Energy and Power Engineering, **2013, 5, 92-96**
doi:10.4236/epe.2013.54B018 Published Online July 2013 (http://www.scirp.org/journal/epe)

Analysis of Re Influence on MILD Combustion of Gas Turbine

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Received January, 2013

ABSTRACT

The paper numerical studied the MILD(Moderate or Intense Low-oxygen Dilution) combustion mode and performances in the designed gas turbine chamber. The influence of air jet Re number on flue gas recycles ratio Kv and hereby on kerosene fuel MILD combustion were modeled. For fixed equivalence ratio, increasing the air jet Re number to the Kv value of 3.3 - 3.8, MILD combustion mode will be formed. It has MILD combustion performances of volume combustion, excellent outlet temperature field and very low pollutant emissions. Combustor confinement has little effects on MILD combustion. Calculating results agree with other's similar experimental data.

Keywords: Gas Turbine; MILD Combustion; Combustion Performance; Numerical Study

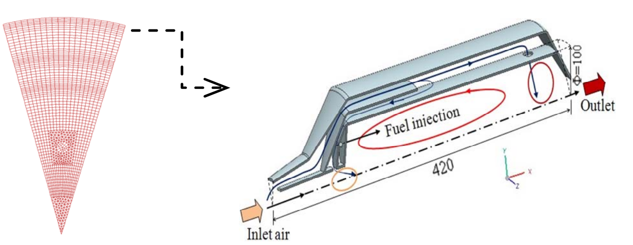
1. Introduction

In the last decades of the 20th century, there are many researches focus on the high efficiency and low emission combustion. New types of combustion mode and theory such as LPP(Lean Premix Pre-vaporized Combustion) and RQL(Rich Burn-Quench-Lean Burn) had put forward. However, these combustion molds can hardly satisfy the requirements of high efficiency and low emissions simultaneously unless combined with the staged combustion or variable geometry combustor, and has not been applied to gas turbine successfully[1]. The current MILD (Moderate & Intense Low Oxygen Dilution) mode have more advantageous performances of high combustion efficiency and super low emissions[2].

MILD combustion is a burning mode under the condition of low oxygen diluted, which is also known as Flameless Combustion, Colourless Combustion or FLOX (Flameless Oxidation). MILD combustion mode has the characteristics of volume or dispersion combustion which eliminates the flame frontal surface under normal temperature air. Gas, liquid, solid and other low caloric fuel can be extensively used to reduce pollutants emission and combustion noise[2]. From 1991 when Wunning[3] applied flameless combustion to industrial furnace by high speed jet entrain flue gas on, it is necessary to preheat the air above 1000K for MILD combustion mode at the beginning. For the current period, all kinds of fuel can be used for MILD combustion based on the air jet of normal temperature[4-6]. The application scope of MILD combustion is expanded from various industrial furnaces to high-tech field includes gas turbine and aeroengine[7-11]. Great differences of operating condition between industrial furnace and gas turbine lead to grand technical challenge [10]. Nowadays, this research is on a stage of rapid development including mechanism analysis, experiment and numerical simulation.

2. Model and Computational Grid

Figure 1 shows the 1/12 symmetrical body of the chamber and the local computational mesh of cross-section near the head of chamber. Tubular combutor model combustor is adopped and the working pressure in chamber is 0.4 MPa with the combustion intensity of 25 MW/(m3·atm). The model chamber is composed of head section and flame tube. The air into the flame tube injected cooling air in the casing, which improve the air flow distribution. 12 air-atomizer noozles and 12 dilution holes are installed circumferential distributed evenly. The



(a) Local grid dissection (b) 1/12 symmetric body

Figure 1. 1/12 Model chamber and local section mesh.

*Sponsored by The Aero Science Foundation of China (NO. 20112B 54005)

chamber dimension is 100 mm × 420 mm with two outlet styles of shrinkage tube and direct tube(labeled by dotted line).

The model chamber is divided by structured and unstructured mixing meshes for its complicated structures. Grid numbers of direct tube and shrinking outlet are 884,869-857,855 respectively.

