 0.8 ÷ 0.9 so that the homogeneous combustion zone can be neglected.

The important thing is to determine, for each section, combustion efficiency and the development of pressure, velocity, and temperature, so as to be in a position to calculat the heat transfer rate at the wall and the concentration of pollutants. The model developed by O.N.E.R.A. [9] neglects the circulation zone, the most important part of the combustion zone consisting of the turbulent propagation of the flame as shown in figure 13.

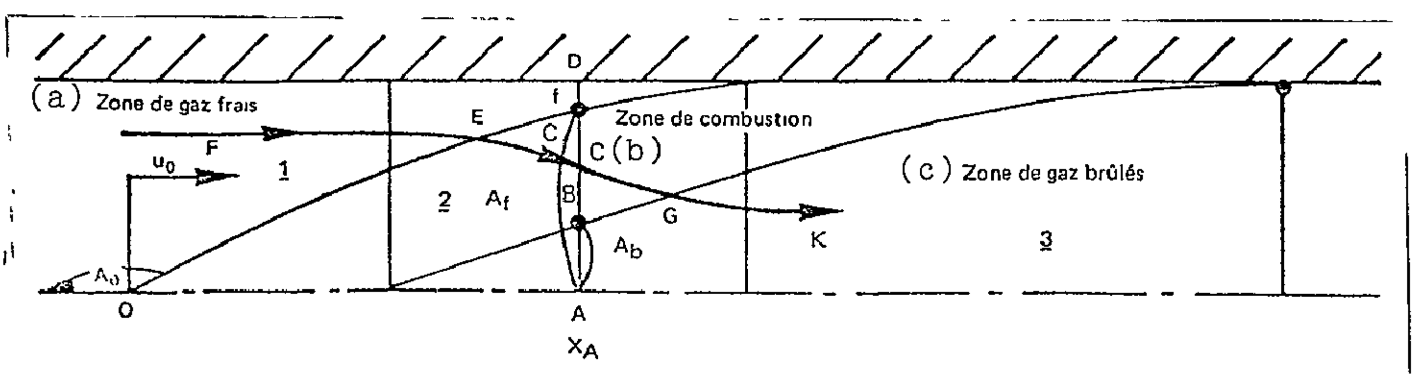



Fig. 13. Diagram of the afterburner
Key: (a) Fresh gas zone; (b) Combustion zone; (c) Burnt gas zone.

Since flow velocity is high with respect to the turbulent combustion rate, the combustion zone (index c) is very long and thick and it separates the fresh gas zone (index f) from the burnt gas zone (index b). The way the system of equations governing flow is written depends on the development of combustion; three zones are marked:

-The zone downstream from the portion where the burnt gases are situated (zone (1)),

-The zone downstream from the portion where the fresh gas ends (zone (3)),

-and, between these two, zone (2).

Let us assume that for an abscissa of $x = 0$, static pressure is $p_0$, flow velocity $u_0$, static temperature $T_0$, density $\rho_0$, and the area occupied by the flame (recirculation zone) $A_0$, the overall continuity equation for zone 2, for example for the abscissa $x = x_A$: /65

$$\rho_o u_o (A - A_o) = \rho_f u_f (A - A_f) + \rho_b u_b A_b + \int_{A_b}^{A_f} \rho_c u_c dA$$

A is the cross section of airflow; velocity is assumed to be uniform in the fresh gas zone and in the burnt gas zone.

Likewise, the equation representing momentum becomes:

$$p_o A + \rho_o u_0^2 (A - A_o) = pA + \rho_f u_f^2 (A - A_f) + \rho_b u_b^2 A_b + \int_{A_b}^{A_f} \rho_c u_c^2 dA.$$

To these two equations we must add the equation of conservation of energy for fresh gases defining $T_f$ and $u_f$:

$$C_p T_o + \frac{u_0^2}{2} = C_p T_f + \frac{u_f^2}{2}$$

and the equation of conservation of energy for burnt gases:

$$C_pT_o + \frac{u_o^2}{2} + \Delta h = C_pT_b + \frac{u_b^2}{2}$$

where $\Delta h$ is the energy brought into play by combustion.

