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Research as a Key in the Design Methodology of Liquid-Propellant Combustion Devices

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In today's context of budget cuts and strong competition, reliability, short delays, and cost reduction have become critical issues for combustion device designers, who must seek out new approaches. In this paper, we address the main design issues and the processes involved in liquid-propellant combustion devices. A modern approach emphasizing the key role research that will become increasingly important in combustion device design and optimization is presented. As an illustration, a research program on high-pressure liquid oxygen/hydrogen injection and combustion is described.

I. Introduction

LIQUID-propellant rocket systems are the main space propulsion systems. They have allowed the conquest of space during the last 30 years. The advantages of liquid systems are their high performance compared with any conventional chemical system and the fact that they are highly controllable in terms of thrust modulation. Disadvantages include complexity and development cost.

Even though the basic concepts of liquid-propulsion systems were established nearly a century ago, considerable efforts in terms of technology investment were necessary to reach a functional maturity for systematic use. The most important work was initiated in the early 1950s in the former Soviet Union and the U.S., followed a short time later by Europe and Asia. At that time the goals were to master the technology and ensure the supremacy of nations, and little heed was paid to economical and commercial aspects. The race to space technology control was made at a time when such sciences as optical diagnostics, computing power, and numerical methods were in their infancy. Developments were mainly based on experimental data, trial-and-error approaches, and rudimentary analysis tools rather than on a development logic combining coherent experimental and theoretical approaches.

Since then, a great deal of progress has been made in diagnostics, computing power, and computational fluid dynamics (CFD) methods. As a result, the design of propulsion systems has evolved from a rudimentary science to a more sophisticated art. Today, the critical issue is how to build better and cheaper. Hard competition in several areas has not spared space propulsion, which has to be viewed more in terms of controlled evolution than technical revolution.

This paper is about research as a main component in the design of liquid rocket combustion devices. In the following discussion, "combustion device" stands for thrust chamber, gas generator, or preburner. How does research help to design new, efficient, reliable, low-cost propulsion systems or to consolidate existing ones? We first address the main issues industry has to face in liquid-propellant combustion device designs and the main processes involved in the operation of such systems, and then we provide an example of the cooperation between research and industry in an existing research program on liquid oxygen/hydrogen (LOX/H_2) propulsion systems.

II. Combustion Device Design Issues

The main components of a liquid-propellant system include the thrust-chamber assembly, the propellant feed system, and the turbine-drive system (gas generator, preburner, etc.). The thrust-chamber assembly generates thrust by providing a volume for combustion and converting the thermal energy to kinetic energy. Depending on the desired application, the propellant feed system is a tank- or pump-pressure fed system. The turbines are driven by energetic high-temperature gases produced in gas generators, preburners, and heat exchangers heated by the main thrust-chamber combustion products, or gases tapped directly from the main combustion chamber.

Functional requirements of a liquid-propellant engine depend on the application requirements and can be classified into three major categories.

1) *Thrust level and operating pressure:* This requirement determines the size and weight of the combustion device; this category includes boosters, second and upper stage engines, reaction control systems, and satellite propulsion engines.

2) *Propellant type:* Cryogenic propellants (LOX/H_2), LOX /hydrocarbon, or storable propellants.

3) *Engine cycle:* Pressurized propellant tanks, gas generator cycle, staged combustion cycle, or expander cycle.

These requirements must be determined prior to any design, and it is also helpful to anticipate the most likely potential development hazards. This allows the organization of priorities to ensure the best solution for the most critical problems.

Combustion devices all have different risks specific to the application requirements.[1] They are, however, all sensitive to the following potential development problems.

A. Combustion Instability

Combustion instabilities have long been recognized as the most difficult problem in engine development. They were dis-

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covered in the late 1930s in both solid and liquid systems. Since then they have occurred in nearly all new development programs. Work on combustion instabilities in liquid rocket engines began in the early 1940s, but no significant progress was made until World War II and the development of large intercontinental ballistic missiles. During the 1960s, a great deal of work was done in the U.S. for the Apollo program, and the effort was rendered particularly important by manned flight missions. A compilation of this work was the first recognition of the importance of this phenomenon.[2] No progress was then made in the U.S. until the mid-1980s, when interest arose in developing new launch systems: the advanced launch systems (ALS) and national launch systems (NLS). In France, limited but significant work was done as part of the Ariane program between 1981 and 1993. This work continues, but at a very moderate level. The First International Symposium on Liquid Rocket Propulsion was entirely devoted to this subject, demonstrating that combustion instability is still a major concern of liquid rocket system designers.[3]

Combustion instability results from the coupling between the combustion and the fluid dynamics of the system. Several types of instability have been observed. They are all characterized by chamber pressure oscillations, although the frequency and amplitude of these oscillations and their external manifestations normally vary with the type of instability.

