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MODELING APPROACH FOR LEAN BLOWOUT PHENOMENON

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ABSTRACT

Modern concepts for reducing thermal NO emissions require the use of very lean fuel/air mixtures. Therefore a problem of lean quench should be solved during design process of gas turbine combustor and it's operational development. Since maintenance of flame stability for wide range of gas turbine engine operational modes is essential, therefore there is a great demand for models which are able to predict lean blow out limits of turbulent, premixed and partially premixed, aerodynamically stabilized flames.

In this paper a model describing flame destabilization process is presented. This model takes into account various physical processes, which lead to flame destabilization. The model is based on equation for reaction progress variable. An expression of source term of this equation contains turbulent flame speed, which is calculated with the use of Zimont's formula modification, proposed by authors.

The results of simulation were compared with test results for our lean premixed combustor. Fuel mass flow rate of pilot zone was decreased during test until heat release of pilot flame front became insufficient and couldn't support a combustion process in a lean premixed zone. Our simulation with modified model allows to get prediction of lean blowout limit.

INTRODUCTION

Modern environmental standards are forcing development and the use of lean premixed combustion systems. Perfect mixing, achieved in a LP combustor at base load , reduces NO_x emission level, but lean extinction may be encountered at part load conditions. To provide safe operation of gas turbine engine over all envelope piloting or fuel staging concepts have been introduced. These concepts based on the use of diffusion pilot burning module to provide flame stabilization at low loads. Pilot module introduces partial unmixedness of fuel and oxidizer and leads to increased NO_x emissions. Also there is another problem, concerning a lean premixed zone of combustor. This is a guarantee of complete burning and flame stability. Therefore there is a need for mathematical models, which are capable to describe a flame stabilization process of diffusion (pilot) and lean premixed zones.

Widely used approach of combustion process for gas turbine combustors, is based on a notion of surface combustion in a flame front. A typical representative of this approach is a flamelet combustion model. Flamelet combustion model is an attractive tool to model turbulent combustion process. A conception of flamelet approach was developed by several groups of researchers as Gibson, Libby [1,2], Williams [3], Kuznetsov [4], Bilger [5], Peters [6]. Within frameworks of this model a combustion process takes place in a thin layer called flame front. This model gives realistic information about spatial O radical distribution for giving reliable thermal NO prediction and allows to get a good agreement with experimental data for NO and temperature level near stoichiometry surface. But this model fails to describe a blow out process correctly.

To avoid this problem a large number of stability models has been developed. These models may be classified as based on scaling laws, using the critical Peclet number [7], reactor-network models [8], models, investigating the energy exchange between different regimes inside the combustion system [9]. Unfortunately, these models do not take into account a complex spatial interaction of mixing, turbulence, heat transfer and combustion processes inside a gas turbine combustion chamber. An attempt to create more perfect model, describing a stabilization process of diffusion flames, was made in work [10]. This model is based on solution of equation for reaction progress variable and takes into account radiation heat transfer.

Within this paper the stability of combustion process inside a gas turbine combustor is investigated numerically in the frameworks of flamelet combustion model, based on the use of modified Zimont's formula.

NOMENCLATURE

Latin

C	reaction progress
C_p	specific heat capacity
l_t	turbulent macroscale;
$\dot{m}$	mass flow rate;
S	flame front speed;
t_η	Kolmogorov time scale;
v'	velocity fluctuation
P	pressure
T	temperature
W	molecular weight
Y	mass fraction
Z	mixture fraction

Greek

α	air/fuel excess ratio; thermal conductivity coefficient
λ	heat conduction coefficient
ρ	density
$\dot{\omega}$	chemical production rate

Subscripts

L	laminar
T	turbulent

COMBUSTION SYSTEM UNDER INVESTIGATION

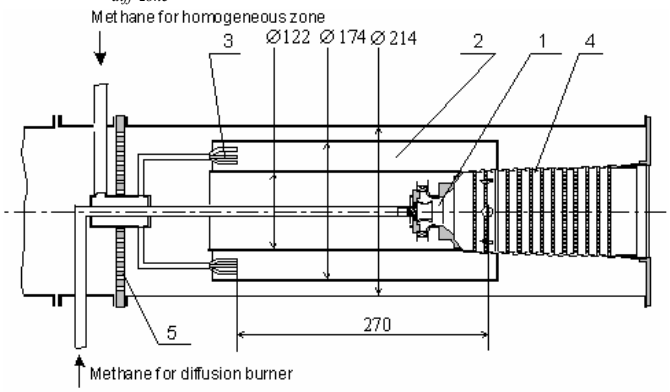
Different schemes of interaction for processes of diffusion combustion in the pilot and lean premixed combustion are used in practice. Considered configuration of the combustor (fig.1) is based on intensive interaction between diffusion and premixed combustion. This scheme presumes entering the fresh fuel-air mixture transversal jets into the diffusion zone combustion products flow. The same scheme was developed in detail in Japan in the 90-s [11].

