Combustion and Environment: How to Match the Future Requirements for Clean and Efficient Combustion Devices?

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Abstract: This paper addresses the presentation of the problems of the environment and of combustion principles. After underlining the still important role for the production of energy, the overview concerns two major issues, the optimisation of combustion facilities and the control of combustion. Several examples of combustion optimisation and control are examined. It appears that progress is evident however, still a lot more should be done the a near future for operational efficiency and for very low emissions.

Keywords: Energy; Environment; Combustion; Biomass; Efficiency.

Introduction

Although combustion is one of the oldest scientific disciplines, significant progress in our understanding occurred only in the second half of the twentieth century. This was mainly due to the tremendous development of ground and aerospace propulsion, power plants, chemical processes, furnaces, boilers and burners and even of domestic cookers or heaters. Combustion is a chemical reaction involving fuel and an oxidizer, typically the oxygen in the air, which release combustion products and heat.

After having conquered space by means of combustion, man has more recently turned his scientific interest to earthly problems. These problems link for one part, the efficiency of the processes (optimisation of the energy output) and the impact of combustion products on our environment, and for the other part on the reduction of unwanted combustion phenomena like fire or explosion. Properly controlled, the extensive use of combustion as an energy source became an economic challenge strongly related to the process of industrialisation. But uncontrolled, it can lead to severe damage and dramatic loss of life.

The literature survey underlines how it is important to develop basic research to better control combustion phenomena for the future of mankind. There are a number of ways to place combustion processes into different categories. Among them, the most fundamental distinction in combustion is that between premixed and non-premixed systems. Premixed combustion proceeds mainly in thin fronts that propagate into the unburned mixture. Contrarity, non-premixed combustion does not really propagate and occurs in a flame into which fuel and oxidizer are transported from opposite sides. Since diffusion transport is essential to this type of combustion, non-premixed flames are often called diffusion flames. In a restrictive sense, a diffusion flame may be defined as steady or unsteady, laminar or turbulent, nearly isobaric flame in which most of the reaction occurs in a narrow zone that can be approximated as a surface.

Most practical systems (stoves, burners, candles, matches, wood fire, coal burners, incinerators, oil–fired boilers, diesel engines, fire spread or suppression, etc.) fall into the "mixing rate control regime" and lead to the so-called diffusion flames. The fuels may be in the form of a gaseous fuel jet or liquid or solid and the oxidizer may be the flowing gas stream or the quiescent atmosphere. Concerning combustion and environment, efficient and clean combustion, there is increasing interest in the application of control to combustion [1]. The objective is to optimize the combustor, furnace or incinerator operation, monitor the process and alleviate instabilities and their severe consequences. One wishes in general to improve the system performance by reducing the level of pollutant emission or to extend the stability domain by reducing the level of oscillations induced by coupling between resonance mode and combustion. Automotive engines and gas turbine combustors are of primary concern, but also any kind of furnace, boiler or burner. For engines, complex after treatment is being applied and dedicated engine schemes are required to ensure or maintain high pollutant conversion efficiency. For gas turbines, premixed combustors, which operate at lower local temperature than conventional systems, have been designed. For these two cases, monitoring and control of the operating point of the process have to be achieved with great precision to obtain the full benefit of the pollutant reduction scheme. For premixed combustors operating near the lean stability limit, the flame is more susceptible to extinction, oscillation and flash back. Research is currently carried out to reduce this dynamical problem with passive and active control methods. In addition to a broad range of fundamental problems, there are important technological issues like the impact of preheated air combustion and swirl flows on the achievement of clean and efficient combustion.

When the fuel is liquid or solid, non-premixed combustion is of concern. Effectively when a condensed phase is introduced into an oxidizing atmosphere, after ignition, a flame surrounds the particle or develops at its surface. Condensed fuels are used in many important combustion situations (fire place and home oven, power plants, incinerators, boilers, furnaces, etc.), since humanity started using wood. The virtue of condensed fuels is enhanced by their relative high density, flame temperature and heat of combustion. They are easy to handle and store and, despite several energy crises, always not too expensive and still available. The primary problems associated with the burning of condensed fuels, apart from optimisation of combustion efficiency and reduction of pollutant emissions [1], are related to the design of fuel delivery systems, residue removal and the need for high temperature resistant materials.