Oscillatory operation of an engine is undesirable for many reasons. One of the most important effects is the very high vibration levels that may impair the operation of the guidance system and have severe effects upon payloads. Another severe effect is the grossly increased heat transfer, which often leads to the destruction of the engine (burnout of the chamber and/or the injector). Combustion instabilities have been classified in two major categories: high-frequency instability (screaming) and low-frequency instability (chugging).

High-frequency instabilities result from a coupling between the combustion process and the chamber acoustics. They are the most destructive kind of instability. For liquid-propellant engines, the problem is more critical for storable propellants and the LOX/hydrocarbon combinations than for the LOX/H_2 combination. Chugging is characterized by a coupling between the combustion process and the feed system. The probability of the occurrence of such instabilities is higher for low injector pressure drop, which may occur during starting and cutoff transients. Such instabilities may lead to payload structural failure.

B. Combustion Chamber Heat Loads

Because of high combustion temperature and high heat transfer rates from the hot gases to the chamber wall, chamber cooling will be a major issue for long-duration applications. These high heat fluxes increase with the increasing chamber pressure needed, for example, for increasing performance, which is always a goal. Several techniques can be used, including regenerative, film, dump, transpiration, ablative, and radiation cooling.

The main factors that influence the choice of the best cooling technique are the propellant combination, chamber pressure, propellant feed system, thrust chamber configuration, and materials. The most widely used technique for high-pressure applications is regenerative cooling, sometimes combined with film cooling.

The design of a regeneratively cooled chamber involves consideration of gas-side heat transfer, coolant-side heat transfer, and wall structure requirements. For instance, for a given material, wall design considerations would suggest reducing the chamber wall thickness to reduce the temperature difference between the inner coolant wall and the outer hot-gas wall for a given heat flux. However, wall thickness is determined by structural requirements to accommodate pressure and thermal stresses as well as by fabrication feasibility limits.

The best design has to deal with several sometimes contradictory requirements, such as long usage life, light weight, low cost, high performance, and good reliability.

C. Performance

Every designer will recognize the importance of thrust chamber performance because every second gained in specific impulse (I_{sp}) is mass gained in payload. Thrust chamber performance is a function of propellant combination, combustion efficiency, which itself depends strongly on the injector design, and nozzle performance. High levels of combustion efficiency require uniform distribution at the desired mixture ratio, fine atomization, and good mixing of propellants. Unfortunately, these requirements for high performance usually reduce the stability margin.

Nozzle extension design also has a large impact on performance for nozzles operating at sea level. Flow separation because of the nonzero external pressure, and side loads during startup because of nonaxisymmetric flow become a critical issue. A more detailed analysis of advanced nozzle design and optimization is given in Ref. 4.

D. Transients

Transient phases such as startup and cutoff are crucial to the reliability and usage life of a rocket engine. To avoid transient mode failure, the transient behavior of each subsystem has to be controlled and predicted. Temporal evolution of physical parameters such as temperature, pressure, and mass flow rate, as well as ignition pressure peaks, must be specified at the design level. Risks of unsafe transients depend on the propellant type and the engine cycle. Storable propellants have the easiest transients compared with LOX/H_2 propellant systems because of the thermal chilling-down constraints. As far as the engine cycle is concerned, pressure-fed systems are the easiest to start. Among the pump-fed systems, the gas generator cycle has the simplest transients. The staged combustion and the expander cycle are the most complex to start.

Nonignition or nonrestarting of cryogenic upper stages is a frequently encountered failure mode. Other unsafe transients are a result of time-delayed ignition,[5] hot gas reversal causing injection element burnout, and gas generator or preburner temperature spikes to the turbine blades.

E. Cost

Because of competition in the space launch market, cost has become one of the most critical issues. The challenge today is to design, in a short period of time, efficient, reliable, and cheaper propulsion systems. Cost will depend on technology maturity, the available resources, and the experience of the research and development team.

