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Advances in combustion and propulsion applications

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ABSTRACT

Over about one hundred years aviation has evolved from an adventurous enterprise of audacious pioneers to a large scale industry providing high performance defense aircraft and world wide transportation. In an even shorter period, initial rocket developments gave rise to a modern industry producing space launchers and satellites allowing space transportation, telecommunications, global positioning, earth observation and space exploration. The technological advances could not have been made without progress in aerospace science and engineering. The Aerodynamics Institute at RWTH has been one important player in this scientific quest. With Theodore Von Kármán as its first director, the institute rapidly became a leader in this field. On its 100th anniversary, it is fit to examine progress accomplished in some key areas. This article focuses on combustion because of its importance for aerospace propulsion. By looking back at some of Kármán's papers, and other studies of a period situated in the middle of the last century it is interesting to delineate advances. Over the period of 60 years starting from the 1950s where Kármán was writing a set of articles on the fundamentals of aerothermochemistry and on laminar flame propagation, combustion has progressed in a remarkable fashion. Advances on the theoretical level have been accompanied by significant developments in experimentation with new laser diagnostics, high speed imaging and numerical data processing. Advances in computational combustion have had a profound effect on scientific research in this field and on engineering applications. Starting with a list of central issues encountered in combustion, advances are illustrated by examining a selected number of topics of interest to aerospace propulsion: Flame structures and detailed modeling of flames, Turbulent combustion, Cryogenic flames and transcritical combustion, Combustion dynamics, Computational Flame Dynamics.

1. Introduction

This article is written on the occasion of the celebration of the foundation of the *Aerodynamisches Institut* a hundred years ago. Under the leadership of its first director, Theodore von Kármán, this Institute rapidly reached a high stature for its research in aeronautics. The period of about a hundred years was rich in extraordinary advancements in aerospace. One may remember that flight was first achieved by the Wright brothers in 1903, that the English channel was crossed by Louis Blériot on July 25, 1909, that Charles Lindbergh flew the Atlantic ocean between New York and Paris on May 20 and 21, 1927, Chuck Yeager broke the sound barrier on October 14, 1947 and that Armstrong walked on the moon, the first time for mankind, on July 20, 1969. One may wonder how we got from there to here in just 100 years, from the 30 m Wright brothers flight to the transportation of an astounding 4000 billion revenue passenger-km (RPK) par year. These remarkable achievements could not have been made without progress in science and technology. Much has been achieved in all fields of knowledge in a short period of time. A central issue in most of these achievements in aerospace was that of propulsion. Engines providing the thrust and power needed were essential to the development of aircraft and rockets. In an interesting analysis of what he calls "The French–American connection in aeronautics", Fred Culick [1] tells the story of early French aviation pioneers. According to Culick, Blériot was first to cross the English channel because he could use the best engines available at the time, engines which had about twice the specific power (the power par unit mass) of their competitors throughout the world. France had the best engines and this allowed the 33 mn flight of Blériot between Calais and Dover, a dazzling accomplishment at that time.

In all current engines energy is derived from combustion, the exothermic conversion of fresh reactants into burnt products. In jet engines the chemical reaction takes place between fuel and air from the surrounding atmosphere while in liquid rocket engines, a fuel and oxidizer which are both stored in the launcher tanks react in the thrust chamber. Combustion not only plays a major role in aircraft and spacecraft but it is essential to most human activities and provides about 85% of the primary energy used by mankind. Combustion technology has a long

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history, it is generally admitted that man mastered fire half a million years ago but that he became able to ignite a flame only 30 000 years from now. The science of combustion has a much shorter history. Little is to be saved from the earlier theories like that of the phlogiston. The scientific analysis had to wait for the fundamental work of Antoine Laurent de Lavoisier just before the French revolution. Lavoisier laid the ground of modern chemistry. The first theory of premixed flames is due to Mallard and Le Chatelier [2] while important theoretical advances were made by Zeldovich and his colleagues (see [3] for a monograph summarizing this effort) but the fundamental understanding of combustion processes is more recent and the state of combustion science was lagging well behind technological developments. Automotive engines were designed without a full knowledge of the flame dynamics in the cylinder, gas turbine combustors were developed with a limited understanding of the interaction between the turbulent flow and the exothermic reaction, rocket engines were conceived without a full description of the complicated processes taking place in the high pressure thrust chamber. Frank Marble indicated in an early article that combustion theory was far from providing the information required by technological developments of combustors and thrust chambers and that effort was needed to establish combustion as an engineering science.