The homogenous fuel-air mixture is prepared in the annular homogenizer (2) equipped with 88 fuel jets. The homogenizer has large relative length (more than 10 calibers). That warrants homogeneous mixture generating with low level of the fuel concentration fluctuations. The front end of a burning zone is equipped with a high-performance diffusion burner (1). Homogeneous air-fuel mixture was added to the diffusion zone combustion products flow through the 8 holes (≈20 mm in diameter) evenly distributed on round. The homogeneous mixture burnout zone (≈250 mm long) was supplied with barrage air-cooling system where cooling air was delivered through circular slots (0.6 mm width) in the chamber walls.

A scheme of combustion process for lean premixed technology with pilot zone is the following: a diffusion pilot zone supports combustion process inside a lean main zone (air excess ratio $\alpha_{lean\ zone} \approx$ 2.0…2.5). A fuel/air mixture (methane/air) flows through the main orifices, creating the main combustion zone.

The conditions of experiment were the following: within a certain time interval a fuel mass flow rate for pilot zone had been gradually decreased: air excess ratio of pilot diffusion zone $\alpha_{diff\ zone} = 3.0 \rightarrow 8.0$. Mass flow rates of fuel into lean homogenous zone through main orifices remain unchanged. Air excess ratio of lean zone is 2.06. Inlet temperature was 700 K, test was carried out at atmospheric pressure. Outlet temperature was measured to determine when a lean blowout starts. The results of measurements are shown on fig. 2.

The second graph on fig 2 (blue) shows the change in temperature for operational regime when a pilot zone is provided by fuel only. So one may see a lean blowout process starts at $\alpha_{diff\ zone} \approx 3.6$.



1 – diffusion burner
2 – homogenizer
3 – fuel manifold
4 – air-cooling system
5 – leveling grid

Fig. 1 – Experimental model of LP combustor with pilot zone.

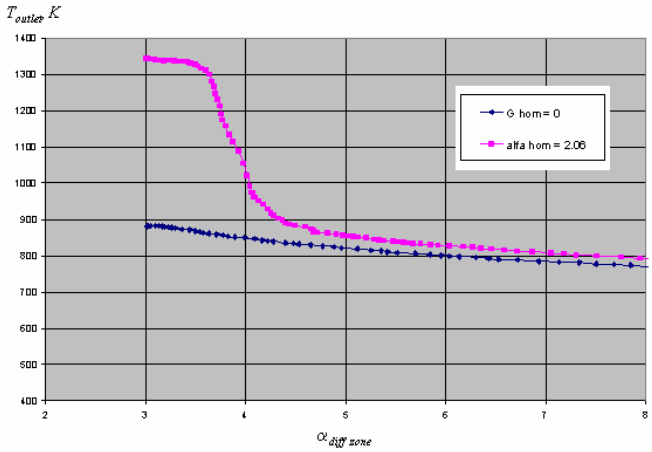


Fig. 2 – Outlet temperature. Test results.

MODELING APPROACH FOR LEAN BLOWOUT PHENOMENON

As is well known a fuel oxidation process and, as consequence, a heat release process, takes place in the so-called flame front zone. Therefore, flame front is a surface dividing unburnt and burnt air/fuel mixture. There are two different types of flame front inside investigated combustor (fig.3). The first is diffusion flame front. Mixing process of fuel and oxidizer develops a surface of diffusion front. Therefore an

origin and existence of diffusion flame front depends on interaction of chemical kinetics and turbulent mixing processes. Location and shape of diffusion flame front is determined by aerodynamics of combustor. The second is a homogeneous flame front. It exists in case of burning of premixed air/fuel mixture. In this case an origin of flame front depends on chemical reactions. Apparently, there is a need in permanent source of heat for an origin and existence of flame front. This source is a high temperature recirculation zones, existing in a gas turbine combustor. In addition to mechanisms, which support a flame front, there are processes limiting it's existence:

