

Flame Stability Analysis of Natural Gas Runners in Heat Recovery Steam Generators

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ABSTRACT

A Heat Recovery Steam Generator or HRSG is an energy recovery heat exchanger that recovers heat from a hot gas stream. The HRSGs are generally fitted in the downstream of a Gas Turbine to recover the Turbine Exhaust Gas (TEG) heat. The HRSG is typically used to produce steam that can be used in a cogeneration process or is used to drive a steam turbine in a combined cycle system. The temperatures in TEG will vary from 350°C to 650°C depending on the class of the upstream Gas turbine. The HRSG is designed with a supplementary firing system to augment its steam output. A supplementary firing system comprises of a log type duct burner arrangement mounted on the inlet duct of HRSG. Duct burner system in the HRSGs is capable of raising the exhaust temperatures from 350°C - 650°C to 600°C - 900°C or even up to 1000°C. In a duct burner arrangement, fuels like oil and gas can be fired in separate dedicated oil burners and gas runners stacked at multiple elevations similar to a log. Fuel gases like Natural gas fired runners are most commonly used in duct burners and the oxygen required for combustion of natural gas is utilized from the Gas turbine Exhaust. Typically the oxygen concentration in TEG will vary from 12-15% depending on the class of Gas turbine. This oxygen content will serve as the stoichiometric and excess air for complete combustion of the hydrocarbons in Natural Gas. Maximum supplementary firing refers to the maximum Natural Gas that can be fired with the oxygen available in the TEG. An advanced class Fr 6FA Gas Turbine is characterized by low oxygen concentration, low GT Exhaust flow and temperatures at lower GT loads. So in order to enhance the HRSG steam generation, very high supplementary firing up to a capacity of 70 Mkal/h of Natural Gas will be fired in the Gas runners of the duct burners. These gas runners that are stacked in multiple elevations will each have number of fuel holes along its axis and will have flame holding stabilizers to obtain a sustained Natural Gas flame. As Natural Gas is let in through these fuel holes, initial ignition energy is provided to obtain flame and with the flame stabilizers directing the TEG oxygen towards the flame, a sustained combustion is obtained. However in case of Fr 6FA GT at lower gas turbine loads, due to lesser TEG oxygen percentage and low exhaust temperatures, instability happens in natural gas combustion and the flame tends to get put off. To understand the flame stability and oxygen concentration, different stabilizer arrangements of the gas runner were analyzed using a Computational Fluid Dynamics study using ANSYS Fluent v 14.5 tool. The results of the study are presented in this paper.

Keywords: Heat Recovery Steam Generator, Gas runner, Flame Stabilizers, Stoichiometric air, Computational Fluid Dynamic Analysis, etc.,

I. Introduction

Heat Recovery Steam Generator (HRSG) is used in tandem with a Gas Turbine (GT) to utilize the excess heat available in the Turbine Exhaust Gas (TEG) and thus generate steam. By a supplementary firing system, burning fuel inside the HRSGs, the output steam generated can be enhanced [5]. The HRSGs require higher levels of safety and reliability while performing this supplementary firing operation. This is possible by ensuring complete combustion, reducing unburnt, continuous flame monitoring etc., which results in sustained steam generations under all operating conditions. The combustion is facilitated by burning fuels like Natural gas in gas runners (log type burners) stacked in multiple elevations in the inlet duct of the HRSG. This arrangement

of duct burners is used as supplementary fired system to enhance the steam generation from HRSGs. Natural Gas combustion in the presence of oxygen from the Turbine Exhaust Gas happens by means of stoichiometric chemical reaction of the hydrocarbons in the presence of an initial ignition source [2]. The heat dissipated from this combustion will further heat the TEG and will enhance the heat transfer in the economizer, evaporator and super-heater modules in the HRSGs. As these gas runners are inside the HRSG in a closed chamber, an effective burner system is highly essential to completely burn the entire natural gas that is let into the chamber. Any unburnt Natural gas will yield to explosion which is not desirable for the availability of a HRSG. Hence, the duct burner arrangement has multiple elevations of fuel injection active runners and dummy runners stacked on the entire cross-section of the HRSG inlet duct. The active runners are where the natural gas is injected for combustion. The dummy runners are for guiding the TEG oxygen towards the flame for sustained combustion and heat release. Although 12-15% oxygen is available in TEG, it is a requirement that the available oxygen should be in the flame vicinity for proper burning [3]. If the available oxygen is not directed towards the flame, combustion tends to go wayward with increased carbon monoxide emission and flame instability [1]. This indicates the importance of dummy runners in combination with the flame stabilizers to assist in complete combustion of Natural Gas. Various arrangements of dummy runner-flame stabilizer combination are to be studied to achieve the right combustion levels. From literature survey it was noticed that, establishment of right oxygen levels by altering the dummy runner arrangement is required for combustion fine tuning and achieving natural gas flame stability [4].

