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Computational Simulation and Effect of Swirl Angle on NOx Generation of 2D Swirl Burner in Gas Turbine

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***Abstract*-The method of introducing small-scale turbulence in the fuel using a swirler in gas turbine combustors are recent trends. The concentration of NOx and HC (Hydrocarbon) in the gas turbine increases due to the local non-uniform mixing of air and fuel. Thus, the uniform distribution of fuel concentration in the combustor is essential to enhancing the mixing with air, which plays a significant role in the improvement of combustion efficiency and control of exhaust gases. Inthis study, a numerical 2D model has been developed to simulatethe flow and combustion in a gas turbine combustor. Swirl flow is generated by the application of tangential component to the axial flow. The numerical model, which is in accordance with anexisting experimental combustor, consists of an air swirler. The mesh has been created in GAMBIT as two dimensional, axis symmetric mesh with approximately 40000-64000 quadratic cells. The characteristics of themodel are; steady, turbulent, two dimensional and swirling flow. Flow patterns, mixing and temperature in a swirl burner with varying geometry have been analysed. The Primary goal is to find the best swirl angle for least NOx emissions for the combustion applications. The results obtained fromthe CFD simulation in FLUENT are compared with theory from literature reviews, experiments and previous simulations done on the same burner. The standard k–ε model of turbulence has been employed to predict the low and medium swirl flows. It is found that standard k–ε model of turbulence predicts the low swirls quite well but at higher swirl flows results are poor. The simulations showed that the NOx reduction is very less due to swirler with a fixed vane angle of 45º. The characteristics of swirl flows are evaluated by means of size of the recirculation which may help better mixing of fuel and air for complete combustion.**

Key words- turbulence, Swirler,NOx, HC, Swirl flow, axial flow, vane angle, recirculation.

I. INTRODUCTION

This study focuses on nitrogen oxides (NOx) reduction techniques. NOx is an unwanted product of a combustion process and can cause health and environmental impacts like ground-level ozone, acid rain, particles, water quality deterioration, climate change, toxic chemicals and visibility impairment. Turbulent swirling combustion is widely encountered in gas turbine combustors, swirl burners, and cyclone combustors. It was found recently that swirl might influence not only combustion characteristics but also NOx formation. One possible measure to reduce the emissions in the oil and gas sector is to introduce low-NOx turbines in the power generators. There exist several low-NOx techniques but due to the cost of retrofitting old process installations, most of these techniques are not economical feasible. Therefore, finding a NOx reducing technique that can be implemented into an existing installation without comprehensive retrofitting is of great interest.When reducing NOx emissions from combustion processes, the methods used are often separated into two main procedures, named primary and secondary measures. The secondary measures focus on treatment of the flue gas, instead of reducing the formation of the pollutants. Examples of secondary measures are catalytic reduction and reactions with for instance ammonia. Secondary measures are economical expensive and technically challenging and therefore a lot of effort has been made to reduce the NOx where it is produced, called primary measures. This study focuses on primary measuring techniques, and for that reason one well known method to reduce NOx in burners will be explained in the followingsections. One promising low-cost NOx reducing technique is to use swirl burner for complete combustion. A swirl burner is modelled in GAMBIT to use on CFD platform.For the purpose of computer simulation of gaseous fuel burners and combustion chambers a mathematical model and numerical solution procedure and for the prediction of the turbulent swirl flow with heat and mass transfer for combustion in two-dimensional geometries plane and axisymmetrical is developed. In this study the model is applied to the analysis of swirl combustion chamber.

II. LITERATURE REVIEW

Zhou et. al[1] worked on “Studies on the effect of swirl on NO formation in methane/airturbulent combustion” and their findings are as followings.

It was shown in both predictions and experiments that as the swirl number increases from 0to1, the thermal NO at first increases and then decreases. In contrast, the fuel NO at first decreases and then increases. The studies also show that the increase in swirl number first leads to a rapid decrease and then as lower increase in turbulence intensity, and first an increase and then as light decrease of temperature near the exit. Spangelo[2] Worked on "Experimental and Theoretical Studies of a Low NOx Swirl Burner" and his findings are as followings.

A novel low NOx swirl stabilized gas burner concept, the swirl burner, has been studied experimentally, theoretically and numerically. Flame stabilization, rapid air and fuel mixing and internal flue gas recirculation are provided by a strongly swirling flow generated in this patented burner concept. NOx emissions have been measured below 25 and 45 ppmv dry corrected to 3% O_2 in the flue gases using methane and propane as fuel respectively. Studying the effect of varying geometrical parameters on the emissions of NOx, fuel and air supply pressure and flame stability, have resulted in an optimized burner design. Meieret. al[3] worked on "Reaction zone structures and mixing characteristics of partially premixed swirling CH4/air flames in a gas turbine model combustor" and their findings are as followings.