III. Physical Processes and Modeling Needs

To fulfill the combustion device development requirements given the potential risks described in the previous section, the designer has to deal with the very complex physical chemical processes that take place during the operation of such engines (Fig. 1). For a given requirement (such as performance or stability) it is necessary to have a complete inventory of processes and parameters that may influence it.

A. Processes of Importance to Combustion Instability

Until the present time, the most reliable method for preventing combustion instability has been the use of stabilizing devices (baffles and/or acoustic cavities). This is because, despite efforts made in this research area, the mechanisms of combustion instability are not yet well explained. As an enclosed system, the combustion chamber has a number of resonant oscillation modes. The heat release associated with the combustion processes can provide a driving mechanism for oscillating combustion. The local burning rate oscillations induced by acoustic pressure and velocity can drive the instability if they have sufficiently large amplitude and are in phase with pressure oscillations.

Potential mechanisms of liquid-propellant combustion instability involve a coupling between chamber acoustics and one

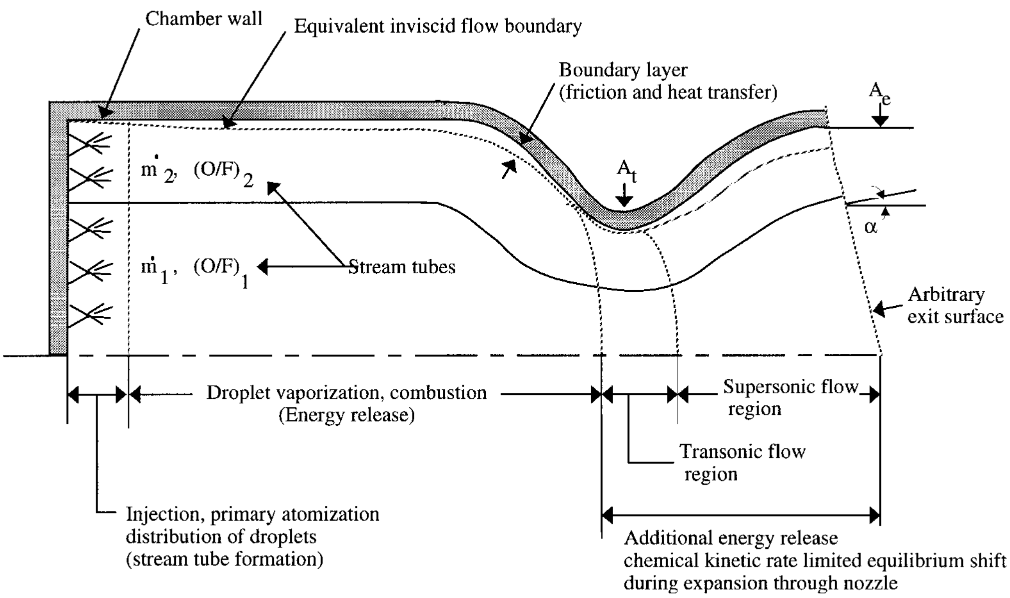

Fig. 1 Combustion processes taking place in a combustion chamber.[2]

or more of the following processes: injection, atomization, chemical kinetics, vaporization, droplet heating, and/or mixing. Nearly all of these processes have been studied experimentally or analytically as potential driving mechanisms for combustion instability.[2,3] More recent work has emphasized vaporization as a driving mechanism for combustion instability.[6,7] In some cases, convincing arguments can be found for a particular driving mechanism for a specific type of combustion instability. However, it does not seem possible to generalize to a single driving mechanism in all cases of instability encountered.

Because of the lack of reliable predictive tools, industry continues to use semiempirical correlations to investigate combustion device stability, and the experimental validation of the stability requirements is still needed, which leads to increased development cost. Moreover, even for a combustion device that is less sensitive to combustion instability, such as an oxygen/hydrogen system, baffles and/or acoustic cavities are still used to increase the stability margin. This results in more complex technology, increased weight, and increased cooling requirements.

The importance of fundamental research on elementary processes occurring in a liquid-propellant combustion chamber, to obtain insight into the combustion instability phenomenon and to develop more predictive analysis tools, seems obvious. Research is needed, firstly, for storable propellant systems, which are the most sensitive to the problem, and for the LOX/methane combination, whose instability characteristics are not well known, and then for LOX/H_2 systems, because, even if these systems have not experienced severe instability problems, their stability has not been characterized over a wide range of operating conditions. The instability risks of such systems with increased performance and increased operational range are not well known.

Today, with increased computing power, improved CFD methodologies, progress in optical diagnostics, and the availability of experimental capabilities, a potential exists for improvements in combustion instability analysis.