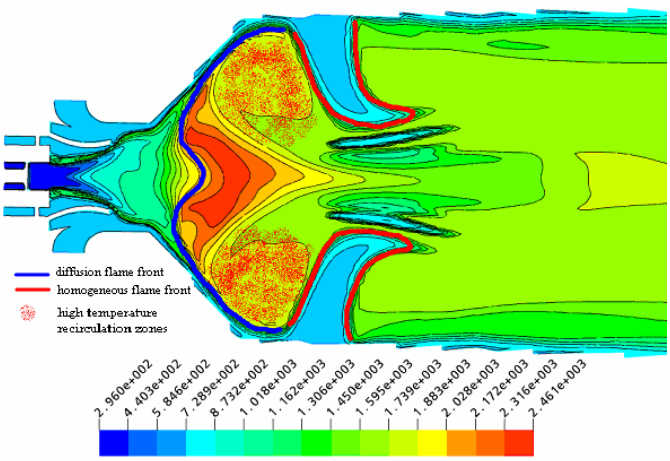


Fig. 3 – A structure of flame fronts inside combustion chamber.

1. Chemical kinetics processes: flammability limits (rich and lean), ignition temperature.

2. Turbulence processes. As is well known, fluctuations near flame front surface promote "implantation" of high temperature burnt mixture into zones of fresh mixture. So, there is an increase of flame front speed in turbulent flow. But, when these fluctuations reach some critical value and heat release is insufficient, corrugated and wrinkled flamefront, affected by small scale vortices, "falls to pieces". So we observe a phenomenon, which is called a lean quench or blowout.

Let us consider Zimont's formula:

$$S_T = AGu'^{3/4} s_L^{1/2} \lambda_u^{-1/4} l_t^{1/4} \qquad (1)$$

Turbulent flame speed S_T is directly proportional to laminar flame speed S_L. In the framework of traditional approach, laminar flame speed is a function of mixture fraction: $S_L = S_L(Z)$. Apparently, this relation is unsuitable for modeling of flame stabilization process. In this case we cannot take into account a process of heat transfer from high temperature recirculation zones for maintenance of flame fronts.

In this work we propose the following relation for laminar flame speed:

$$S_L = S_L(Z,T,C). \qquad (2)$$

Laminar flame speed depends on fuel/air mixture composition, temperature and reaction progress. We don't take into account pressure because of its value in combustion chamber is nearly constant.

Let us consider an influence of Z, T, C parameters on S_L. Apparently, dependence $S_L = S_L(Z)$ determines lean and rich flammability limits and flame speed regarding mixture composition. A maximal laminar flame speed is reached under stoicheometric conditions.

Calculated lean and rich laminar flame speed limits for methane/air mixture are Z_{rich}=0.10947, Z_{lean}=0.02235. A relation $S_L = S_L(Z)$ is approximated by function:

$$S_L(Z) = a_1 * \exp(-a_2 * (Z - a_3)^2) + a_4 * \exp(-a_5 * (Z - a_6)^2) + \qquad (3)$$
$$+ a_7 * \exp(-a_8 * (Z - a_9)^2) + a_{10}$$

A heating of air/fuel mixture increases laminar flame speed. On fig 5 a relation $S_L = S_L(T)$ at stoichiometric conditions is presented.

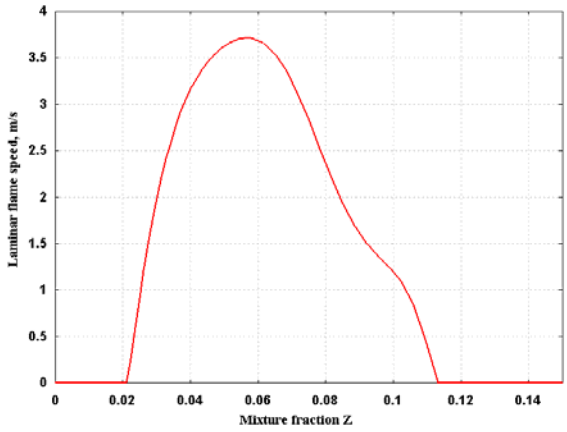


Fig 4 – Graph of $S_L = S_L(Z)$ relation at T=1000 K for methane/air mixture.