II. Natural Gas fired Duct Burner

The Duct Burner System has array of active burners and dummy runners through-out the cross section of HRSG inlet duct. The active burner has fuel injection holes in it and also is attached with flame stabilizers. Between these active runners, the dummy runners are stacked. The material of construction of these items is stainless steel to withstand the TEG temperature as well as the flame temperature. A typical arrangement of a duct burner with active and dummy runners is as depicted in Figure 1.

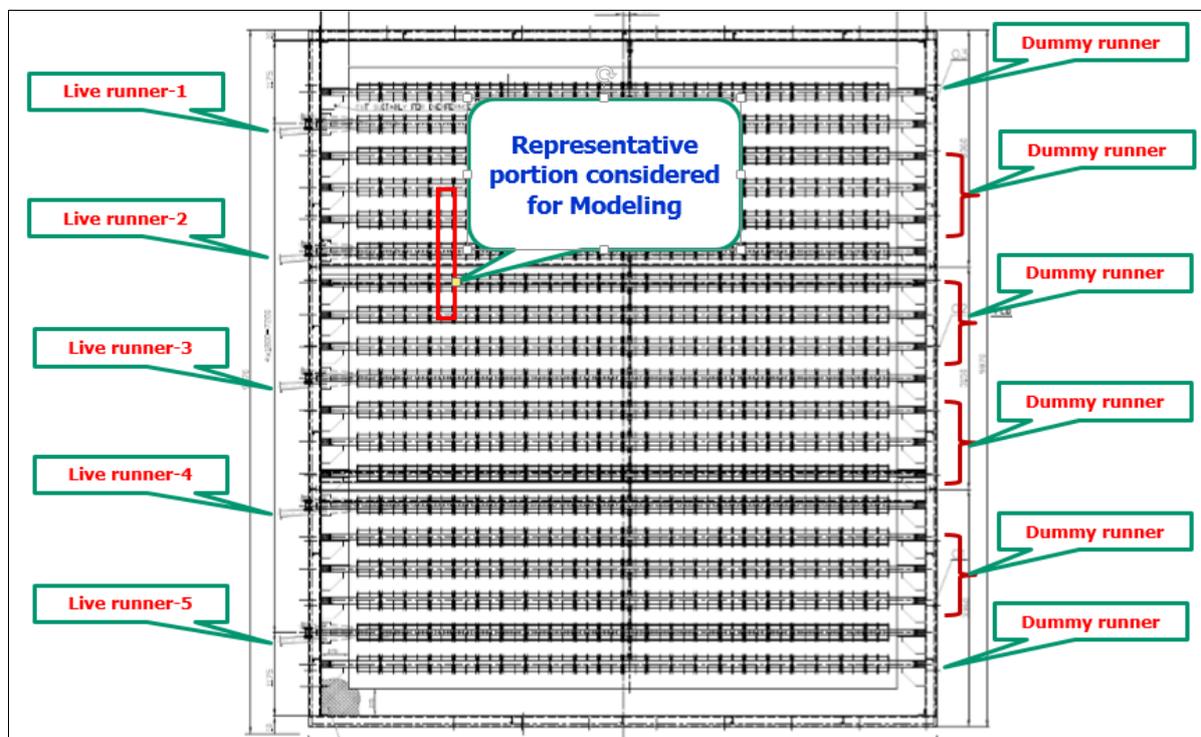


Figure 1. Duct burner Arrangement

The Turbine Exhaust gas will flow in between the gaps of active runner-dummy runner and dummy runner-dummy runner. For improving the flame stability in way of diverting the TEG oxygen more towards the flame emulating from the main active runner, block plate arrangement is proposed in between the dummy runner-dummy runner flame stabilizers. The flame characteristics to study the stability pattern of natural gas combustion for the following categorization as indicated in Table 1. which has been made in the active runner-dummy runner stabilizer components.