The gas is assumed to be perfect, so that:

$$\frac{p}{p_o} = \frac{\rho}{\rho_o}\frac{T}{T_o}$$

and the development of $p$ and T is assumed to be isentropic:

$$\frac{p}{p_o} = \left(\frac{T_f}{T_o}\right)^{\frac{\gamma}{\gamma-1}},$$

In order to obtain the aerodynamic field, it is first necessary to characterize turbulent combustion; two magnitudes of turbulent combustion phenomena are used, the first is the turbulent combustion rate $u_{bT}$, which will define the geometry of the area separating the fresh gas zone from the combustion zone and, particularly the inclination of the flame front with respect to the mean flow is given by the quotient of axial flow velocity $u$ by the turbulent combustion rate $u_{bT}$; the second characteristic magnitude of the combustion phenomena is the time $t_b$ necessary for combustion, which will determine the thickness of the flame. If, for example, we follow a flow line F, E, G, K, the end of combustion, i.e., point G, is defined by $t_b = \int_F^G \frac{ds}{u}$, $s$ being the distance travelled along a flow line on which, by virtue of the slight inclination of EG with respect to the axis, the local flow valocity resembles axial velocity $u$. It may be assumed that turbul nt state combustion occurs in bursts whose initial dimension depends on the scale of the turbulence $l_o$; the combustion rate of these bursts $u_b$ is equal to

$$u_b = u_{bL} + u'\frac{l}{l_o}$$

where $u_{bL}$ is the laminar combustion rate, $l$ the dimension of the burst at moment $t$ and $u'$ is the eddy velocity, velocity

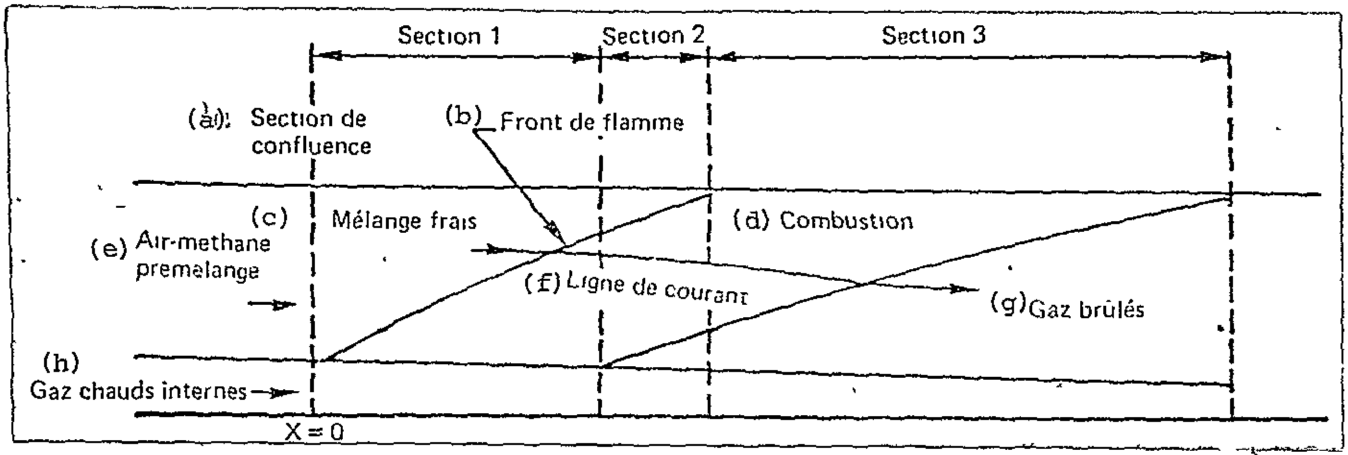



Fig. 14. Simplified diagram of the combustion chamber

Key: (a) Confluence section; (b) Flame front; (c) Fresh mixture; (d) Combustion; (e) Premixed air/methane; (f) Flow line; (g) Burnt gases; (h) Internal hot gases.