3. Mathematical Models

3.1. The Governing Equations

The basic governing equations for continuous phase of turbulent combustion reaction flow are expressed as

$$\frac{\partial}{\partial x_j}(\rho \bar{u}_i \phi) = \frac{\partial}{\partial x_j}(\Gamma_\phi \frac{\partial \phi}{\partial x_j}) + S_\phi + S_{p,\phi} \quad (1)$$

in which $\overline{u_i}$ is the time average value of velocity component, Φ is the universal variant of turbulent velocity component, turbulent kinetic energy k and its dissipation rate ε, total enthalpy h and mass fraction m_i ($i = C_{12}H_{23}$, O_2, CO_2, H_2O, N_2, CO, H_2, NO). Γ_ϕ is effective diffusion coefficient, S_ϕ is the source term of the gas continuous phase, $S_{p,\phi}$ is the interaction source term between the particles phase of kerosene and continuous phase, ρ stands for density of gas phase, which depends on the gas state equation. The governing equations are closed by Realizable k- ε turbulence model and standard wall function is adopted near the wall. $C_{12}H_{23}$ represents aviation kerosene. A joint model with multistage finite-rate chemical reaction and EDC model is adopted to simulate the interaction between the turbulence and chemical reaction, revealed in formula(2). The reaction rate is controlled by the minor rate of EDC conceptual model (3) and finite-rate chemical reaction model rate (4)

$$R_i = -\min\left(R_{eddy}, R_{Chem}\right) \quad (2)$$

$$R_{eddy} = 4.0\frac{\varepsilon}{k}\min\left(\frac{m_{ox}}{r_{fu}}, m_{fu}\right) \quad (3)$$

$$R_{Chem} = A[fuel]^a[oxygen]^b \exp\left(-E/RT\right) \quad (4)$$

r_{fu} is chemical equivalence ratio. A, E and T stand for pre-exponential factor, activation energy and gas temperature respectively. Thermal NO and fast NO model are both used for NOx generation. P_1 Radiation model and radiative properties calculation of flue gas are used. Discrete phase of oil fuel particles are calculated by discrete random wander model, and the Lagrange equation describing fuel particles speed, mass and rate of temperature change is solved. The source term $S_{p,\phi}$ in equation (1) is calculated by PSI-CELL model. The size of atomized particles conforms Rosin-Rammler distribu- tion, and the effect of gas turbulent fluctuation on particles speed is considered. Temperature polynomial function is used for describing physicochemical properties of gas component and fuel. Thermal-gas-solid coupled boundary condition is advisable. CFD calculation is carried on the commercial software FLUENT6.3 designed by ANSYS[12].

3.2. Calculation Conditions

Air inlet temperature from the compressor of gas turbine is assumed 800 K and equivalence ratio Φ is 0.62. Effect of outlet on MILD combustion defined by geometric factor g = doutlet/dtube is 0.44 and 1 for shrinkage and direct outlets respectively. The calculation conditions are listed in **Table 1**.

4. Results and Discussion

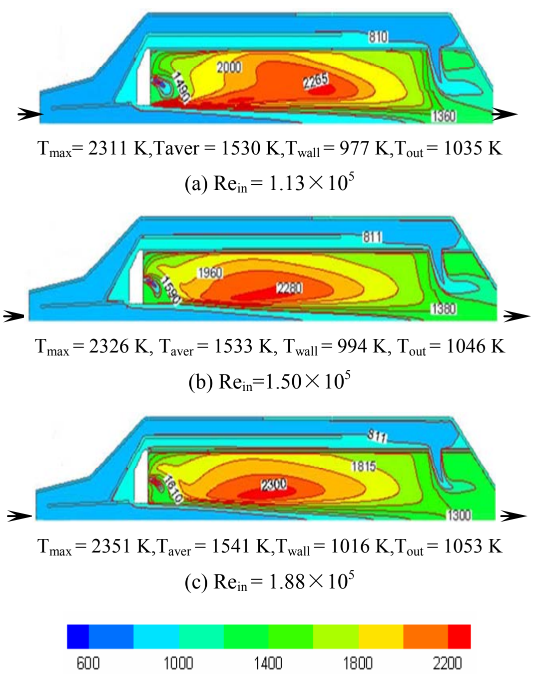
4.1. Effect of Rein on MILD Combustion

1) MILD Combustion Temperature Field

Figure 2 shows that, when Rein is larger than 1.13× 105, MILD combustion mode has formed volume flame of flame front surface disappears, local temperature difference is less than 50 K after flame lift off zone, T_{aver} is about 1540 ~ 1541 K.

Table 1. Calculation conditions.