Table 1. Pictorial representation of different Cases

Case No:	Description	Schematic representation
1.	Active runner-Dummy runner block without Block plate	
2.	Active runner-Dummy runner block with Block plate	

2.1. Combustion Kinetics of Natural Gas

Natural gas is a naturally occurring hydrocarbon gas mixture consisting primarily of methane and other components including varying amounts of other higher alkanes, and sometimes a small percentage of carbon dioxide, nitrogen, and/or hydrogen sulphide. These hydrocarbon chemical species combust in the presence of oxygen to give carbon di-oxide and water vapor, which are the products of combustion released in flue gas.



Table 2. indicates the Natural Gas composition that is selected for the combustion pattern analysis. As seen from the gas composition, Natural Gas is dominated by Methane/Ethane and hence for combustion analysis in CFD, assumption is made that only methane and ethane is present in Natural gas.

Table 2. Natural Gas Analysis

Component	Methane (CH ₄)	Ethane (C ₂ H ₆)	Propane (C ₃ H ₈)	Total
% by Volume	98.69%	1.29%	0.02%	100%
Molecular weight of Component (g/mol)	16.042	30.069	44.095	-
Molecular weight of Gas (g/mol)	15.832	0.388	0.009	16.229
Density	kg/Nm ³			0.7245
Lower Heating Value	kcal/kg			11929.3

III. Geometry Development in GAMBIT

The portion of the active runner-dummy runner block as indicated in Figure 1. that injects Natural gas for combustion and distributes oxygen for aiding combustion is considered and local analysis of flame pattern has been carried out. The model chosen depicts the portion of the duct burner for combustion study and the results obtained can be extrapolated for the entire burner because of the symmetry nature of the gas runners. Two configurations are considered – one with the gap between two dummy runners and other with the gaps shut between the two dummy runners with a block plate. The effect of oxygen distribution on combustion for each of the two cases as indicated in Table 1. are compared. For a geometry – a representative portion comprising of one active runner, two full dummy runners each on top and bottom of the active runner, two halves of dummy runners each on top and bottom of each full dummy runner and finally the block plates (as applicable for the relevant case) are considered. Dimensional and arrangement details of the gas burners and block plates are considered confidential and hence not revealed. The individual configurations selected are modeled in ANSYS GAMBIT [8]. Case 1 and Case 2 are shown in Figure 2. and Figure 3. respectively.

