FLAMELESS OXIDATION AT THE GT26 GAS TURBINE: NUMERICAL STUDY VIA FULL CHEMISTRY

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(Received 25 January 2001)

Abstract: Sequential combustion was first applied to gas turbines more than 40 years ago, and almost half of these early machines are still operating. This form of oxidation leads to the flameless combustion at a second chamber. In GT26, the second stage combustor has 24 SEV burners which are similar in action to the well known ABB EV burner. In this paper, a 3D numerical simulation of the first EV combustor and the second SEV-combustor are performed for normal operating conditions (exhaust mass flow 542 kg/s, exhaust temperature 610°C). Physical modelling of the flameless oxidation is based on an original implementation of the GRI-MECH mechanism (325 chemical reactions) into the Fluent 5.4. Precise estimation of NO_x emission and other pollutants has been done.

Keywords: combustion, full kinetics of chemical reaction, CFD, flameless combustion

1. Introduction

Brown Boveri installed the first gas turbines with sequential combustion at Beznau, Switzerland, in 1948 and operated them on distillate at 30% simple cycle efficiency, with a turbine inlet temperature of 575°C. Contemporary gas turbines without sequential combustion could achieve about 15% efficiency [1]. So even then it could be seen that sequential combustion offered a way of raising output and decoupling efficiency and temperature. Since form 26 gas turbines with sequential combustion which were built between 1948 and 1959, 11 are still operating, therefore a new idea of ABB gas turbine with the modern EV and SEV burners has been worked out [1]. Sequential combustion allows the hot gases to pass to a second combustion chamber so that more work can be extracted as shaft horsepower. There is enough oxygen in the exhaust gases of the first stage to support combustion, but not enough to form a flame and to add significantly to thermal NO_x production.

2. Physics of flameless combustion

In contrast to the combustion in stabilised flames, the combustion at flameless oxidation is mixture temperature controlled, achieved by specific flow and temperature conditions [2]. The main criteria of burners' designer is creating flow conditions for flame stabilisation. Swirl and buff-body are most often used to create stabilisation conditions. Concentration of species plays an important role – air (about 21% oxygen) and many fuels can create flame-stable mixture. Exhaust gas recalculation is a function of content of inert of a mixture. Let's define recalculation rate [2]:

$$K_v = \frac{\dot{m}_e}{\dot{m}_f + \dot{m}_e} \tag{1}$$

where e – recalculation exhaust gas, f – fuel, a – combustion air. To provide reliable operating conditions, exhaust gas recalculation rates of less than 0.3 are used as a NO_x-reducing technique. It has been found, that under special conditions, the combustion takes place without any visible flame. For that reason it was named flameless oxidation. In flameless oxidation fuel and air are gradually mixed with large amounts of recalculated exhaust gas, thereby reducing the adiabatic flame temperature of mixture and heating up the air and fuel or air/fuel mixture at the same time. A large enough amount of exhaust gas should be mixed into the combustion air and into the fuel or into the fuel air mixture before the reaction takes place. When reaching the self ignition temperature, a large enough amount of exhaust has to be mixed in to make high temperature increases during reaction impossible. In every part of the combustion chamber the presence of high temperature and a mixture with a high adiabatic flame temperature should be avoided. Both conditions could occur, but should not be simultaneous at the same location [2].

3. Sequential combustion in industrial application: gas turbine GT26

An efficient 22-stage compressor feeds combustor air into the 1st combustor at pressure 2 bar. There fuel is mixed with the high pressure air and ignited in the first combustor chamber – the annular EV combustion chamber. The EV combustion chamber has an annular arrangement fitted with 30 EV burners. The hot gases drive the 1st turbine (single-stage high pressure turbine) and exit the 1st combustion chamber and enter the SEV combustor. In the annular SEV combustor, the combustion process is repeated in a similar fashion as in the EV: vortex generation, fuel injection, premixing and vortex breakdown. The SEV combustor consists of 24 diffusor-burner assemblies, distributed annularly, followed by a single annular combustion chamber surrounded by convection-cooled walls. Exhaust gas from the high pressure turbine enters the SEV combust through the diffuser area [3, 4].