B. Processes of Importance to Heat Transfer

Analysis of heat transfer of regeneratively cooled thrust chambers is a relatively hard task. Prediction of wall temperature and heat fluxes must take into account heat transfer from the hot gas to the wall, heat conductance through the wall, and heat transfer from the wall to the coolant. The heat flux increases with operating pressure and can reach very high values at the chamber throat, making the prediction of chamber life very sensitive to the accuracy of wall temperature prediction.[8]

If heat conductance through the wall and coolant-side heat transfer from the wall can be predicted with enough confidence using experimental data and/or simplified tools (one-dimensional models), gas-side heat prediction is much more difficult because of the very high complex flow in the chamber (high Reynolds number and thin boundary layer). The near-injector zone heat transfer analysis is rendered even more complex because of three-dimensional effects and the interaction between the flame and the wall.

Improvements of the chamber heat load require research on both the theoretical side, with improved physical modeling (spray combustion, turbulence, and boundary-layer treatment) and the experimental side, with specific tests for model validation.

C. Processes of Importance to Performance

The state of the art of engine performance prediction is reported in Ref. 9. The method of performance prediction starts with the calculation of ideal performance (maximum theoretical performance) and then the evaluation of all losses to be subtracted from the theoretical performance.

1. *Energy-Release Related Losses*

a. Mass flow and mixture ratio distributions. The purpose of an injector is to distribute the fuel and the oxidizer in such a way that they mix and react completely. In general, a uniform mass flow and mixture ratio distribution (uniform temperature and density) must be achieved prior to the throat area with a minimum chamber length, to meet the performance requirement of the thrust chamber and to avoid damage to the turbine blades in a gas generator or preburner cycle engine. However, to reduce the heat fluxes to which the combustion chamber is exposed, a lower mixture ratio region is deliberately produced near the wall. Additionally, the presence of baffles for preventing combustion instability, the injector propellant manifolding, and the orifice pattern may lead to variations in local propellant mass and local mixture ratio. This variation in mixture ratio will lead to a performance loss that the designer has to predict using cold-flow tests and more or less complex analyses. The mass weighted stream-tube model is the simplest one that accounts for performance loss resulting from nonuniform distribution.

b. Incomplete vaporization. Incomplete droplet vaporization results in energy release degradation and, thus, in performance loss. Assessment of vaporization losses needs a reliable initial droplet size distribution prediction, along with realistic vaporization models. A great deal of work has been reported on droplet vaporization and combustion under subcritical conditions, and methods such as those described in Ref. 10 can be applied. For supercritical conditions, such as those encountered in high-pressure rocket engines, more suitable models must be used.[11,12] Another important issue in spray combustion is the effect of high spray density on evaporation rate. Such high densities are usually encountered near the injector zone.

Predicting the losses caused by injection and incomplete energy release is a very difficult task because of the very complex processes that take place in the combustion chamber and their interaction: atomization, evaporation, turbulent combustion, etc. These phenomena have to be well understood and controlled, not only for a reliable estimation of performance and heat transfer analysis, but also to help the designer to assess the effect of any change in either engine design, e.g., injector dimensions and spacing, or operating conditions (such as pressure or mixture ratio), on engine performance and heat loads (for a combustion chamber), and temperature stratification (for a gas generator or preburner).

c. Microscale mixing. Adequate mixing of fuel with oxidizer is essential to achieving efficient combustion. It is also required to achieve a uniform temperature at the exit of the gas generator and preburner. On the other hand, increasing mixing will increase heat flux to the wall. Depending on the injector type, mixing may occur in the liquid and/or vapor phase. Hypergolic propellants spontaneously react at the impinging point, such as in a different doublet injection for instance, and the reaction products formed between the two jets may prevent liquid/liquid mixing. This phenomenon is referred to as reactive stream separation or blow apart. For liquid/gas systems, e.g., in a shear-coaxial LOX/H_2 injector, when atomization is achieved, droplets formed near the injector undergo vaporization, and the vapor then mixes in a turbulent manner and reacts. Microscale mixing modeling is needed for performance and temperature field prediction. Improved mixing models involve a probability density function (PDF) approach to describe local mixture ratio fluctuations (see Sec. V.B.1).