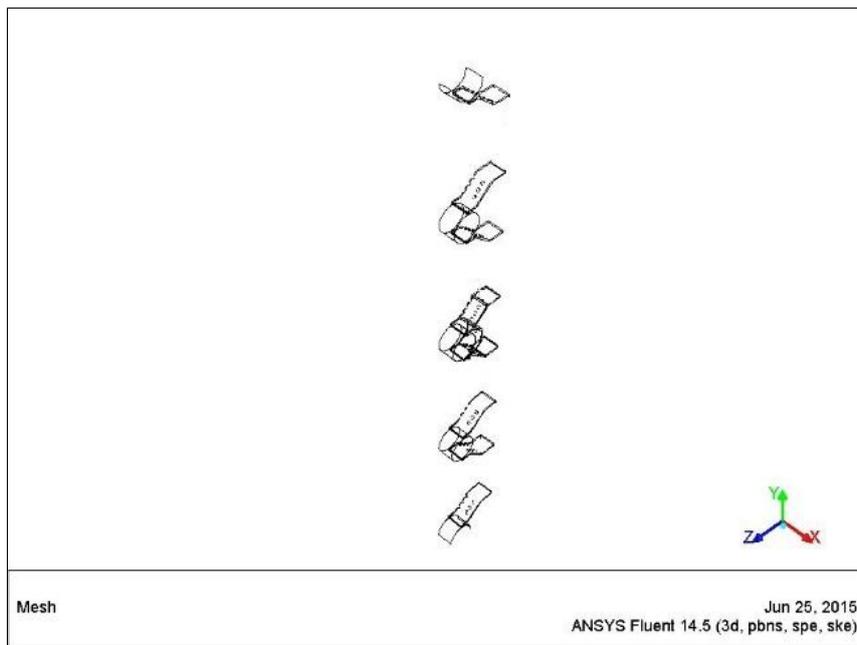


Figure 2. Geometric model of Configuration-1 - Case 1

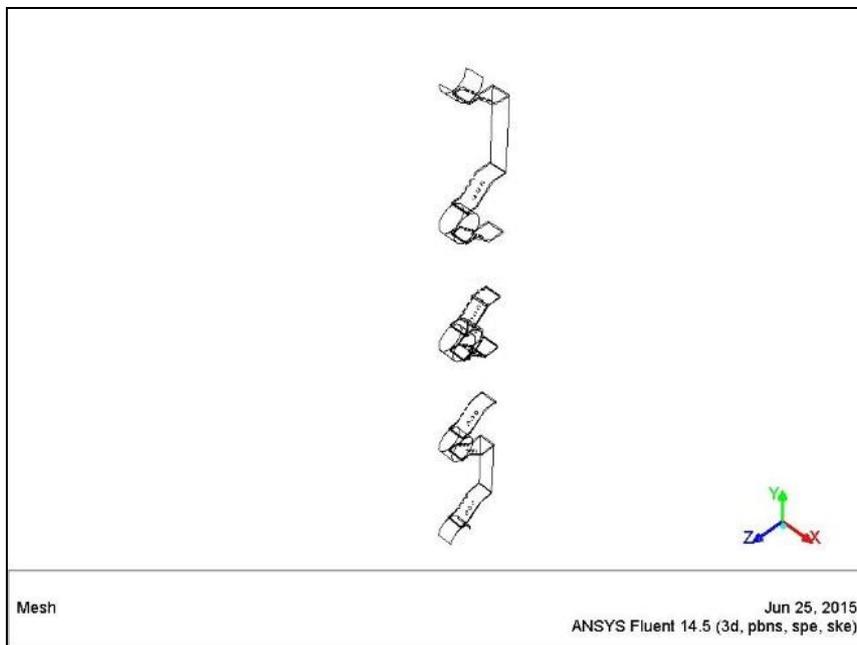


Figure 3. Geometric model of Configuration-2 - Case 2

3.1.Elements and Meshing

The representative geometry of the duct burner is modeled for the two configurations in Gambit with solver as Fluent 5/6. Meshing of the volumes were done with respect to face by providing size functions from the finer meshes of faces. The active gas runner with gas injection nozzles that had critically the lowest dimension in the entire model is meshed in a finer manner. As the accuracy of the fuel mass flow through the gas hole is of highest concern, hexahedral mesh is selected for this. The hexahedron with 8 vertices, 12 edges and bound by 6 quadrilateral faces is the element. The density of the mesh is sufficiently high in order to capture all the flow features. Hex/wedge element of Cooper type is used for this mesh with Interval size of one as shown in Figure 5. The block plate, dummy runners along with HRSG gas path are less critical compared to active runner nozzle. The faces of these are meshed and size function to mesh these volumes with tetrahedron was selected. The tetrahedron with 4 vertices, 6 edges and bound by 4 triangular faces is the element. Tet/hybrid element of T-grid type is used for this mesh with Interval size of one as shown in Figure 6. The representative elements of tetrahedron and hexahedron that are used in the meshes are indicated in Figure 4. The mesh skewness and grid independent test has been checked for the model in both configurations. For Case -1 the mesh has 4753282 elements and 828211 nodes. For Case -2 the mesh has 4791264 elements and 920417 nodes.