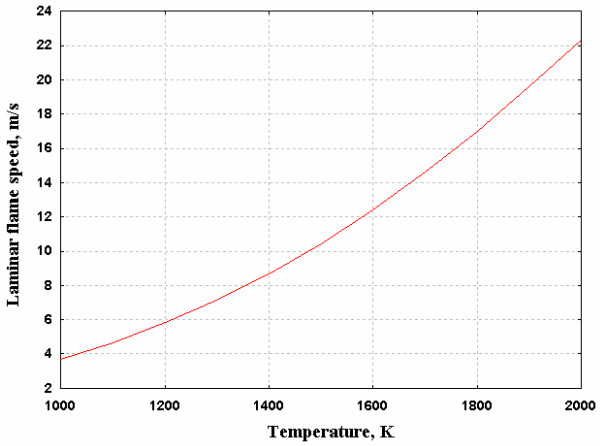


Fig 5 – Graph of $S_L = S_L(T)$ relation at $Z = Z_{stoich}$ for methane/air mixture.

A relation $S_L = S_L(T)$ is approximated by formula

$$S_L(T) = b_1 * \exp(b_2 * T) + b_3 * \exp(b_4 * T). \qquad (4)$$

A shape of dependences $S_L(T)$ is similar for all values of Z, therefore a dependence $S_L(Z,T)$ we may be represented as superposition:

$$S_L(Z,T) = S_L(Z) * \bar{S}_L(T) \qquad (5)$$

For different air/fuel mixture compositions there are definite values of ignition temperature when reaction starts. A

dependence of calculated ignition temperature on mixture fraction is shown on fig. 6. A perfectly stirred reactor problem was solved to calculate ignition temperatures. An approximation of T_{ign} is realized by formula:

$$T_{ign}(Z) = c_1 \cdot (Z - c_2)^{C_3} + c_4 + \frac{c_5}{(Z - c_6)^{C_7} + c_8} \qquad (6)$$

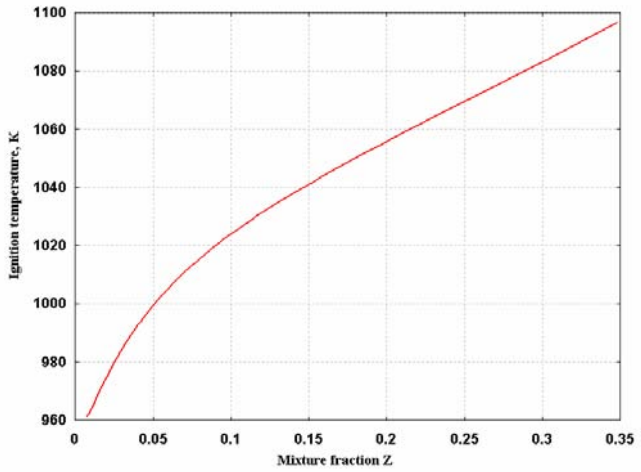


Fig.6 – Graph of ignition temperature versus mixture fraction for methane/air mixture.

Let us consider a dependence $S_L = S_L(C)$. It is obvious that S_L=0 at C=0 (unburnt mixture) and C=1 (burnt mixture). In a common case $S_L(C) \neq 0$ if $C \in (C_{low\,\lim}, C_{high\,\lim})$. It is worth to note that dependence for C is very difficult to get by numerical method. So, it was assumed that S_L remains unchanged between C-limits, i.e. $S_L(C) = 1$.

To calculate low and high limits we evaluate rate of global reaction of methane oxidation at stoichiometric conditions. A composition and temperature of fuel/air mixture depending on reaction progress were calculated by solving a perfectly stirred reactor problem. Reaction progress values were calculated from oxygen concentration. We used GRI-MECH 3.0 mechanism for our simulations. Reduced reaction rate for global reaction is shown on fig. 7.

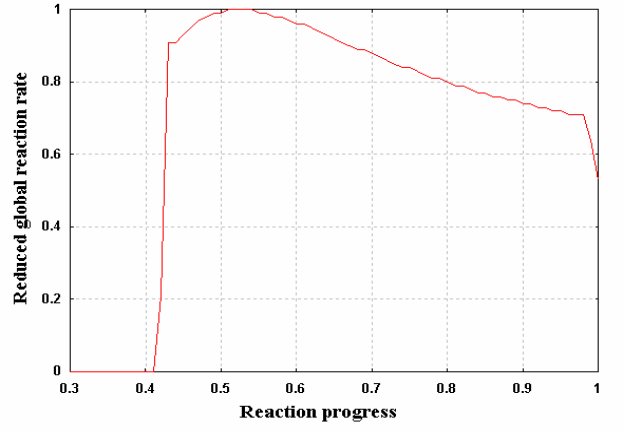


Fig. 7 – Reduced global reaction rate versus reaction progress.