Combustion temperature uniformity in the SEV, like in EV, is determined by the spatial homogeneity of the fuel/air mixture which is again accomplished by the use of vortices. Each SEV burner contains delta-shaped wings, formed like ramps and locaded on all four of the burner's interior walls, which swirl combustion air into vortices. Fuel is then injected through 24 air-cooled fuel nozzles, distributing it in a manner which forms a perfect fuel/air mixture prior to combustion. The fuel jet is surrounded by cool carrier-air which postpones spontaneous ignition until the combustion chamber, beyond the burner area.

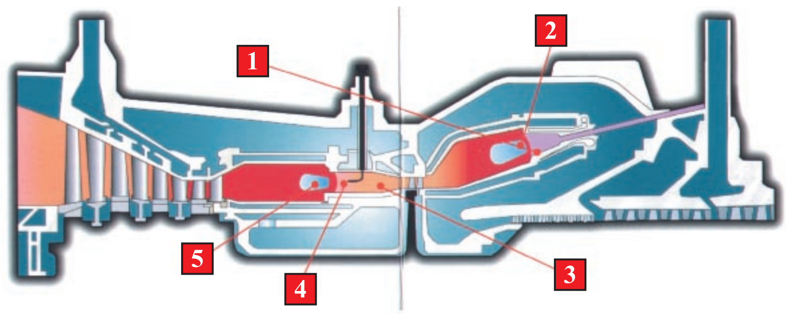

Figure 1. GT26 gas turbine [1]. (1) Compressed air is fed into the double-cone EV burner, creating a homogeneous, lean fuel/air mixture. The vortex flow, induced by the shape of the burner, breaks down at the EV burner exit into the combustion chamber, forming a recirculation zone. (2) The mixture ignites into a single, low temperature flame ring. The recirculation zone stabilises the flame in the free space within the chamber, avoiding contact with the combustor wall. (3) The hot exhaust gas exits this first combustion chamber, moving through the high pressure turbine stage before entering the SEV combustor. (4) Vortex generators in the SEV combustor enhance the SEV mixing process, while carrier air, injected with the fuel at the fuel lance, delays spontaneous ignition until outside of the SEV combustor. (5) Ignition occurs when the fuel reaches self-ignition temperature in the free space of the SEV combustion chamber. The hot gas then continues its path into low pressure turbine

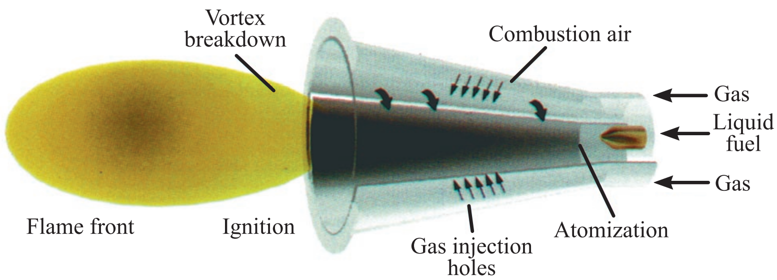

Figure 2. EV burner [1]

4. Implementation of GRI-MECH mechanism of natural gas combustion

Physical modelling of the flameless oxidation is based on an original implementation of the GRI-MECH mechanism [5] (325 chemical reactions) into the Fluent 5.4. Details have been described in [4].

5. Boundary conditions, geometry and fluid properties

5.1. Geometry

The 3D geometry of low and high pressure chamber with SEV and EV burners are presented in Figure 3. Figure 3a corresponds with zones 1, 2 denoted in Figure 1 and Figure 3b corresponds with zones 3, 4, 5 in Figure 1. Approximately 120 000 hexatedral cells where used in the simulation of high pressure chamber and 180 000 in low pressure chamber.