Existing technologies and the ones under development are briefly surveyed together with the diagnostic and numerical tools presently in use. In addition, a tentative attempt to foresee the most promising research tracks in the near future is proposed as conclusion according to the adage of the scientist H. Poincaré *"It is better to foresee with a little uncertainty than not to foresee at all"* [2]

1. The role of combustion in the world energy production

Despite several energy crises, combustion is still playing a major role in the overall economy and especially for the production of energy. Today nearly 75% of the world total energy production relies on fossil fuels through a combustion process, leaving 15% using renewable energy sources and only 10% on nuclear and hydraulic power plants. Also as only 35% of energy consumption is due to the activities of 75% of the population, the overall world energy consumption, and consequently the use of combustion technologies, should rise to sustain the development of activities in poor and emerging countries. Everybody can notice that energy is the foundation of industrial societies.

As we prepare for a world of diminishing fossil fuel reserves, but with an increasing demand for the protection of our environment, the combustion community has two major goals to fulfil:

- the enhancement of combustion efficiency,
- the reduction of pollutant emission.

As already assessed [3], notwithstanding the great efforts which have been accomplished in diagnostics, computing, chemical kinetics, heat transfer, materials and more generally on the development of new combustion methods, there is no doubt about the fact there is still a lot to do. As shown in Table 1 below, combustion phenomena are very complex, multi-dimensional, unsteady and multi-disciplinary. Very often, the physico-chemical description of the combustion phenomena cannot be formulated through a detailed and exact analytical analysis. Then, one should model the description of the phenomena, using physical and numerical models.

Table 1. Links between fundamental disciplines and engineering situation.

Engineering situations	Engines	Combustors Gas turbines	Rockets	Power plants	Blast furnaces Incinerators Burners	Fire Explosions
Few significant models	Ignition/extinction Laminar/Turbulent Combustion Detonation Droplets/Particulates Burning Soot formation/oxidation Radiation Pollutants formation/dispersion Lean/Rich Combustion Combustion Catalytic Combustion Shock waves Laminar flame speed					
Fundamental disciplines	Thermody-namics	Fluid mechanic	Heat & mass transfer	Chemical kinetics	Theoretical physics	

We can suggest that in the very near term, energy utilisation will be enhanced through energy conservation. To focus our effort on the improvement of combustion efficiency, is going into the right direction. It is not enough, because we should simultaneously rely less on fossil fuel to preserve the resource and guard against the greenhouse effect through CO_2 emission. It is reasonable to replace high carbon-content fuels as much as possible with high hydrogen-content fuels. In France, natural gas replaces more and more fuel oil for operating large facilities like power plants, chemical plants and even in domestic usage. The replacement of fossil fuels, partly by biomass, agricultural, industrial and of course municipal waste is presently a solution under development. A good compromise could be through the co-firing of fossil fuels with alternate fuels, mostly waste products. Of course, of great interest is also the development of the technology to burn hydrogen, which could be also be produced from biomass or from photovoltaic solar energy. Automotive transportation is one the great consumers of fossil fuel, 58% of total oil consumption in the world is due to transportation and took up around 50 Mtoe among the total consumption of 92MTep in France, in the year 2000. It is the reason why we will presently continue to use liquid fossil fuels and natural gas, but also mixtures of liquid hydrocarbons with biomass fuels like alcohols and vegetable oils. The development of new combustion technologies and their transfer to large plants or factories is on the way, because the competitiveness has already become a worldwide issue among the international economic actors. But the transfer of these novel technologies to the small and mid-sized manufacturing industries could be essential for the rising of the economy of countries under development. According to the recent developments in fundamental research, the design and implementation of the above mentioned technologies will mainly rely on progress in the conception of more reliable materials (optimization of heat transfer, of thermal and mechanical resistance, lengthening of lifetime), on the efficiency and reliability of energy production and energy saving (reduction of fuel consumption, alternate fuel, reduction of pollutant emissions) and the control of combustion processes (operating point control, active combustion control). The present paper will only concern the last two points.