We have got the following data: $C_{low\,\lim}$=0.42, $C_{high\,\lim}$=0.98. It is worth to note $C_{low\,\lim}$=0.42, due to an ignition delay, i.e. time when initiation reactions are starting before main fuel oxidation reactions will start.

So, we have the following expression for laminar flame speed:

$$S_L(Z,T,C) = \underbrace{S_L(Z) \cdot Z_{\lim}(Z)}_{\text{inf luence of air / fuel mixture composition}} \cdot \underbrace{\bar{S}_L(T) \cdot T_{\lim}(Z,T)}_{\text{inf luence of heating}} \cdot \underbrace{C_{\lim}(C)}_{\text{inf luence of burnt mixture composition}} \qquad (7)$$

where

$S_L(Z)$ - laminar flame speed as function of mixture fraction,

$$Z_{\lim}(Z) = \begin{cases} 1, & Z \in [Z_{rich\,\lim}, Z_{lean\,\lim}] \\ 0, & Z \notin [Z_{rich\,\lim}, Z_{lean\,\lim}] \end{cases} \qquad (8)$$

– Z-limiter, responsible for flammability limits of burning;

$\bar{S}_L(T)$ – reduced laminar flame speed as function of T, i.e. multiplier in superposition $S_L(Z,T) = S_L(Z)\bar{S}_L(T)$, responsible for heating of air/fuel mixture.

$$T_{\lim}(Z,T) = \begin{cases} 1, & T \geq T_{ign}(Z) \\ 0, & T < T_{ign}(Z) \end{cases} \qquad (9)$$

– T-limiter, responsible for ignition of air/fuel mixture at certain temperature value;

$$C_{\lim}(C) = \begin{cases} 1, & C \in [C_{low\,\lim}, C_{high\,\lim}] \\ 0, & C \notin [C_{low\,\lim}, C_{high\,\lim}] \end{cases} \qquad (10)$$

– C-limiter, responsible for a change in flame speed due to reaction progress (burnt mixture composition).

In order to take into account a flame front destabilization process under the influence of small scale turbulence, we propose the following modification of Zimont's formula:

$$S_T = AE_{\lim} u'^{3/4} s_L^{1/2} \lambda_u^{-1/4} l_t^{1/4} \qquad (11)$$

where E-limiter is a term, responsible for extinction of flame:

$$E_{\lim} = \begin{cases} 1, t_\eta^{-1} \leq g_{cr} \\ 0, t_\eta^{-1} > g_{cr} \end{cases}, \qquad (12)$$

here

$$t_\eta = \left(\frac{\nu}{\varepsilon}\right)^{0.5} \qquad (13)$$

is Kolmogorov time scale, the critical velocity gradient for quenching $g_{cr} = t_{chem}^{-1}$ is the inverse of the chemical timescale of the reaction. The following well-known formula is used for critical velocity gradient:

$$g_{кр} = 0.5 \frac{S_L^2}{\alpha}. \qquad (14)$$

We modified this formula, taking into account a fact that front of high temperature diffusion flame is more stable than front of lean premixed flame because of comparatively fast reaction rates:

$$g_{cr} = g_{chem} \frac{S_L^2}{\alpha}, \qquad (15)$$

$$g_{chem} = B \frac{\exp(-E_a / R_c / T)}{\exp(-E_a / R_c / T_{\max})}, \qquad (16)$$

where E_a is activation energy of global reaction, $T_{\max}$ is maximal adiabatic temperature, B is a model constant .

Let us consider an influence of terms in formula (7). A field of laminar flame speed depending on mixture fraction is shown on fig. 8. Values of $S_L(Z)$ are limited by function $Z_{\lim}(Z)$ (fig. 9). Flame speed grows because of heating inside recirculation zones (fig. 10) and is limited by zones where temperature of mixture greater than ignition temperature (fig. 11). A shape of flame front is limited by reaction progress (fig. 12) and by an influence of fine scale turbulent structures, expressed by E-limiter (fig. 13). As a result of calculations we have the following field of turbulent flame speed (fig. 14).