Re_{in}	Fuel mass flow(*kg/s*)	Φ	*g*
$1.13×10^5$	0.001 44	0.62	1/0.44
$1.50×10^5$	0.001 92	0.62	1/0.44
$1.88×10^5$	0.002 40	0.62	1/0.44



T_{max}= 2311 K,Taver = 1530 K,T_{wall} = 977 K,T_{out} = 1035 K

(a) $Re_{in} = 1.13×10^5$

T_{max} = 2326 K, T_{aver} = 1533 K, T_{wall} = 994 K, T_{out} = 1046 K

(b) $Re_{in}=1.50×10^5$

T_{max} = 2351 K,T_{aver} = 1541 K,T_{wall} = 1016 K,T_{out} = 1053 K

(c) $Re_{in} = 1.88×10^5$

Figure 2. Effect of Rein on temperature field.

2) Flue Gas Recirculation Rate K_v

Previous MILD combustion results of experiment and calculation indicated flue gas recirculation rate K_v was important for MILD combustion mode[2]. The larger the combustion air jet momentum is, the greater of flue gas recirculation rate K_v, and the lower oxygen concentration[11]. High velocity air jet which induced stiring action of momentum, that accelerated by combustion heat release and viscous shearing force is main influence factor of K_v. Numerical simulation is an effective means of researching on this complicated action. Local $K_v(x)$ value is defined as

$$K_v(x) = \frac{M_{rec}(x)}{M_{air} + M_{injection} + M_{fuel}} = \frac{\iint_{A(x)} \rho_{rec} v_{rec} dA(x)}{M_{air} + M_{injection} + M_{fuel}} \quad (5)$$

M_{rec} is the mass flow of flue gas, kg/s. M_{air} and M_{fuel} are mass flow rate of air jet and kerosene, kg/s. $M_{injection}$ is the secondary mass flow rate of injected air from the casing. A(x) is local across section area of flame tube, m^2. ρ_{rec}, v_{rec} is local density and velocity separately.

For ordinary combustion mode like bluff body burning, K_v is kept 0.3 - 0.5, but Kv for MILD combustion is larger than 3[2]. The calculating results of Kv in the gas turbine this MILD chamber for kerosene fuel is showed in **Figure 4**, which can be verified by Craya-Curtet experimental formula[13].

$$K_v(x) = 0.32\sqrt{\frac{\rho_{flue}}{\rho_{in}}} \cdot \frac{x - x_0}{D_{in}} + 1 \quad (6)$$

D_{in} is the inner diameter of the injector, m. ρ flue is flue gas density in the reference temperature, kg/m^3. ρ in is the reactant density of inlet temperature, kg/m^3. x_0 is the original injecting coordinate, m.

Levy Y. *etc*. had researched on the MILD combustion mode in the gas turbine chamber and indicate that MILD combustion mode may be built as Kv is larger than 3.0[10]. **Figure 3** showed that when Rein ⩾ 1.13 × 105, at the flame lift-off location x = 0.132m, its local Kv is 1.365, 1.191 and 1.182 respectively, are both larger than 0.3~0.5 of ordinary stable combustion mode such as bluff body combustion. The backflow entrainment of high temperature flue gas has effects of heating and ignition on lift off zone of combustible mixture and may induce MILD combustion mode. Furthermore, Kv at recirculation zone center is between 3.3 and 3.8 in the **Figure 3**, which represents the formed MILD mode and corresponds to the existing experiment results of fuels. The entrainment air from casing has a stabilized effect on the Kv, which is beneficial to MILD state. K_v calculation results fit the Craya-Curtet formula in **Figure 3**.

3) NOx Emission

MILD combustion performance of pollutant of NOx emisssion show in **Figure 4**.

When Rein ⩾ 1.13 × 105 *i.e.* Kv is larger than 3.3, the average combustion temperature is about 1530~ 1541 K and NOx emission is between 15 and 16.5ppm analogous to 18ppm of experiment result[14].

4) Outlet temperature field quality

The temperature distribution coefficient can be described as OTDFmax, which is showed as

$$\text{OTDF}_{\max} = \frac{T_{4\max} - \overline{T}_{t4}}{\overline{T}_{t4} - \overline{T}_3} \quad (7)$$

T_{4max} is outlet temperature peak value, T_4 is the outlet circumferential average temperature, T_3 is the entrance average temperature. $OTDF_{max}$ calculation results are between 0.293 and 0.267, decrease with Rein increasing, but far less than 0.35 of ordinary combustor. The lager Rein, the smaller OTDFmax. Temperature field quality of outlet section is clearly uniform.