2. Optimisation of combustion facilities

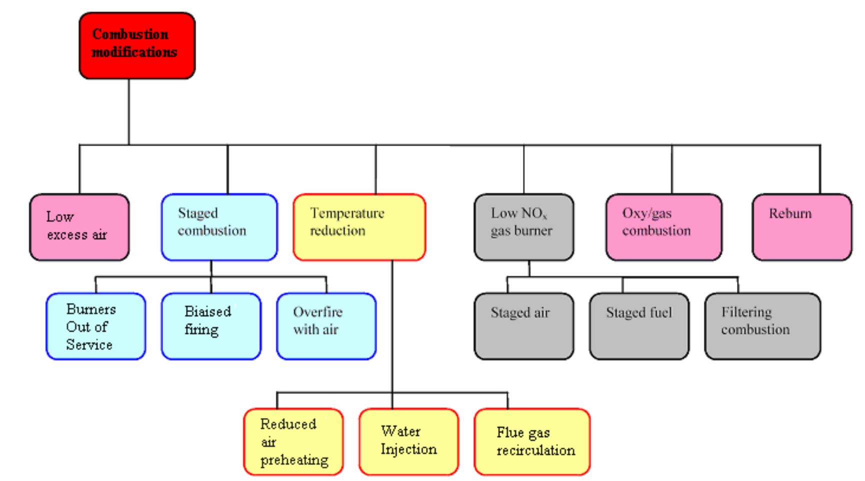
The French research program on energy relies, for the optimisation of combustion facilities, on four points:

- Flame control,
- Valorisation of alternate fuels,
- Development of new concepts of combustion,
- Development of new adapted diagnostic tools.

The control of the flame is essential for the optimisation of the combustion chamber, then of the combustion efficiency and also of the emission of pollutants. Several combustion modifications, listed below in Table 2, should be readily put into practice and the most adaptable implemented in the given installation.

The flame is controlled with different diagnostic techniques: visualisation based on visible emission, CH emission, OH emission and PLIF, CARS, temperature measurements via thermocouples, IR camera, thermocouples and optical diagnostics for CO_2, H_2O and soot absorption, PIV and LDV for velocity, fluxmeters and other sensors, as will be shown in the chapter on the control of combustion. The control of the flame, of the combustion process, is also based on the so-called “3 T rule” “Temperature – Turbulence – Time”: Temperature for the reaction rate (together with the equivalence ratio), Turbulence for the mixing of the reactants which could enhance the reaction, Time for residence time, transport of reactants and products, reaction time and pollutant formation. The optimisation of the process is very often based on the ratio between reaction and mixing time, the Damkhöler number, of great importance for the characterisation of turbulent combustion.

Table 2. In use combustion modifications.



Concerning the study of fundamental phenomena one of the most important points is the formation and oxidation of soot. Very few studies concern the kinetics of soot formation and destruction in the drastic conditions prevailing in a gas turbine or combustion chamber, or also in a diesel engine. Not many also concern the formation of soot during the burning of mixed fuels, especially biomass fuels or waste fuels. The understanding of these phenomena should also be useful for the understanding of the formation of fly ashes and other unburnt mineral particulates.

The use of alternate fuels, and especially of biomass or “waste fuels” alone or mixed with other fossil fuels, has been studied around the world during the last decade. Some years ago the author already reviewed the main characteristics of the burning of solid materials, including fossil fuels and biomass fuels [4]. This paper will review some of the recent and most significant contributions to the understanding of these kind of fuels.

In an overview paper [5] various issues related to the combustion of agricultural residues have been discussed. The authors are very concerned by the problems associated with the properties of the residues such as low bulk density, low ash melting point, high volatile matter content and presence of nitrogen, sulphur, chlorine and sometimes high moisture content. It appears that in some cases densification may be a good issue, but it depends on the type of residue and the need or not for transportation. Moreover, agricultural residues are characterized by high content of volatile matter. Devolatilization starts at low temperature and the volatiles released are mainly combustible gases like CO, H2 and C_xH_y. The design and operation of combustion devices for such fuels relies on the devolatilization and combustion characteristics. Two-stage combustion with appropriate air distribution is required. The low melting point of the ash is a real problem. This includes agglomeration, fouling, slagging and even corrosion. Thus, in the first stage of combustion the gasification should be carried out at low temperature and the ash removed from the flue gas. The second combustion stage can then take place in air with less ash. The necessity of operating at low temperature leads to high concentration of unburnt gases which act as pollutants. However, in general these kind of residues produce low emissions of SO_x and NO_x, the reduction of their release is easily achieved through staged combustion. One of the solutions to efficiently burn these residues appears to be co-firing.