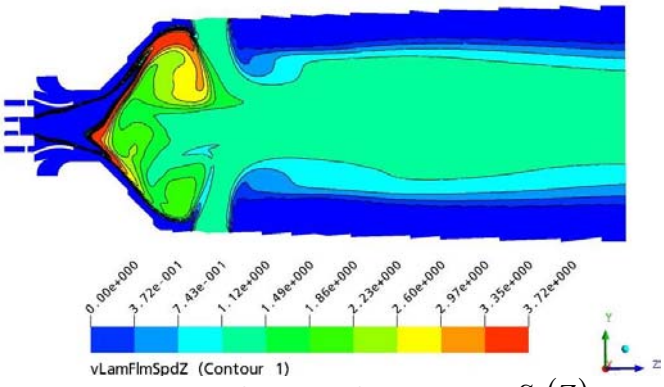


Fig. 8 – Field of laminar flame speed $S_L(Z)$.

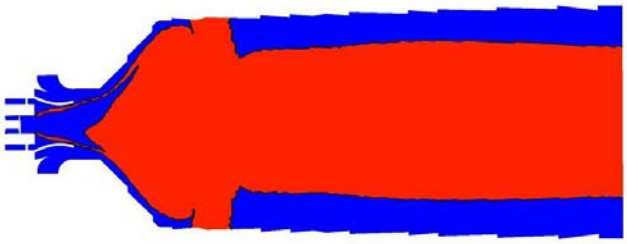


Fig. 9 – Field of Z-limiter (0 – blue,1 – red).

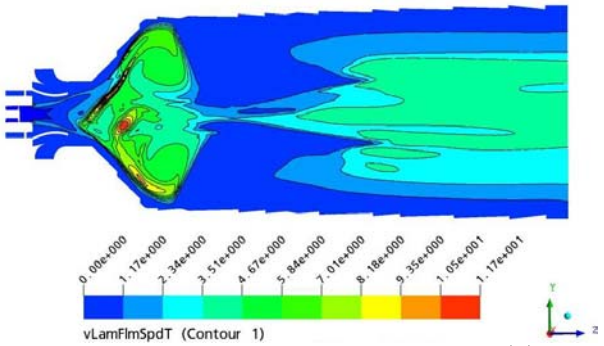


Fig. 10 – Field of reduced flame speed $S_L(T)$.

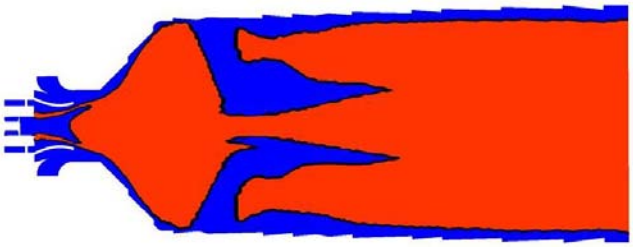


Fig. 11 – Field of T-limiter (0 – blue,1 – red).

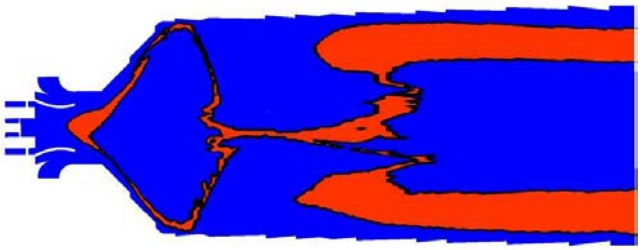


Fig. 12 – Field of C-limiter (0 – blue,1 – red).

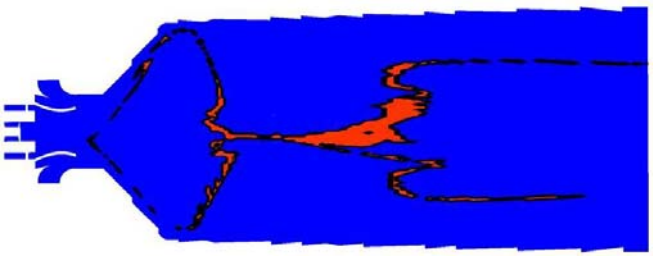


Fig. 13 – Field of E-limiter (0 – blue,1 – red).