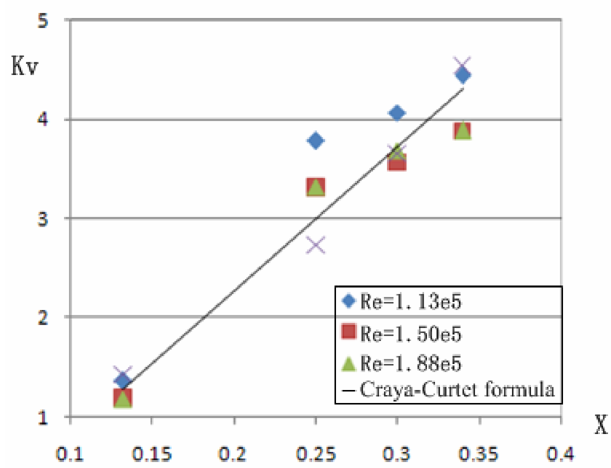


Figure 3. Kv(x) calculating vs. experimental.

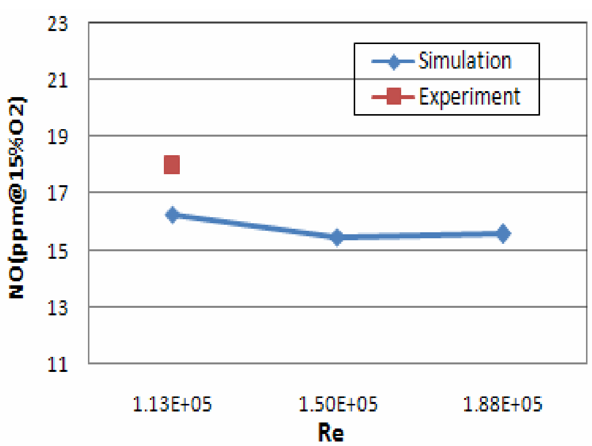


Figure 4. NOx Emission(ppm@15%O_2).

Table 2. Impact of confinement on MILD combustion.

Re_{in}	1.13×10^5		1.50×10^5		1.88×10^5	
Factor g	1	0.44	1	0.44	1	0.44
Kv	3.52	3.78	3.50	3.31	3.51	3.32
T_{aver}(K)	1469	1530	1464	1533	1541	1469
$OTDF_{max}$	0.16	0.29	0.16	0.27	0.16	0.27
NO_x	14.1	16.3	13.3	15.5	12.3	15.6
ε(%)	98.3	99.5	99.4	99.4	99.4	99.4

Table 3. Calculation vs. similar experiments.

Similar items	calculation	experiment
Fuel	Kerosene	Liquid propane
T_{air}(K)	800	798
Φ	0.62	0.62
Kv	3.5	3.5
Tmax(K)	2323~2332	≈1 873
NO_x (ppm@15%O_2)	12.3~14.1	≈18
CO(ppm@15%O_2)	8.1~37.8	≈20

4.2. Effect of Geometric Constraint

The calculating result of changing chamber constraint condition is stated in **Table 2**.

The combustion efficiency ε in **Table 2** is defined as

$$\varepsilon = \left[1 - EI_{CO} \times \left(\frac{\Delta H_{CO}}{\Delta H_{C_{12}H_{23}}}\right) - EI_{HC}\right] \times 100\% \quad (8)$$

EI_{CO} and EI_{HC} are emission index of CO and HC, g/kg. $\triangle H_{CO}$ and $\triangle H_{C12H23}$ is the low heating value of CO and $C_{12}H_{23}$. In the **Table 2**, MILD combustion mode and performance influenced by Re number conform to the gas turbine flameless combustion experiment results [14].

4.3. Simulation Comparison with Test

Table 3 contains the numerical results comparison with the experimental of similar conditions[14]. The calculation results are coincidence with experiment.

5. Conclusions

For the designed MILD model chamber, effect of Reynolds number on MILD combustion has been numerical simulated, which is concluded as follows:

1) Air jet Reynolds number has important effect on the high temperature flue gas recycling rate K_v and MILD combustion mode. MILD combustion mode is formed when K_v larger than 3.3 ~ 3.8.

2) The formed MILD combustion has characteristics of space reaction, high combustion efficient, very lower NOx and CO emissions, and good equality temperature field of outlet section.

3) MILD chamber constraint condition has little effect on MILD combustion mode.

The calculation results are conformed to the associated experiments and laws, which have engineering reference value for MILD applications to gas turbine.

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