Influence of Air-Fuel Ratio and Air Temperature on Combustion Time of Air-Methane Mixtures in Stationary and Turbulent Condition

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INTRODUCTION

Within the sphere of combustion processes in the electric power production systems, the development of techniques and innovative procedures plays a major part in the design and the management of energetic systems oriented to the protection of environment. The development of electric power production systems and CHP (combined heat & power) plants in the range of 5 up to hundreds of MW (electric) has been growing up basing on gas turbine technology, mostly burning methane. Particularly in gas turbine air-fuel global ratio is always in lean or very lean condition so the methodological approach to the analysis of combustion process is very complex also due to random parameters involved. A critical role is played by turbulence: its influence as well as on transport phenomena, is directly connected to the reduction of airflow and on the improvement of fuel air mixing. Chemical reactions and mixing are strongly influenced by turbulence intensity ([2]...[6]): that’s why it’s necessary to assign the right mixing condition for air fuel mixture in order to have a good combustion process. Another critical role is played by residence time in combustion chamber which must be very small in order to minimize chamber dimension and very high to reduce pollutant formation; the lean condition combustion doesn’t allow to have short residence times so the burning process has to be divided into a number of steps, starting from a richer pilot flame and going on with lean premixed ones.

OBJECTIVES OF THE WORK

The starting point of this work is the analysis of Dry Low NOx combustion chambers of gas turbines for cogeneration plant in the range from 5 to 150 MW of electric output. In particular the attention was focused on the premixed air-methane stream and its interaction with the pilot flame. In fig. 1 a typical configuration of this type of combustion chamber is reported. The lean premixed air-methane mixture, coming from premixers has to be heated from the pilot flame in order to reach the ignition condition and to burn completely and quickly during its passage through the chamber. The main objective of the work has been the analysis of the correlation between the residence time and so the space needed form the lean mixture to burn completely and the heat needed to be achieved from the pilot flame in order to do it. This is an useful information in design phase, in sizing the correct amount of heat to be delivered from the pilot flame to the lean mixture coming from premixers.
NUMERICAL MODEL ADOPTED

The burning process of the lean premixed mixture has been simulated by a plug flow in a cylindrical duct. The heat transfer from the pilot flame has not been simulated but only taken into account by a temperature increase of the lean mixture before its passage in the combustion zone.

$\rho V \frac{dA}{dx} + \rho A \frac{dV}{dx} + V A \frac{d\rho}{dx} = a_i \sum_{gas} \dot{g}_k W_k$ (1)
Here is the (mass) density and $V$ the axial velocity of the gas, which consists of $K_s$ species; $W_i$ is the molecular weight of species $k$, and $\dot{g}_k$ is the molar production rate of this species by all surface reactions. The quantities $A$ and $a_i$ are the cross-sectional (flow) area and the internal surface area per unit length, respectively, of the reactor; each can be a function of $x$. Equation (1) simply states that the mass flow rate of the gas can change as a result of generation or consumption by surface reactions. A similar equation can be written for each species individually:

$$\rho V A \frac{dY_k}{dx} + Y_k a_i \sum_{gas}^k \dot{g}_k W_k = W_k \left( \dot{g}_k a_i + \dot{\omega}_k A \right) \tag{2}$$

Here $Y_k$ is the mass fraction of species $k$ and $\dot{\omega}_k$ is its molar rate of production by homogeneous gas reactions. Such reactions cannot change the total mass of the gas, but they can alter its composition.

Turning now to the energy equation, one finds,

$$\rho V A \left( \sum_{gas}^k h_k \frac{dY_k}{dx} + \overline{C}_p \frac{dT}{dx} + V \frac{dV}{dx} \right) + \left( \sum_{gas}^k h_k Y_k + \frac{1}{2} V^2 \right) a_i \sum_{gas}^k \dot{g}_k W_k = a_i Q_e - a_i \sum_{bulk}^k \dot{b}_k W_k h_k \tag{3}$$

where $h_k$ is the specific enthalpy of species $k$, $\overline{C}_p$ is the mean heat capacity per unit mass of the gas, $T$ is the (absolute) gas temperature, and $\dot{b}_k$ is the molar production rate of bulk solid species $k$ by surface reactions. The distinction between bulk and surface species is discussed somewhere else.

The momentum equation for the gas expresses the balance between pressure forces, inertia, viscous drag, and momentum added to the flow by surface reactions. Thus

$$A \frac{dP}{dx} + \rho V A \frac{dV}{dx} + \frac{dF}{dx} + V \cdot a_i \sum_{gas}^k \dot{g}_k W_k = 0 \tag{4}$$

where $P$ is the absolute pressure and $F$ is the drag force exerted on the gas by the tube wall, to be discussed below. The pressure is related to the density via the ideal-gas equation of state:

$$P \overline{W} = \rho R T \tag{5}$$

where $R$ is the universal gas constant and $\overline{W}$ is the mean molecular weight.

Since the heterogeneous production rates and will depend, in general, on the composition of the surface as well as that of the gas, equations determining the site fractions $Z_k$ of the $K_s$ surface species are now needed. Assuming that these species are immobile, the steady-state conservation equations are extremely simple:

$$\dot{s}_k = 0 \tag{6}$$

i.e., the net production rate of each surface species by heterogeneous reactions must be zero. The dependent variables $u$, $T$, $P$, $Y_k$ and $Z_k$. The functions $\overline{W}$, $h_k$, $\overline{C}_p$, $\dot{\omega}_k$, $\dot{g}_k$, $\dot{s}_k$ and $\dot{s}_k$ can all be expressed in terms of these and are obtained from calls to CHEMKIN and SURFACE CHEMKIN subroutines.

**NUMERICAL RESULTS**

Numerical results are summarized in the diagram reported in fig. 3. Different duct lengths have been considered: for each of them the inlet temperature of the stream versus the
air/methane volumetric ratio is reported: that is the temperature needed from an assigned (air/fuel ratio) mixture to completely burn in the assigned duct length.

![Inlet mixture temperature vs air fuel ratio, for different geometrical configuration.](image)

**Fig. 3** Inlet mixture temperature vs air fuel ratio, for different geometrical configuration.

It can be noticed by this plot that the shorter is the duct length the higher is the influence of the air fuel ratio on combustion: that’s for low air fuel ratio an higher inlet temperature is needed in order to burn completely along the duct length.

This diagram is an useful tool in combustion chamber design, because it allows to evaluate the heat amount needed by an air fuel mixture to burn in a given length, starting from a given inlet temperature and composition. Particularly it allows to size the pilot flame in order to give the right amount of heat to the lean premixed stream.

**REFERENCES**