2. *Other Processes Affecting Performance*

a. Two-dimensional nozzle flow. The two-dimensional shape of the nozzle affects the flow in two ways. Near the throat curving of the flow distorts the pressure distribution, leading to a decrease in the mass flow rate as compared with one-dimensional sonic flow through the geometrical throat area; and the divergence of the exit flow results in a loss of axial momentum and, thus, in a loss of performance.

b. Finite rate chemistry. High temperature in the combustion chamber can cause dissociation of many stable molecules. As the hot gases expand through the nozzle, the pressure and temperature decrease. At the reduced pressure and temperature, the dissociated species tend to recombine and liberate energy. There, however, recombination reactions are rate limited and are partly completed during transit through the nozzle. The effect is always a loss in performance.

c. Boundary layer and heat transfer. Because of high Reynolds numbers in large rocket engines, the effects of friction and heat transfer are confined to a relatively thin layer next to the wall. The effect of boundary layer on performance can be analyzed by treating the core flow as an inviscid flow, and the solution of the boundary layer can be uncoupled from the core flow. Because of the effect on the core flow of regenerative cooling, often used in such systems, the classical method of boundary-layer thickness is not sufficient. Solution procedures with improved turbulence modeling are needed for boundary-layer equations.

As compared with energy heat release losses, the losses described in Sec. III.C.2 are better characterized and can be estimated with some confidence. Methods of evaluation, including parabolized Navier–Stokes and full Navier–Stokes equations, are discussed in Ref. 9, with their advantages and limitations.

3. *Interaction Between Processes*

Each combustion process occurring in the combustion chamber interacts with any other process to some extent. These interactions must be accounted for in a reliable performance prediction. Some of the most important interactions are the effect of incomplete energy release on kinetic losses and on the nozzle expansion process; the effect of two-dimensional flow kinetic losses; the effect of nonuniform mass and mixture ratio distribution on kinetic losses; and the effect of incomplete energy release, kinetics, nonuniform mixing, and of two-dimensional flow on boundary-layer losses.

D. Processes of Importance to Ignition and Transients

As mentioned previously, transient phases are critical issues and have to be understood and optimized to avoid damage to the device or even mission loss.

To simplify discussion, let us consider a LOX/H_2 system, for which chilling down, startup, and ignition are very complex. Analysis of chilling down involves modeling of hydrogen flow in the cooling channels of the regenerative circuit. A reliable predictive tool has to deal with unsteady two-phase flow and transition from the sub- to supercritical regime of hydrogen flow.[13] One issue in the analysis of such flows is the modeling of heat and friction transfer coefficients.

Analysis of startup and ignition are necessary to optimize startup sequences and to avoid hard or delayed ignition, to control mixture ratio evolution for uncooled devices (gas generator), etc. The flows in the regenerative circuit and the combustion chamber must be dealt with. Modeling includes unsteady two-phase flows and multispecies and chemical reacting flows. One important parameter in the startup transient is the ignition delay. Determination of this parameter is still beyond reliable prediction and remains based on experience and experimental data.

The prediction of ignition involves the detailed modeling of the chemistry of oxygen/hydrogen at low pressure and low temperature and must also account for the igniter combustion products. An example of the numerical analysis of the Ariane third-stage cryogenic engine ignition is presented in Ref. 14.

IV. Today's Approach to Combustion Device Design

A. Industrial Needs

In the context of budget cuts and hard competition, reliability, short delays, and cost reduction become the highest priority, even compared with, for instance, performance. To face these constraints, the primary design phase must be optimized by means of calibrated tools to make the best design choices associated with a reduced cost technology. Delays may be reduced by reducing manufacturing cost, reducing the total number of qualifying tests to only the identified critical operational range of the combustion device, and generally, by reducing development risks by improving the capabilities of predicting tools.

Validated tools developed through research efforts should not only help to make the best choices in terms of design and technology and allow the prediction of operational behavior of the combustion device, they will also be helpful in directing developmental tests, analyzing test results, and reducing both the required number of qualification tests and analysis phase delay, particularly when a problem is encountered during engine development. For instance, the Phedre code,[15] which was developed for combustion stability studies during the Ariane4 and Ariane5 programs, is now used to help design combustion stability damping devices and to direct stability rating tests for the upgraded cryogenic propellant engine Vulcain 2.