The mixing, reaction progress, and flame front structures of partially premixed flames have been investigated in a gas turbine model combustor using different laser techniques comprising laser Doppler velocimetry for the characterization of the flow field, Ramanscattering for simultaneous multi-species and temperature measurements, and planar laser-induced fluorescence of CH for the visualization of the reaction zones. Swirling CH4/air flames with Re numbers between 7500 and 60,000 have been studied to identify the influence of the turbulent flow field on the thermochemical state of the flames. Owaki and Umemura[4] worked on "Premixed swirl combustion modes emerging for a burner tube with converging entrance" and their findings are as followings.

The fluid dynamics underlying swirl combustion was experimentally investigated by observing the sub-sequent behaviour of a conical premixed flame which was formed at the nozzle exit when the air flow rate was increased step wise for each fixed fuel flow rate. In theexperiment, the swirling flow of a methane–air mixture was produced by a vane swirler, resulting in a nearly unit swirl number at the nozzle exit for any net gas flow rate. A Study [5] on the effect of various parameters on flow development behind vane swirlers had been doneand findings are as followings.

This main focused attention was on arriving at best vane angle from aerodynamic aspects for the combustion applications. As there are large number of flow and geometric parameters involved arriving at the best design by experimental methods is rather difficult compared to CFD analyses. The important geometric parameters are vane angle, vane numbers and hub to tip ratio. The flow parameter involved the selection of appropriate turbulence model for the prediction. The uniqueness of this study is in arriving at the best vane angle using appropriate turbulence models for both weak and strong swirl. To this end experimental and numerical studies have been carried out. It was found that no single turbulence model is able to handle both weak and strong swirl. Huang and Yang[6] worked on "Dynamics and stability of lean-premixed swirl-stabilized combustion" and their findings are as followings.

Combustion instability remained a critical issue limiting the development of low-emission, lean-premixed (LPM) gas turbine combustion systems. The work provides a comprehensive review of the advances made over the past two decades in this area. Recent developments in industrial dry-low-emission (DLE) swirl-stabilized combustors were first summarized. Various swirl injector configurations and related flow characteristics, including vortex breakdown, processing vortex core, large-scale coherent structures, and liquid fuel atomization and spray formation, are discussed. Finally, recent progress in both analytical modelling and numerical simulation of swirl-stabilized combustion were surveyed.

III. COMPUTATIONAL SIMULATION

Computation modelling has been done by using computational fluid dynamics based software.

A. Modelling of Geometry

The swirling flow inside the combustor has been simulated using FLUENT 6.3 CFD codes. To reduce the complexity of the problem the burner is simplified to a two dimensional, axis symmetric mesh with approximately 45000-91000 quadratic cells. The mesh can be seen in fig. 1 and fig. 2. In addition, the swirl generator is modelled by defining a tangential velocity as an internal condition where the swirl generator is located. This has been done by usinga user defined function (UDF) [2]. The fuel used is methane (CH_4).The operating pressure is set to 1.01x10^5 Pascal. Other conditions are shown in table 1.At exit gauge

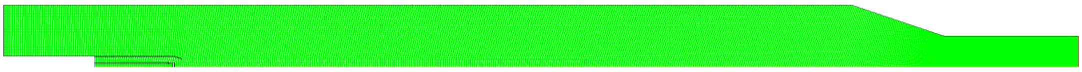

Fig. 1. Computation mesh used for swirl burner

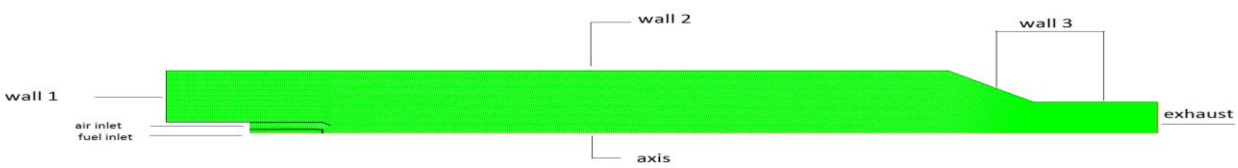

Fig. 2. Boundary conditions for the model

TABLE I. BOUNDARY CONDITIONS FOR DIFFERENT ZONE

Zones	**Boundary Conditions**
Air Inlet	Diameter = 20.5mm, T = 298K, P = 1.01×10^5pa
Fuel Inlet	Diameter = 11.5mm, T = 298K, P = 1.01×10^5pa
Exhaust	Diameter = 100mm, T = 650K, P = 50pa
Wall 1	Material = insulated steel, T = 298K
Wall 2	Material = steel, T = 373K
Wall 3	Material = uncooled steel, T = 650K

pressure is set to 50 Pascal to prevent ambient air to seep into combustion chamber.