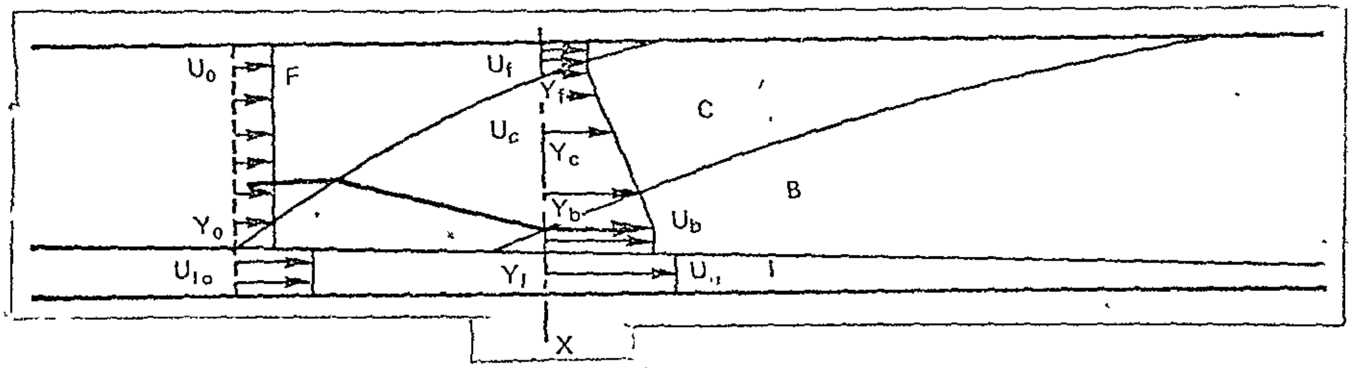



Fig. 15. Representation of parameters

$u_b = -\, dl/dt$ so that after integration combustion time is written:

$$t_b = A_1 \frac{l_0}{u'} ln \left(1 + \frac{u'}{u_{bL}}\right)$$

$A_1$ is a constant ($A_1 \simeq 4.3$) this relationship has been duly verified by experiments, combustion time depends on three parameters, laminar flow velocity $u_{bL}$, the scale of turbulence $l_0$ and eddy velocity. When turbulence is substantial ($u' \gg u_{bL}$), this is the case of an afterburner chamber, the turbulent combustion rate is given by