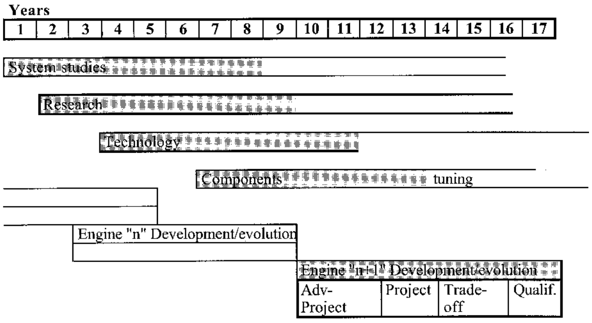

Fig. 2 Typical sequence of a new engine development.

B. General Methodology

In today's design approach, each new development must start at the engine component level with previously validated technology. Hence, upstream of a new engine development, it is necessary to achieve component development, e.g., a new injector for instance. The design of this component will result from a technology evaluation program, whose basic tools will use research results. The orientation of this research is determined by system studies determining the amount of progress needed in each subsystem of the engine.

Research activities are embedded in a long and complex set of activities. A typical sequence of such activity lines is given in Fig. 2.

1. System Studies

System studies derive typical missions to evaluate the relative functional requirements of the engine in terms of performance, size, reliability, and costs.

2. Research

The main feature of the "research" line is the long delay between the beginning of the research and its culmination in a new engine, and this has strong consequences for the basic choices made at this stage of the process. Although those choices are very uncertain with regard to results (a characteristic inherent to research activities), one must have a clear idea of the priorities in the research to build up know-how applicable to new launchers.

3. Technology

Technological development involves a process described in more detail in Ref. 16. Choice of the best technology to be developed is based on tradeoff analytical studies and evaluation criteria.

4. Components

The final step before integration into a new engine is the development of a full-scale component to be tested in representative conditions.

V. An Example—Research and Development on High-Performance Injection for LOX/H_2 Systems

As LOX/H_2 systems will probably continue to be the preferred propulsion systems for space propulsion for the next 15 years, research efforts in Europe are being concentrated on such systems. In France, Société Européenne de Propulsion (SEP) and Centre National d'Études Spatiales (CNES) are conducting both research and technological programs on LOX/H_2 coaxial injectors. The objective of the research is to get insight into the main physical processes to be accounted for in designing new systems or optimizing and consolidating existing ones. In practice, calibrated physical models provided by research will be implemented into CFD codes, which in turn will be implemented in the design and optimization loop of combustion devices.

A. Technological Program

A combustion device development cost may be reduced by reducing manufacturing cost. This can be achieved by limiting the total number of components, e.g., number of injection elements. Decreasing the number of injection elements will result in a new design, in which the mass flow per element will be increased.

As a support to technological investigations, the research program, which is discussed in more detail in the next paragraph, permits a far more efficient approach. For example, the LOX postdiameter influences the liquid core and the flame length, and this leads to the search for an injector concept that correctly handles these features. Numerical analysis of flame anchoring shows that a combustion model neglecting chemical kinetics can be used as a quick tool to iterate toward an optimal injector design. Finally, at the end of this process, some carefully chosen tricoaxial injector elements were designed and are being tested at the P8 test bench[17] in Germany.

Models of atomization, high-density gradient mixing, and multiphase combustion currently under development will permit the study, at a lower cost, of injector designs that previously required more experiments (and hence, higher costs), because they were not easily predictable by simple models.

B. Research Program

In France, a research program (GDR Research Program) on high-pressure LOX/H_2 combustion is being conducted in the framework of a joint venture between Industry (SEP), the Space Agency (CNES), and Research Organizations [ONERA and Centre Nationale de la Recherche Scientifique (CNRS)].

Research activities are articulated around three poles, among which interaction is essential as shown in Fig. 3: *Numerical analysis*, which is increasingly becoming the key design tool for new technologies (allowing more extensive tradeoff studies and reducing testing). It is fed by *fundamental research*, to provide models more suited to the very complex situation industry has to deal with. This situation requires *specific validation* for LOX/H_2 high-pressure combustors that cannot be modeled by conventional models in widespread use.

1. Fundamental Research

Fundamental research is carried out by research teams under the responsibility of a scientific committee. Studies may be split up into three domains:

a. Identification of key processes. 1) Atomization: The main factors are the momentum ratio that governs the liquid core length and LOX mass fraction distribution, and the surface tension that governs droplet size distribution. 2) Combustion: Emphasis is put on the influence of the liquid phase on combustion through turbulence, vaporization, local mixture ratio distribution, and flame shape.

b. Development of advanced models (new transport equations). 1) Atomization: New models are being developed using a high-density gradients mixing-layer approach, with a flamelet-like model to treat droplet diameter (liquid-gas interface transport equations). 2) Combustion: Development and/or adaptation of both PDF and flamelet models[18,19] to account for multiphase effects on combustion are also conducted.