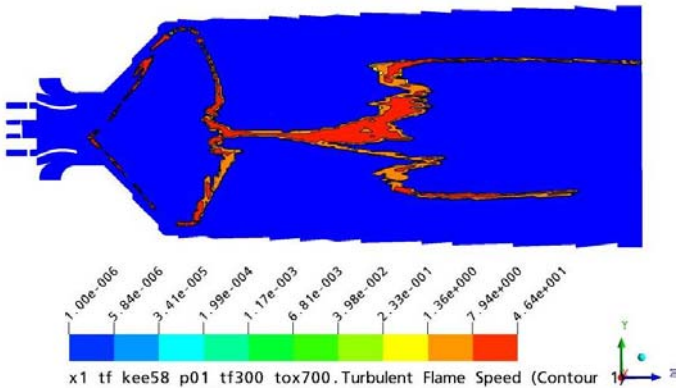


Fig. 14 – Field of turbulent flame speed.

CALCULATION OF LAMINAR FLAME SPEED

To calculate a value of laminar flame speed an in-house code was developed. This code allows to calculate laminar flame front speed for homogeneous mixture of fuel and oxidizer taking into account a multicomponent diffusion.

A system of governing equation is

$$\rho\frac{\partial T}{\partial t}+\dot{m}\frac{\partial T}{\partial x}-\frac{1}{C_p}\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+ \tag{17}$$

$$\frac{1}{C_p}\sum_{k=1}^{K}\rho Y_k V_k C_{pk}\frac{\partial T}{\partial x}+\frac{1}{C_p}\sum_{k=1}^{K}\omega_k h_k W_k=0$$

$$\rho\frac{\partial Y_k}{\partial t}+\dot{m}\frac{\partial Y_k}{\partial x}+\frac{\partial}{\partial x}\left(\rho Y_k V_k\right)-\omega_k W_k=0 \tag{18}$$

$$\rho=\frac{pW}{RT} \tag{19}$$

It was assumed:

$$\frac{\partial(\rho v)}{\partial x}=0, \tag{20}$$

Therefore we get the following expression:

$$\dot{M}=\rho v=const=\rho S_L \tag{21}$$

Boundary conditions were used for the system of equations (17-19):

$$x = 0 : T = T\big|_0 \; Y_k = Y_k\big|_0 \qquad (22)$$

Simulation and experimental data of laminar flame speed S_L for chemical kinetics mechanisms KEE, GRI-MECH 1.2 and GRI-MECH 3.0 are shown on fig. 15.

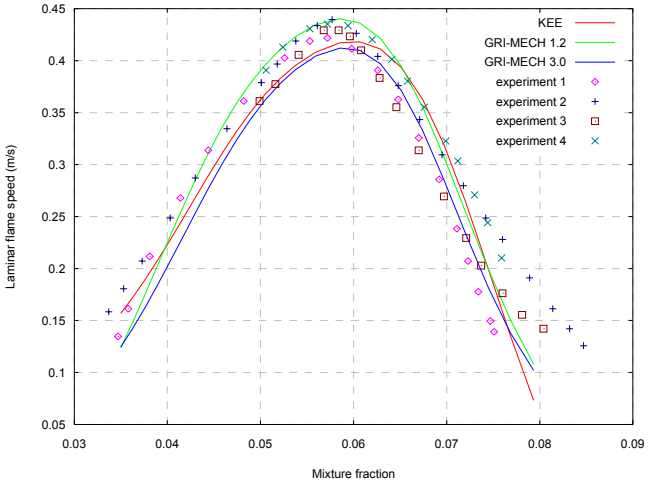


Fig. 15 – Simulation and experimental data for $S_L(Z)$. Atmospheric pressure.

SIMULATION OF LEAN BLOWOUT

We had implemented our model in CFD commercial package ANSYS CFX and tried to obtain simulation results for lean combustion limit at conditions of our test.

A grid size of computational domain was 900 thousands nodes. A view of computational model is shown on fig. 16.

For our simulation we used the following models: unsteady RANS, k-ε RNG turbulence model, flamelet model for partially premixed combustion. This combustion model is based on solution of equations for mixture fraction Z, mixture variance and reaction progress:

$$\frac{\partial(\overline{\rho}\tilde{c})}{\partial t} + \frac{\partial(\overline{\rho}\tilde{u}_j\tilde{c})}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_c}\frac{\partial \tilde{c}}{\partial x_j}\right) + \rho_u S_T |grad\tilde{c}| \qquad (23)$$

Fuel mass flow rate to a pilot zone was changed by linear law during simulation. Simulation time step was 0.0025 s.