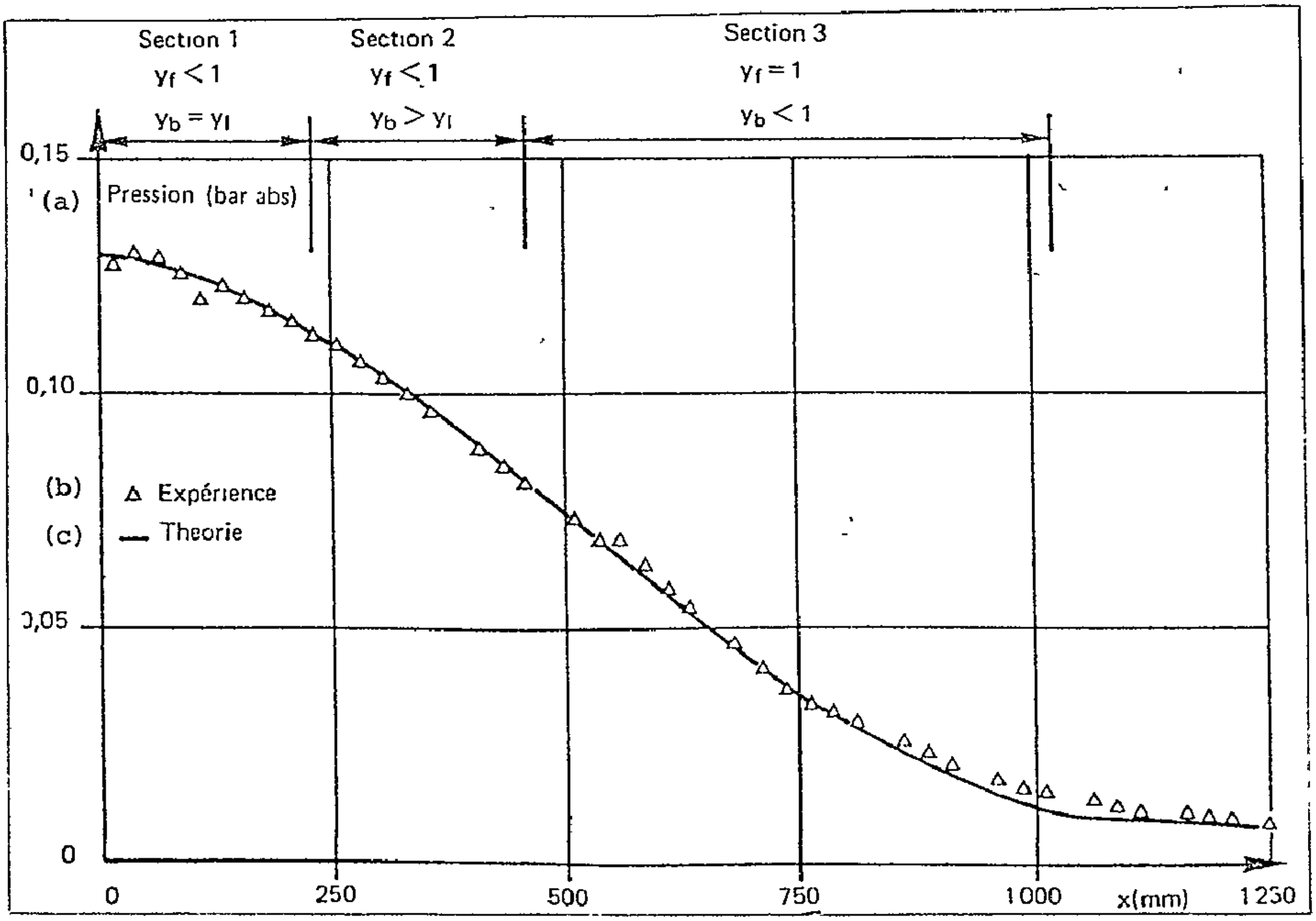



Fig. 16. Distribution of pressure along the axis.
Key: (a) Pressure (abs. bar); (b) Experiment; (c) Theory.

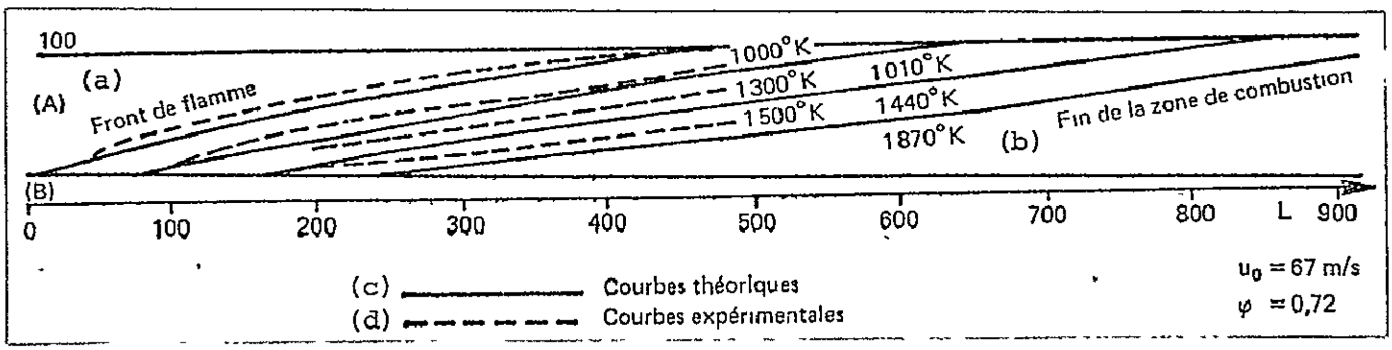



Fig. 17. Distribution of temperature.
Key: (a) Flame front; (b) End of combustion zone; (c) theoretical curves; (d) Experimental curves.