B. Grid Independence Test (GIT)

A high quality grid is critical to an accurate CFD (computational fluid dynamics) solution; a poorly resolved or low quality grid may lead to an incorrect solution. It is important, therefore, it is necessary to test the solution dependency on size of the grid. The standard method to test for grid independence is to increase the resolution by a factor and repeat the simulation. If the results do not change appreciably, the original grid is probably adequate. There exists a level of refining of a computational domain beyond which there is no significant changes in the results achieved. Based on the different grids, analysis have been made and it has been observed that after refining the grid from nodes 91013, results are not varying significantly. So, nodes 91013have been used for further analysis as shown in fig. 3.

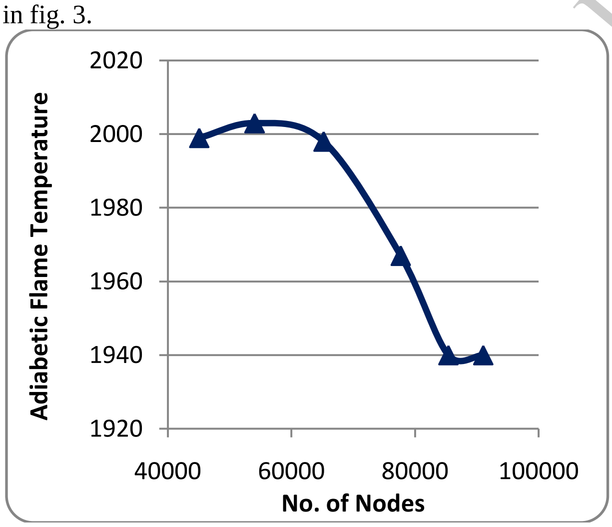

Fig. 3. Graph ofGrid Independence Test.

IV. MATHEMATICAL MODEL

A. Turbulent Swirl Flow Modelling

From the previous work [2] done on the 20 kW swirl burner, it was concluded that Reynolds stress model (RSM) and flamelet models is the most appropriate respectively turbulence and combustion models whereas the k-ε turbulence model can on the other hand be used to get more accurate initial conditions before introducing the RSM. The standard k–ε model of turbulence has been employed to predict the low and medium swirl flows.

B. NOx Formation Model

The NOx concentration is in FLUENT calculated in a postprocessor. In the calculations of the NOx concentrations in this work, only models for thermal and prompt NOx formations [7] are included. The prompt NOx formation rate is calculated from equation (1).

$$\frac{d[NO]_{prompt}}{dt} = f k_{pr} [O_2]^a [N_2][FUEL] e^{\frac{-Ea}{RT}} \qquad (1)$$

Where f is a correction factor that incorporates the effect of the fuel type and equivalence ratio, k_{pr} is the rate coefficient, a is the oxygen reaction order, Ea is the activation energy, R is the universal gas constant and T is the temperature.

V. RESULTS AND DISCUSSION

In order to investigate the effect of vane angle on the flow pattern within the combustor model, comparison and prediction results using Fluent code for 30°, 45° and 60° vane swirler are presented and discussed.

Contours for different models of NOx formation at swirl vane angle 45° have been discussed.

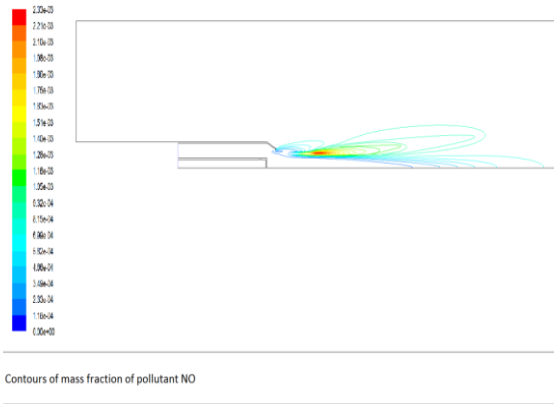

Fig. 4. Contours of thermal NOx formation

The peak concentration of NO is located in a region of high temperature where oxygen and nitrogen are available. The Mass-Weighted Average field shows that the exit NO mass fraction with only thermal NOx formation (i.e., with no prompt NOx formation) is approximately 0.00432 as shown in fig. 4.