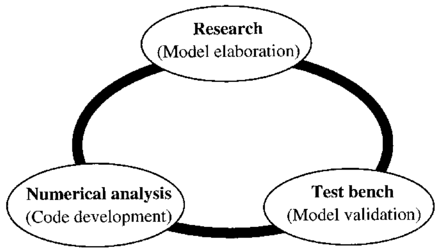

Fig. 3 Three main components of research activity on LOX/H_2 systems.

c. Closure and source terms (elaboration, calibration). To elaborate and to calibrate closure hypotheses (source terms), direct numerical simulation [tridimensional volume of fluid (VOF) method and two-dimensional VOF method with chemistry] and basic experiments (droplet combustion and breakup, counterflow flame measurements) are also being carried out.

2. Experimental Validation

Two technological challenges are at the core of this set of activities.

a. LOX/H_2 high-pressure test facilities. The need here is to have a bench that is capable of high pressure (100 bar) and high temperature (3500 K), and that has, on the other hand, optical access and a very adaptable design, to allow easy implementation and operation of complex and varied diagnostic techniques.

b. High-pressure diagnostics. New ways of measuring reacting flows have to be developed or adapted to high-temperature and pressure conditions. Optical diagnostic behavior is not known for such operating regimes.

3. Numerical Analysis

Numerical analysis involves the development of an industrial code that is both a receptacle for validated research results and a design tool for technology, component, and engine development phases. This code consists of a strong numerical core where a wide variety of models may be implemented.

C. Program Organization

A research program will work if some basic principles are respected:

1. Role Identification and Activity Sharing Between Different Partners

1) Code development (software company), 2) model elaboration (laboratories), 3) bench development and operation (space research organization), 4) technology development (rocket engine manufacturer), and 5) program main directions (space agency).

2. Work Package Sharing Based on Balanced Implicit or Explicit Financial Support

1) Eventual commercialization of the software must be supported by the software company, and 2) industry and the space agencies must financially support research teams to direct the program toward applicable achievements.

Research partners must keep their separate identities by having a self-financed contribution to the operating costs or investments. These rules have been observed for the GDR Research Program.

D. Analysis of Injection and Combustion of LOX/H_2 on the Mascotte Test Bench

On the experimental side, tests may be performed either in university laboratories using simulant fluids or under more realistic conditions at the ONERA Mascotte test bench. In this section we will discuss the Mascotte activities and the preliminary results.

1. Mascotte Cryogenic Test Bench

To have test conditions more representative of actual engine operation (high pressure, high temperature, cryogenic propellants), two test benches were built for basic research on LOX/H_2 combustion processes: 1) Mascotte in France at the Palaiseau ONERA center,[20] and 2) P8 in Germany at the Lampoldshausen DLR center. The P8 facility was built to meet two main objectives: 1) to allow fundamental studies on LOX/H_2 combustion, and 2) to allow assessment of combustion-device-related new technologies. It can be operated at pressures up to 300 bar with high-mass flow rates. Compared to university laboratories and heavy industrial test facilities, Mascotte is an intermediate-range test bench. The advantages are flexibility and ease and the low cost of operation.

Development of Mascotte was achieved progressively, with increasing complexity. Three successive versions were built:

1) In the first step (V01), only low chamber pressures (10 bar) and the use of hydrogen at room temperature were available.

2) In the second version (V02), a heat exchanger was implemented in the hydrogen line to cool hydrogen down to 100 K, which is typically the injection temperature for the Vulcain engine thrust chamber. This enables the increase of the maximum flow rate of gaseous hydrogen (increased density) at low pressure without choking the injector exit.