$$u_{bT} = A_2 \beta u_{bL} + \frac{A_3 u'}{\sqrt{\ln\left(1 + \frac{u'}{u_{bL}}\right)}}$$

where β is the temperature-combustion ratio, $A_2$ and $A_3$ are constants, when combustion is confined $A_2 = 1$ and $A_3 = 2$; this last magnitude $A_3 = 2$ stresses the role of combustion as a generator /67 of turbulence.

This model was first verified by means of a simplified experiment, the diagram of which is shown in figure 14; the air-methane premix is initiated by a parallel flow of hot gases, the turbulent flame develops from this point. The velocity profile is the one in figure 15; a linear distribution of velocity is assumed in the flame zone.

The only parameter that is not known is the eddy velocity $u'$, which has to be introduced in the expression of turbulent combustion velocity and combustion time. The comparison of theory and experiment deals primarily with the development of pressure throughout the combustion chamber; by adjusting the value of $u'$ we have, as shown in figure 16, a good agreement between theory and experiment. The geometry of the flame front is quite well described by this model, and so is the development of the isotherms (fig. 17). This model has been applied to actual revolution combustion chamber, and the results obtained also agree with experiments, verification deals with the mean combustion efficiency.

We thus have means for describing the development of combustion in an afterburner chamber (pressure, temperature, velocity); this model is based on the knowledge of the turbulent eddy velocity; it also assumes that the mixture is initially homogeneous; by means of certain complications in the writing of the program it is possible to introduce a certain distribution of the richness downstream.

## 4. Conclusion

Knowledge of the structure of flow in the combustion chamber is of great importance if we wish to advance in this field. In closing, we shall stress certain specific points.

(1) The fuel-air mixture zone is essential in the operation of a short combustion chamber or a chamber that is only slightly polluting. The analysis of this zone is based on the study of two-phase flows, and particularly on the study of the vaporization of the drops in a hot turbulent flow, which is an area for which we have only few practical results as yet.

(2) Combustion starts in the recirculation zone. The aerodynamics of this zone that is likened to a homogeneous reaction engine are very poorly known and basic research in this area is necessary.

(3) The dilution zone limits the temperature downstream from the combustor; even there, while it is possible to duly represent the development of the mean flow, there are few results insofar as the turbulent diffusion of jets and the degree of homogeneity at the chamber exhaust are concerned.

(4) In order to produce a combustion chamber with a minimum pressure loss, it is necessary to prepare a realistic model of this combustion chamber. This model is, for the time being, simplistic, and a great effort should be made to improve the situation

(5) The aerodynamics of the afterburner chamber are based on a better knowledge of the development of turbulent combustion; In order to advance, it is therefore urgent to have more data on turbulent combustion; it is particularly necessary to have a better knowledge of the levels and scales of turbulence upstream and in the flame.

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16. Abstract

Aerodynamic considerations in the design of high-performance combustors for turbojet engines are discussed. Aerodynamic problems concerning the preparation of the fuel-air mixture, the recirculation zone where primary combustion occurs, the secondary combustion zone, and the dilution zone are examined. An aerodynamic analysis of the entire primary chamber ensemble is carried out to determine the pressure drop between entry and exit. The aerodynamics of afterburn chambers are discussed. A model which can be used to investigate the evolution of temperature, pressure, and rate and efficiency of combustion the length of the chamber is developed.

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