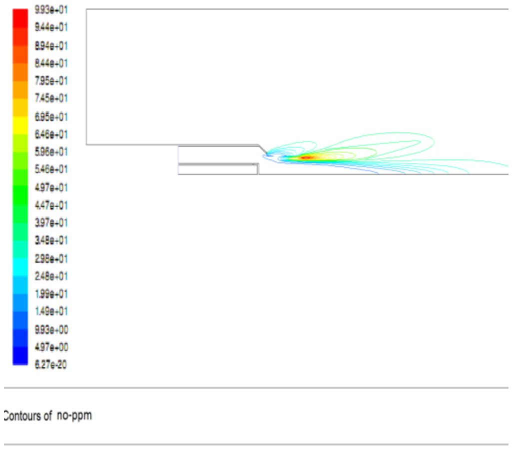

Fig. 5. Contours of prompt NOx formation

The Mass-Weighted Average field shows that the exit NO mass fraction with only prompt NOx formation is approximately 6.943e-05 as shown in fig. 5.

through the oxidation of nitrogen in the combustion air (thermal NOx) and through oxidation of nitrogen with the fuel (prompt NOx). NOx formation for the cases of 30° and 60° vane angle have been calculated in a similar way as calculated for 45° vane in the previous section.

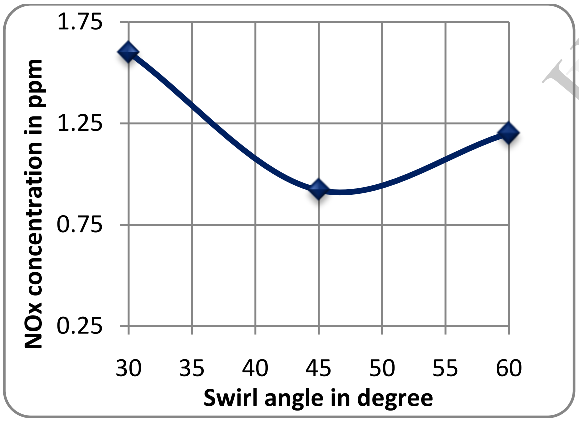

Fig. 7. Comparison of NOx generation at different swirl angles

The effect of swirl angle is quite significant on NOx generation. It is evident from the figure 7 that burner having swirl angle 45° is reducing the NOx generation maximum among three different swirl angle simulations. Similar finding was achieved [8] where NO concentration at exit of the industrial boiler exhibited a minimum value at around swirl angle of 45°.

VI. CONCLUSION

The study of the NOx generation inside a gas turbine combustor model using numerical simulation has been achieved. Numerical simulation has been done using Fluent 6.3 and based on standard k-epsilon turbulence model. In

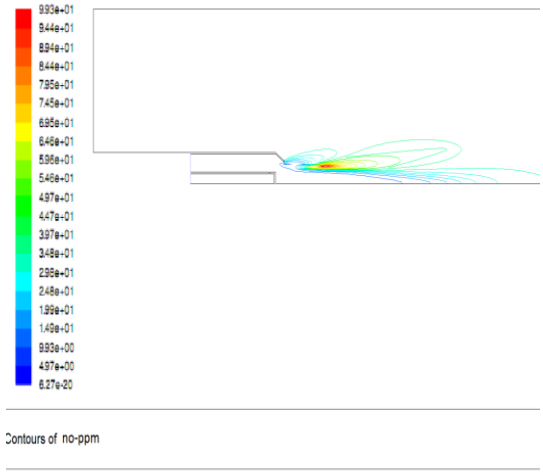

Fig. 6. Contours of prompt NOx formation (in ppm)

The calculated NOx ppm (part per million) is found to be 0.92 as shown in fig. 6.

A. Comparison of NOx Generation at 3 Differenet Swirl Angles.

As it has been known that NOx formation during the combustion process occurs mainly

this present study detailed NOx generation models are presented for vane angle 45°. In similar fashion NOx generation are calculated for 30° and 60°. It is found that 45° swirler is the best for minimizing the NOx generation in gas turbine. It would be more beneficial if numerical simulation can be validated by some experimental data.

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