To measure scientific progress, one may look back at research articles in this field and specifically those of the first director of the *Aerodynamisches Institut*, Theodore von Kármán. Kármán had a lasting influence on the development of mechanics and aerodynamics at RWTH and rapidly established the leadership of this Institute. During a later period while Kármán was the director of the Graduate Aeronautical Laboratory at Caltech and in the 1950s where he was taking responsibilities in AGARD (Advisory Group on Aerospace Research and Development), his scientific interests were focused on combustion. He identified the importance of propulsion but considered that there was a lack of physical insight and mathematical rigor in the analysis of combustion problems. Kármán was concerned with providing a suitable framework for aerothermochemistry [4]. Other articles written with Millán and Penner [5] deal with the calculation of laminar burning velocities. This is illustrated with the flame formed by hydrazine decomposition and with the two step reaction of the ozone decomposition flame. One can measure the analytical effort expanded by the authors to extract the burning velocity of a fairly simple flame. At that time, this required considerable mathematical ingenuity and clever algebra. It is also interesting to examine the first edition of Combustion theory written by Forman Williams and published in 1965 [6] which has remained a reference for theoretical investigations to measure how much has been accomplished. It is interesting to read the introduction of the second edition published in 1985 where Williams underlines the remarkable progress in combustion theory during the twenty years separating the two editions. The present article begins with a review of fundamental issues in combustion. Advances in flame structures are then examined. The next topic is that of turbulent combustion which constitutes a central problem in most applications and in particular in high performance devices like aeroengines. The next section has a more applied character as it deals with cryogenic combustion which is of special importance to liquid rocket engines. Combustion dynamics is then reviewed in relation with the many instability problems encountered in practice. The final section is concerned with combustion simulation and deals more specifically with what may be designated as "Computational Flame Dynamics". This may be distinguished from the more standard Computational Fluid Dynamics by the many additional issues associated to the exothermic chemical conversion taking place in thin reactive layers. While a nice historical review of Computational Fluid Dynamics is proposed by Hirschel and Krause [7], it is interesting to review current research in the relatively new CFD.

2. Fundamental issues in combustion

Combustion science combines in a complex manner a set of disciplines including fluid dynamics, heat and mass transfer, thermodynamics, chemical kinetics and transport phenomena. It adds up all the difficulties of these different fields and those arising from their coupling. Combustion problems give rise to a variety of issues of which only a few are listed in what follows:

- There are many modes of combustion. Flames can take the form of nearly isobaric exothermic waves propagating at relatively low speed in the form of deflagrations or of much faster reactive fronts inducing a large change in pressure and propagating at high speeds as detonation waves,
- Combustion takes place in an infinite variety of geometrical configurations and for a broad range of operational parameters,
- The chemical reaction is characterized by complex kinetics including a large number of species giving rise to an even larger number of elementary steps,
- Chemical kinetic reaction rates are governed by Arrhenius rates of reaction. A typical rate of reaction is a function of temperature and takes the form:

$$k_f = BT^{\beta} \exp\left(-\frac{E_a}{RT}\right) \quad (1)$$

  where B is a pre-exponential factor, β is a temperature exponent and E_a is an activation energy. These chemical reaction rates introduce mathematical stiffness in the balance of species and energy complicating the numerical integration of these equations,
- Flames are thin layers in a flow which usually features a broad range of spatial scales so that combustion problems are essentially multiscale. This can be exploited in the analysis of combustion waves by making use of asymptotics, a feature which has been extensively advocated in studies of premixed laminar flames,
- There are critical conditions defining ignition and extinction thus leading to multiple solutions,
- In many combustion problems, the flame is close to rigid boundaries and its interaction with walls gives rise to additional complications,
- Reactants can be in various forms as solids, liquids or gases. In aeroengines, fuel is injected in liquid form as a spray of small droplets and the dispersion and evaporation of these droplets in the air flow defines many of the flame characteristics,
- In many propulsion applications combustion takes place at high pressure. In some cases the pressure exceeds the critical value while the reactant is injected at a temperature which is below the critical temperature. This gives rise to a situation designated as "transcritical" which is typically found in high performance rocket engines fed by cryogenic propellants like liquid oxygen and hydrogen,
- In most practical applications the flow is turbulent to enhance the level of heat release. It is then necessary to account for turbulent mixing and interactions between chemical kinetics and turbulent fluctuations,
- Combustion can couple with many other processes like radiation or acoustics giving rise to essentially multi-physics problems.

This list is not exhaustive but already serves to show the diversity and complexity of combustion problems. This complexity characterizes modern gas turbine combustors which combine most of the phenomena described previously. In these devices, fuel is injected as a spray formed by an aerodynamic atomizer giving rise to liquid sheet break-up, atomization into a spray, droplet dispersion, evaporation from the spray, group combustion of the