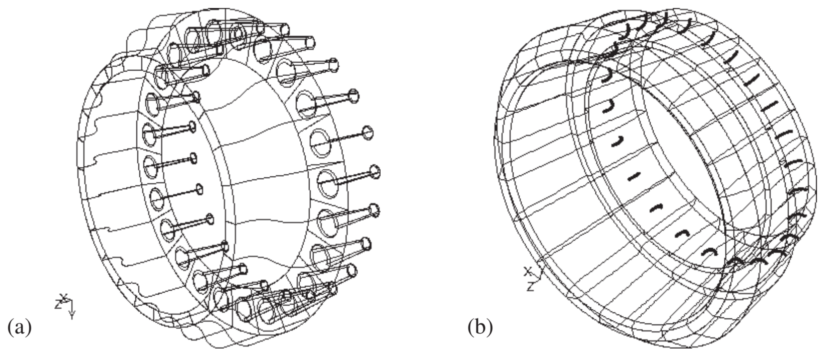

Figure 3. Geometry of (a) high and (b) low pressure chamber

5.2. Species

The mixture for calculation with the eddy-dissipation finite-rate reaction [6] model is assumed to consist of 53 different species and radicals: H_2, H, O, O_2, OH, H_2O, HO_2, H_2O_2, C, CH, CH_2, CH_2(S), CH_3, CH_4, CO, CO_2, HCO, CH_2O, H_3O, CH_3OH, C_2H, C_2H_2, C_2H_3, C_2H_4, C_2H_5, C_2H_6, HCCO, CH_2CO, HCCOH, N, NH, NH_2, NH_3, NNH, NO, NO_2, N_2O, HNO, CN, HCN, H_2CN, HCNN, HCNO, HOCN, HNCO, NCO, N_2, AR, C_3H_7, C_3H_8, CH_2CHO, CH_3CHO.

5.3. Boundary conditions

- EV fuel: $T = 773.3$ K, $p = 30.0$ bar, $\dot{m} = 12.5$ kg/s, species concentrations in Figure 4;
- EV oxygen: $T = 773.3$ K, $p = 30.0$ bar, $\dot{m} = 545.5$ kg/s, species concentrations in Figure 6;
- SEV fuel: $T = 1302.76$ K, $p = 15.0$ bar, $\dot{m} = 4.0$ kg/s, species concentrations in Figure 4;
- SEV oxygen: $T = 1302.76$ K, $p = 15.0$ bar, $\dot{m} = 558.0$ kg/s, species concentrations in Figure 5.

5.4. Fluid properties

The specific heat capacity $c_{p,i}$, thermal conductivity k_i, viscosity μ_i, standard-state entropy S_i^o, standard-state enthalpy H_i^0 of $i = 1,\ldots,53$ species, are defined as piecewise-polynomial functions of the temperature T:

$$\frac{c_{p\,i}^0}{R} = \sum_{n=1}^{5} a_{i,n} T^{n-1} \tag{2}$$

$$\frac{H_i^0}{RT} = \sum_{n=1}^{5} \frac{a_{i,n} T^{n-1}}{n} + \frac{a_{i,6}}{T} \tag{3}$$

$$\frac{S_i^0}{R} = a_{i,1} \ln T + \sum_{n=2}^{5} \frac{a_{i,n} T^{n-1}}{n-1} + a_{i,7} \tag{4}$$