A very complete review of the co-firing of coal and biomass is presented in [6]. For the authors the word biomass concerns also organic matter produced as a result of photosynthesis as well as municipal, industrial and agricultural waste. It has been clearly shown that co-firing biomass fuels with coal has the capability to reduce both SO_x and NO_x levels from existing pulverized-coal fired power plants. Because biomass is a neutral fuel for CO_2 formation, this approach contributes to the overall reduction of CO_2 emissions. It has also been demonstrated, through a European Community program and in the USA, that co-firing biomass with coal is also beneficial for the utilities by lowering fuel costs, reducing waste and consequently soil and water pollution, depending of course of the nature of the biomass considered. However, several technological problems still survive. The alkaline nature of the ash leads to severe corrosion as the temperature rises and also the grinding of the fuel and its feeding by pulverization requires more study to achieve high blend ratios and optimum combustion efficiency. To maintain a constant heat throughput as with coal, the fuel flow rate should be increased (lower heating value for biomass). This may cause flame instabilities, lifted flames that are known to cause higher NO_x levels. Fundamental studies, like the one developed in [7], are required to provide, at laboratory scale, the data to validate the full-scale approach so useful for the design and optimization of large facilities. Concerning the modelling of such phenomena, a review paper [8] presents the current status of the understanding of pulverized coal and pulverized biomass from the viewpoint of numerical modelling. It appears that approach relies first on coal burning, but should be applied to biomass fuel combustion. At first the existing codes are able to predict accurately the yields of char and volatiles. A great effort has also been made to try to predict the kinetic parameters of char combustion and the amount of nitrogen released by the char also. The final objective is to provide a close tie between technology of coal combustion and coal science in order to increase the combustion efficiency. Another paper reviews only comprehensive combustion models implemented in so-called commercial computer codes [9]. It appears that the simulations, which have been made with such codes, offer great potential for use in analyzing, designing, retrofitting and optimizing the performance of fossil fuel combustion and conversion systems.

Another possibility to reach greater efficiency is to modify or adapt the existing technologies [10]. It is known that gas turbines, modern reciprocating engines and fuel cells may play a relevant role in the production of power, both for electricity generation and mechanical drive applications. The opportunity, or even the necessity, to use different fuels on the same equipment requires complementary studies; because most of the time, the careful balance between low emissions and high operating performance corresponds to an optimization with only one fuel. Three different technologies have been examined: advanced gas turbines, reciprocating engines and fuel cells. For gas turbines, premix combustion has become the first choice for reducing NO_x emissions. Premix has plenty of advantages for emission but less for flame stability, which is affected by the variation in fuel composition. As will be presented later, the control of combustion could play an essential role in flame stability. The behaviour of low heating value fuels, in comparison with natural gas or fuels containing ammonia, helps in the understanding of flame stability limits. Looking at high performance reciprocating engines it appears very difficult to produce low emissions and high efficiency by using lean combustion. Lean operation can allow high compression ratios with lower knock potential, but the NO_x emissions are higher than for stoichiometric engines, which can use a catalytic bed at the exhaust. Decreasing the lower ignition limit can lead to reduced NO_x emissions but running the engines near this limit is severely complicated by changes in fuel properties. The control of combustion will be very useful to adjust engine operation to fuel variability. The influence of fuel composition on the operation of fuel cells seems easier to handle and less important. Fuel cells could be a very attractive option to use fuels with variable properties in situations where fuel costs are high and emission regulations very tight.