3) The third version (V03) is aimed at reaching high pressures (100 bar) in the combustor and at increasing the maximum LOX flow rate from 100 to 400 g/s. It is by far the most critical version, for a research test bench, with regard to the complexity of the bench components, the combustor technology, and the computing and monitoring systems.

a. Mascotte operating range. The maximum reachable chamber pressure with versions V01 and V02 was 10 bar. V03 will permit operation at 100 bar in the combustion chamber. At the moment, the limiting factors are the technological issues associated with the design of a high-pressure combustor. The available mass flow rate ranges of Mascotte V03 are 40–400 g/s of LOX at 85 K and 5–75 g/s of gaseous hydrogen at room temperature or 100 K.

b. Combustion chamber and operating conditions. A low-pressure combustor (V01 and V02) was designed and extensively fired at pressures up to 10 bar. This combustor had to meet two main design requirements, to allow optical access for diagnostics and long-duration runs (30 s). It is a square duct (50 mm × 50 mm) made of stainless steel and fitted with four fused silica windows for optical diagnostics. The two lateral windows are 100 mm long and 50 mm high for visualization. Their internal face is cooled by means of a helium film. The upper and lower windows, for longitudinal laser sheet entrance and exit, are 100 mm long and 10 mm wide. The combustor is made up of interchangeable modules, which enables the investigation of the entire flowfield by mounting the optical module at different longitudinal locations.

For the high-pressure combustor, the two main ultimate functional design requirements are to allow optical access and sufficiently long duration runs (15 s) at the maximum chamber pressure (100 bar). As first step, a new combustor was designed for operation at pressures as high as 60 bar.

As far as similarity conditions between low- and high-pressure operation of shear-coaxial injector are concerned, the gas to liquid momentum ratio is defined as

$$J = (\rho V^2)_{H_2}/(\rho V^2)_{LOX}$$

this is recognized as a governing parameter for jet breakup and atomization. This choice is based on Hopfinger and Lasheras' work.[21] This parameter has been kept approximately unchanged when operating Mascotte at different chamber pressures under hot conditions and in cold-flow tests using another simulant gas (helium or argon) at atmospheric pressure. Maintaining J at a constant value when operating at different pressures will result in a change of the mixture ratio M.

Table 1 gives, for each operating point, the chamber pressure, the mass flow rate of each propellant ($\dot{m}_{LOX}$ and $\dot{m}_{H_2}$), the momentum ratio J, and the mixture ratio M. *A and C* correspond to 1 bar, A10 and C10 to a chamber pressure around 10 bar. The previous versions of Mascotte (V01 and V02) were run extensively at these four working points. A60 and C60 are the equivalent working points in terms of the J number for a chamber pressure of approximately 60 bar. The facility will be run at these points in the near future.

Table 1 Mascotte operating points

Point	Pressure, bar	$\dot{m}_{LOX}$, g/s	$\dot{m}_{H_2}$, g/s	J	M
A	1	50	15.0	13.4	3.3
C	1	50	10.0	6.3	5.0
A10	10.5	50	23.7	14.5	2.1
C10	9.5	50	15.8	6.5	3.2
A60	67.6	100	75	16.1	1.3
C60	55.9	100	40	5.5	2.5

2. Results and Achievements

Most of the preliminary results obtained by the CNRS and ONERA teams at Mascotte have been published.[22,23] Jet breakup and atomization experiments on a LOX jet were performed under cold- and hot-flow conditions using three complementary techniques: stroboscopic visualization, phase Doppler particle analyzer (PDPA), and an optical-fiber based method that allows measurements of liquid presence probability of oxygen. Visualization permitted the investigation of the flame structure near the injector exit, whereas with PDPA it was possible to measure droplet size and velocity distribution at several locations in the combustor. Planar laser-induced fluorescence of oxygen was used to characterize oxygen vapor mass fraction near the injector. The reaction zone was investigated by means of PLIF of the OH radical along with spontaneous emission and Mie scattering techniques. Temperature measurements were finally obtained by CARS on the hydrogen molecule.

VI. Conclusions

In the context of budget cuts and hard competition, reliability, short delays, and cost reduction become critical issues for combustion device designers.

To face these constraints, a new design approach has to be built up, including technological and research activities. Technological development is aimed at exploring, with the help of research results, new efficient and low-cost concepts. Research becomes necessary and has to be accounted for in every development program. Indeed, because of cost reduction and short delay requirements, developments will increasingly rely on analysis tools for design and optimization. These tools, which will be implemented in the design loop, must be calibrated, easy to use, and not time consuming. To meet this ultimate goal, progress is needed in fundamental research (physical model elaboration), validation experiments (tests facilities and optical diagnostics), numerical methods (CPU time reduction), and software quality (easy use).

In this paper we have addressed the main issues that industry has to face in the design of combustion devices, as well as the main physical processes involved in their operation. As an illustration we have also discussed the French research program on LOX/H_2 combustion, emphasizing the needs and the objectives, the methodology and the organization, and the research achievements.

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