$$\ln \mu_k = \sum_{n=1}^{4} b_{i,n} (\ln T)^{n-1} \tag{5}$$

$$\ln \lambda_k = \sum_{n=1}^{4} d_{i,n} (\ln T)^{n-1} \tag{6}$$

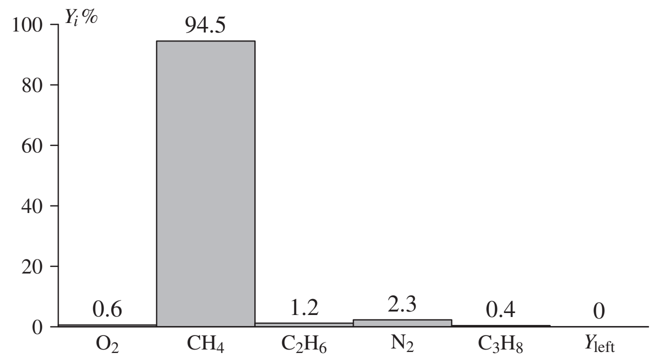

Figure 4. Concentrations of species in fuel inlet of EV and SEV burner

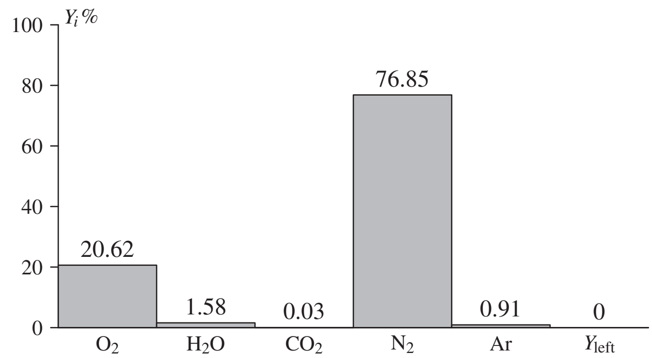

Figure 5. Concentrations of species in oxygen inlet of SEV burner

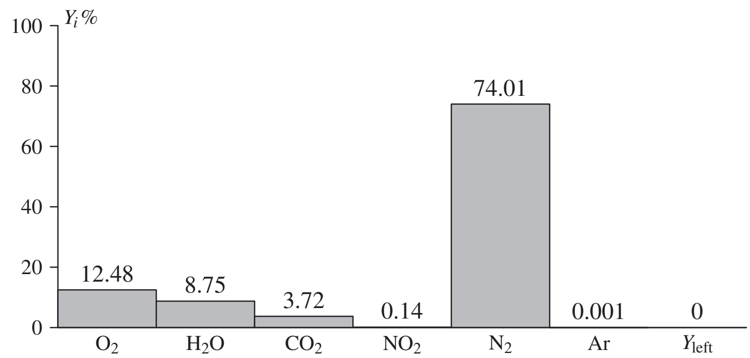

Figure 6. Concentrations of species in oxygen inlet of EV burner

Thermodynamic and transport coefficients have been implemented in Fluent code on the base of thermodynamic [7] and transport [8] data base from Chemkin [9] package.

6. Results

In Figure 7 stream lines are shown comming from EV burner. Figure 8a shows a temperature field around the SEV and a field of the NO_2 related with smooth field (flameless) of temperature (Figure 8b). The characteristic for flameless oxidation is the absence of steep gradients in distribution of all species. Figure 9 shows the distribution of