Several years ago, a review paper about the applications of fluidized bed technology to combustion was published [11]. It mainly focuses its interest on large facilities. One of the major points is the definition of the principal criteria used for the determination of the form and of the size of the combustion chamber. The influence of fuel and air mixing on the process is analysed in detail and appears to be a key factor. Unfortunately, the prediction of large differences in concentration cannot be predicted. The role of mixing also appears very important on sulphur capture through the localisation of reducing zones. The influence of sorbent, on limestone reactivity, on residence time, of attrition and fragmentation phenomena is underlined. The analysis of the chemical kinetics of nitrogen oxides formation, and especially on N_2O, leads to propositions to reduce N_2O formation without affecting the other emissions of NO and SO_2. The great potentiality of fluidized beds to burn efficiently solid fuels with high content of sulphur and nitrogen is reinforced by the opportunity of developing circulating and pressurized fluidized beds.

The combustion of liquid fuels or of fuels with a very high content of water is also of great importance to reduce the amount of all these wastes. Nevertheless, water is also injected together with the fuel to favour the pulverization, to enhance the devolatilization, to affect combustion phenomena by reducing pollutant formation. Among the different and various situations, three will be briefly presented here: combustion of water emulsion [12], combustion of black-liquor drops [13] and the combustion of orimulsion [14].

The first analysis relies on the study of the influence of water on the combustion of an emulsion of fuel with water. More precisely it concerns the fundamental mechanism relevant to the micro-explosion phenomena leading to secondary atomization, which is not common to the combustion of pure fuel. It appears that the water emulsification in droplet combustion reduces the burning rate constant, increases the ignition delay, but suppresses the formation of soot in the flame. The phase separation, not well understood, seems to play a major role. The microexplosions favour, as noticed above, secondary atomization and consequently a better mixing and a larger reaction rate due to the increase of the surface of the droplets. In addition, it must be noticed that emulsification has the potential to improve significantly the thermal efficiency and to suppress the formation of thermal NO, PACs, soot and its carbonaceous residues.

The second paper concerns the elimination of a very special industrial waste, released by the paper industry: the combustion of Kraft or black-liquor. The combustion of the liquor has been practiced for more than 50 years but only recently some efforts were focused on the improvement of combustion efficiency and pollutant formation. A detailed analysis of the combustion of a drop of black liquor, and of several drops, has been performed in a vertical flow reactor.

The third research has to do with the combustion of a bitumen-in-water emulsified fuel produced in Venezuela called orimulsion, whose calorific value is below mean heavy oil value but above coal value. From a combustion perspective, orimulsion behaves similarly to heavy oil but contains rather high levels of heavy metals (nickel, vanadium, etc.) and of sulphur. Previous experiments show that orimulsion ignites easily in boilers, results in stable flame and is compatible with existing ignition and flame detection systems. Air emissions from its combustion are very similar to air emissions due to other fossil fuels, and are somehow dependant upon power plant specific design (standard NO_x emission, NO_x reduction using re-burning, conventional wet limestone scrubbers efficient to remove 90-97% of sulphur, HAP concentration at equivalent level and dependent of trace element in the fuel). Differences between orimulsion and other fossil fuels from an air pollution control point of view include an increased flue gas volumetric flow rate, when compared to heavy fuel oil, that can impact electrostatic precipitator performance in retrofit situations, a less dense fly ash that could lead to potential handling problems, and SO_3 emissions as a result of high fuel sulphur and vanadium contents. After controlling the possible impact of transition metals on health, and fly ash formation, orimulsion could be considered as an alternate fuel using an efficient, but readapted technology.

3. The control of combustion.

For several years there has been increasing interest in the application of control to combustion. In general, engineers are willing to improve system performance, for example by reducing the levels of pollutant emissions or by smoothing the pattern factor at the engine exhaust. As combustion systems have to meet increasingly more demanding air pollution standards, their design and operation become more complex. The trend towards reducing NO_x levels has led to new developments in different fields and is of primary importance for automotive engines and gas turbine combustors. In the first case, complex exhaust after treatment is being applied and dedicated engine control schemes are required to ensure and maintain high pollutant conversion efficiency. For gas turbines, premixed combustors, which operate at lower local temperatures than conventional systems, have been designed.

Today's standard practice is to control combustion processes in an open loop without feedback of information to the injection system. This way does not allow a real optimisation of the process and the lack of closed loop control may pose serious problems for future developments. Automotive engines already use closed loop concepts [15], which allow a fine-tuning of operating conditions. This adjustment of operation with sensors monitoring the exhaust gases is considered in many current applications including biomass combustion [16] and gas turbines [17]. Sensors are critical elements for combustion control and combustion monitoring. Their integration in combustion systems is presently being explored. While they share some of their features and objectives, it is convenient to distinguish two categories of combustion control: (ACC) Active Combustion Control and (OPC) or Operating Point Control.