Simulation had been run on workstation with 2 Opteron 2.2 GHz dual-core processors. Total time of calculations was about 30 hours.

As one of results of simulation we obtained a visualization of flame front locations (reaction progress gradient variable), shown on fig. 17-20. A lean zone starts to blow out at air excess ratio $\alpha_{diff\ zone} \approx 3.9$. This value is in good agreement with data of experiment.

Fig. 16 – Computational model of LP combustor with a pilot zone.

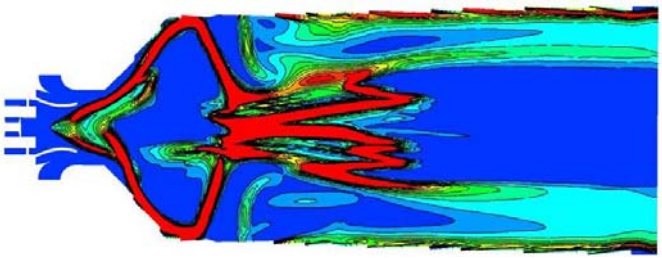


Fig. 17 – Flame front location at $\alpha_{diff\ zone}$=3.64 (t=1 s)

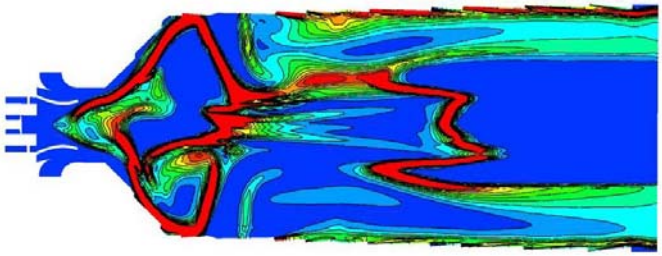


Fig. 18 – Flame front location at $\alpha_{diff\ zone}$=3.90 (t=1.25 s)

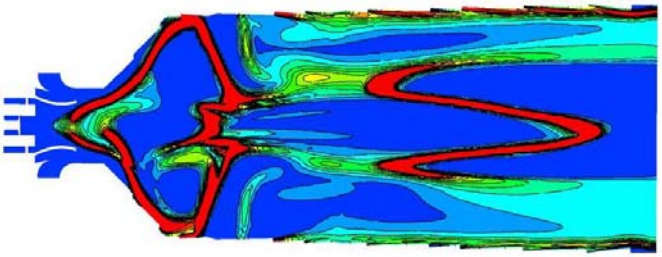


Fig. 19 – Flame front location at $\alpha_{diff\ zone}$=4.20 (t=1.5 s)

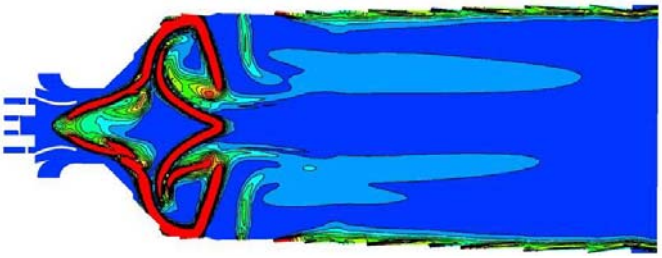


Fig. 20 – Flame front location at $\alpha_{diff\ zone}$=6.06 (t=2.5 s)

CONCLUSIONS

An approach was developed to simulate a lean quench phenomenon. This approach is based on principles of flamelet combustion model with modification of Zimont's formula to take into account a flame destabilization due to an influence of turbulence. Also, new kind of expression for laminar flame speed was proposed. It takes into account an influence of flammability limits, additional heating of air/fuel mixture, ignition temperature and composition of partially burnt mixture. A proposed approach was applied to model a lean blowout process in lean zone of LP gas turbine combustor.

Results of simulation show a good agreement with obtained data of test. Nevertheless, the proposed approach requires further validation and development. Universality of modeling approach should be proved. Also, an influence of partially burnt mixture (C-limiter) on flame speed should be investigated fundamentally.

ACKNOWLEDGMENTS

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