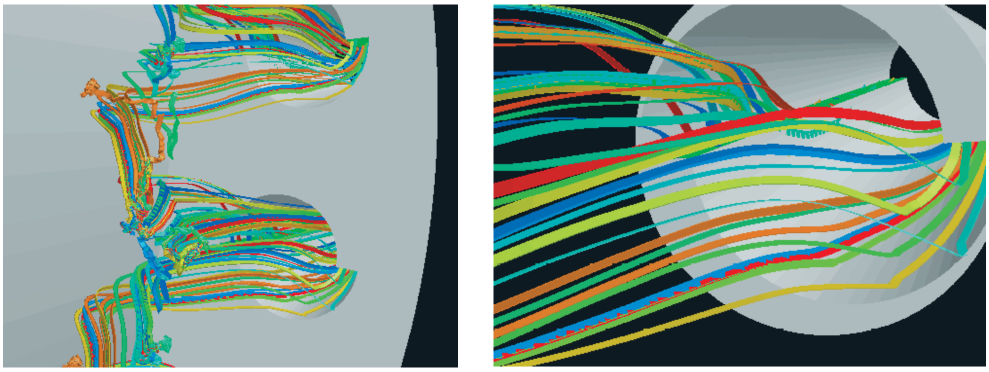

Figure 7. Stream lines on EV burners

Table 1. Concentrations of species on outlet from SEV combustion chamber

0.101E-05 H_2	0.164E-07 H	0.988E-06 O	0.102E+00 O_2	0.646E-04 OH	0.110E+00 H_2O
0.600E-06 HO_2	0.550E-07 H_2O_2	0.367E-20 C	0.858E-17 CH	0.765E-13 CH_2	0.131E-14 CH_2(S)
0.229E-11 CH_3	0.687E-11 CH_4	0.539E-04 CO	0.489E-01 CO_2	0.549E-13 HCO	0.111E-10 CH_2O
0.775E-15 CH_2OH	0.160E-14 CH_3O	0.282E-11 CH_3OH	0.546E-13 C_2H	0.249E-08 C_2H_2	0.587E-16 C_2H_3
0.740E-15 C_2H_4	0.610E-21 C_2H_5	0.273E-19 C_2H_6	0.374E-12 HCCO	0.188E-09 CH_2CO	0.223E-06 HCCOH
0.746E-12 N	0.824E-10 NH	0.146E-07 NH_2	0.389E-06 NH_3	0.297E-12 NNH	0.142E-02 NO
0.273E-04 NO_2	0.630E-05 N_2O	0.162E-08 HNO	0.562E-11 CN	0.660E-06 HCN	0.169E-14 H_2CN
0.361E-18 HCNN	0.165E-04 HCNO	0.767E-06 HOCN	0.109E-05 HNCO	0.283E-08 NCO	0.737E+00 N_2
0.999E-04 AR	0.172E-28 C_3H_7	0.109E-28 C_3H_8	0.596E-16 CH_2CHO	0.126E-18 CH_3CHO	

(a) CO_2 and (b) OH concentration. The results show a significant increase of OH, NO_2 and CO_2 emissions with the increase in temperatures.

In particular, Table 1 contains concentrations of species in the outlet flue gas where one can see high level of OH radicals. As a result the characteristic colour of flameless oxidation (deep green where observed) follows from the high level of all radicals.

7. Conclusion

The numerical simulations of turbulent, non-premixed, flameless combustion for SEV-combustor have been carried out using the k-ε turbulence model, finite-rate-eddy-break-up model of chemical kinetics and the GRI-MECH model of full chemistry consisting of 53 species and 325 equations.

One significant result has been a discovery at the second GT26 combustor of a phenomenon called "green flame" effect, taking place in the diluted high temperature and