Basic concepts of active control were mainly demonstrated in small-scale laboratory experiments [18,19] and in turbulent and large-scale devices [20] (Heavy duty gas turbine of 260MW). A first case of technological interest is that of lean premixed combustors, which are being developed to reduce the exhaust emissions of gas turbines. These devices have excellent emission characteristics and bring a significant reduction of nitric oxide levels. As the lean premixed mode can lead to instabilities, flashback, blow-out, active control may then be used to avoid this phenomena and to increase the stability margin of the system. The second case of interest concerns combustors operating in the non-premixed mode. The mixing, often poor, controls the combustion and in such circumstances the emissions may be really high. Active control can then be used to enhance mixing, thus modifying the flame temperature, conversion rate, combustion efficiency and pollutant formation and consumption [21, 22].

Control of the operating point concerns every combustion device designed to date. From the early problem of load control to the more recent concern of pollutant emissions reduction, any engine or combustion process relies on a control system in order to operate in an acceptable way as regards power, safety or environment. As major examples the literature provides the following: 30MW premixed gas turbine combustor (OPC by fuel regulation using air flow calculation, hygrometry and fuel properties measurements) [23]; liquid spray flame burner (OPC by atomising air regulation and OH imaging using CCD camera) [24]; Hencken flat plate burner (temperature control by methane regulation using laser diode absorption T measurements) [25]; gasoline direct injection engine (engine and catalyst management using O_2 and T sensors) [26]; classical gasoline engine (using lambda probe for stoichiometric measurement) [9]; 20 MW waste incinerator (combustion monitoring and control based on laser diode absorption O_2 and H_2O measurements) [27].

To adapt the control strategies to future requirements such as pollutant emissions reduction or combustion instabilities suppression, it will be necessary to monitor a broad range of parameters. Detection should be carried out with fast, reliable and preferably low cost sensors. Recent advances in optical components will drive further developments of optical sensors for combustion control application. As an example, spatially resolved temperature data were recorded in a domestic burner using an imaging device recording spectral information at the level of each pixel between 3 and 5µm every 10mn [28]. Also, the temperature field in a 40MW waste incinerator has been recorded using a classical infrared camera scanning light radiated by the fuel bed surface between 3.8 and 4.0 µm [29]. This sensor was successfully integrated in the controller of the plant and allowed a notable reduction of CO and HC emissions. Operating point control gas turbine combustors were also investigated using an IR emission temperature sensor [17]. Because they are simple, naturally robust and relatively easy to set-up, light emission sensors will find further applications in the estimation of important combustion parameters like the equivalence ratio, the temperature or the heat release fluctuations.

However, status observation and performance estimation are central issues in combustion control. It appears that the main obstacles to the development of combustion control are practical aspects related to the improvement of sensor technology. Consequently, extensive testing in well controlled laboratory scale experiments reproducing real conditions should be carried out, together with larger scale experiments to bring sensor technology to maturity.

Conclusion

Clean and efficient combustion appears to be less a dream than a few years ago. The development of combustion technologies like staged combustion, post-combustion, lean combustion, high temperature air combustion, flue gas recirculation, re-circulating and pressurised fluidised bed facilities, together with the use of alternate fuels appear to be very adaptable. Moreover, the development of more sophisticated tools to control combustion and of faster and more reliable numerical codes has also been of great help in the design and operation of modern combustion facilities. However there is still a lot to do. At first, it appears very important to enhance fundamental research in the field of chemical kinetics and pollutant formation, turbulence and mixing, radiation and heat transfer, to better control the flame efficiency. It will also be of great interest to focus basic research on the development of sensors and other sophisticated tools and to implement them on real industrial situations. Regardless of these developments, in the near future, it will be necessary to work more intensively on the replacement of fossil fuels by high hydrogen content fuels and to start to shift from natural gas and other fossil fuels to hydrogen. The future of our planet could depend on our success in this task.

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