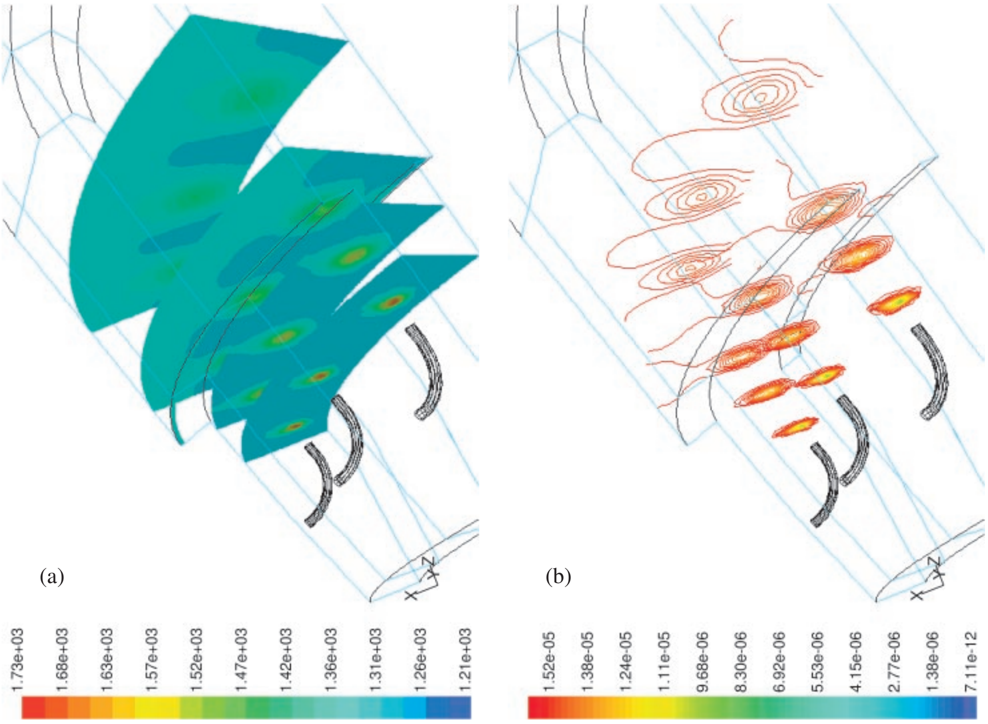

Figure 8. (a) Temperature, (b) NO_2 distribution

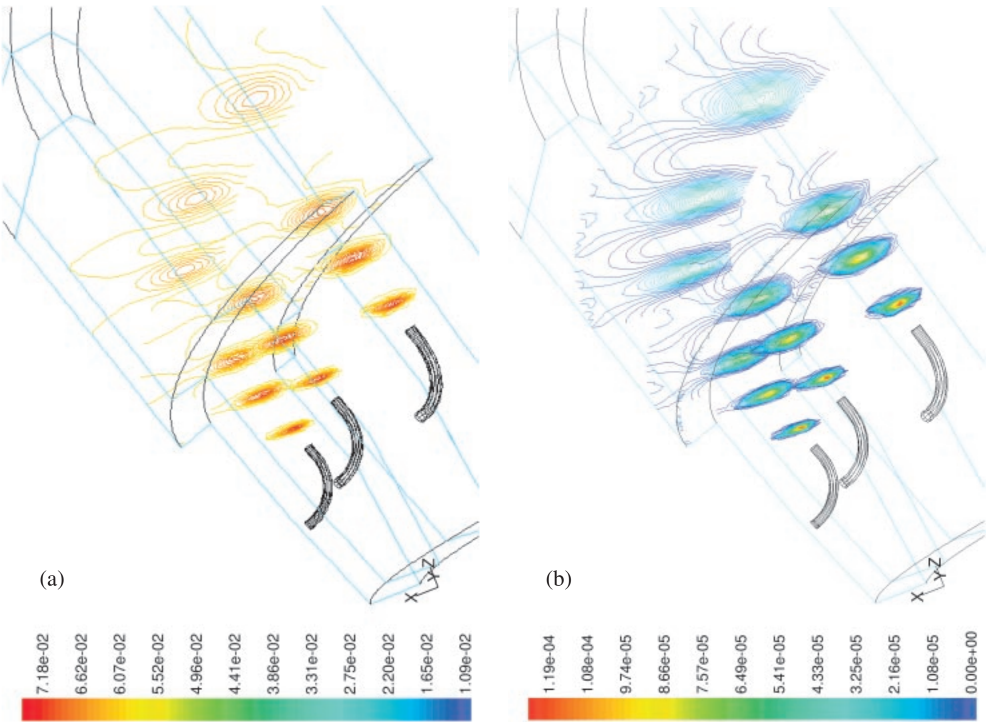

Figure 9. (a) CO_2, (b) OH distribution

low oxygen flue gas combustion. It is shown that the reason of the flame colour change into green for GT26 condition is the decrease of CH radical and the increase of OH, C_2 radicals.

This application of the GRI-MECH mechanizm of combustion illustrates the posibility of using computer simulations for research and to optimize the work of complex industrial installation.

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