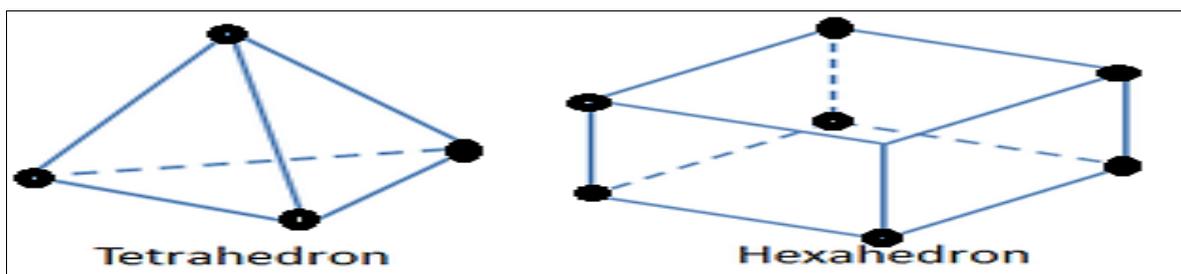


Figure 4. Representative Tetrahedron and Hexahedron

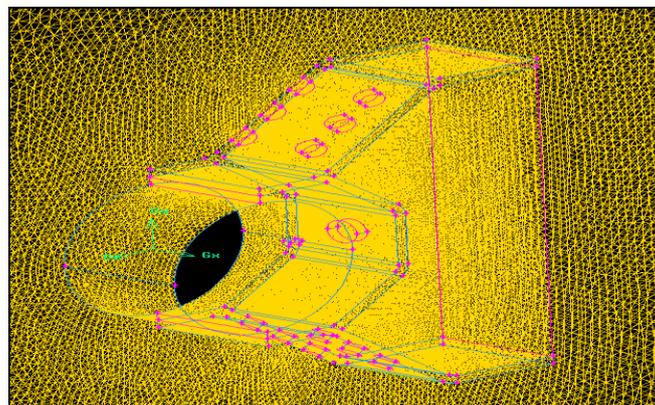


Figure 5. Mesh of Active Gas runner with flame stabilizer

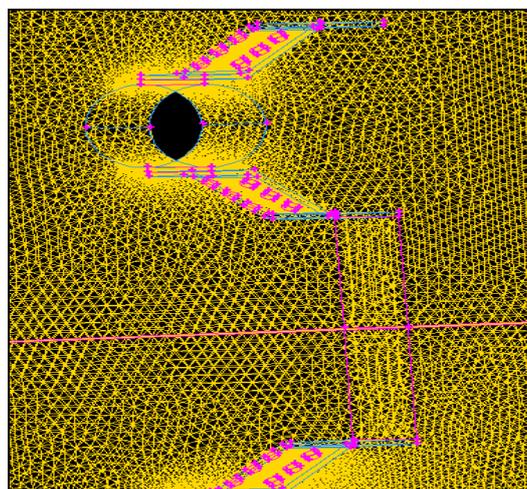


Figure 6. Mesh of Dummy runner with Block plate

3.2.Boundary Conditions and Continuum

Natural Gas as combustion fuel is injected out through the active runner gas pipe and this pipe inlet is selected as ‘Mass flow Inlet’. The fuel injection holes in the gas pipe is selected as ‘Interior’. The Gas turbine Exhaust flowing around the natural gas burners is selected as ‘Velocity Inlet’ at the HRSG duct model inlet. All the area surrounding the representative HRSG duct model comprising the active runners, dummy runners and block plate are selected as ‘Symmetry’. Symmetry type of condition is used for taking values of properties just adjacent to the solution domain as values at the nearest node just inside the domain thereby the model mesh size is reduced by not requiring to simulate for total cross section. The runner pipe surfaces, the flame stabilizer surfaces and the block plate surfaces are selected as ‘Wall’ which acts as no participation medium in the flow model. The continuum inside the active runner gas pipe is given as gas for modeling Natural Gas combustion. The continuum inside the HRSG chamber is given as Air for modeling the TEG oxygen for combustion.

IV. Computational Fluid Dynamic analysis in FLUENT

The processing of the model is done in Ansys FLUENT [6-7]. The Fluent processor divides the processing to pre-processing and post-processing and details on the same are elaborated below.

4.1.Pre-Processing of the model

The solver mainly utilizes the Navier-Stokes equations which is the basic governing equations for a viscous, heat conducting fluid. It is a vector equation obtained by applying Newton's Law of Motion to a fluid element and is also called the momentum equation. It is supplemented by the mass conservation equation, also called continuity equation and the energy equation. Usually, the term Navier-Stokes equations is used to refer to all of these equations. The following are the details on models selected for combustion flame study. Energy equation for the model is activated to model the fluid flow with along with the associated thermal properties. Further, k-ε – 2 equation model is used to capture the turbulence in natural gas and turbine exhaust gas flow patterns. To capture the combustion of methane in natural gas, species transport is modeled using Eddy-dissipation model.

The Eddy-dissipation model [6] captures the Turbulence-Chemistry interaction for the volumetric reactions. Most fuels are fast burning and the overall rate of reaction is controlled by turbulence mixing. In the non-premixed flames, turbulence slowly mixes the fuel and oxidizer into the reaction zones where they burn quickly. In premixed flames the turbulence slowly mixes cold reactants and hot products into the reaction zones where reaction occurs rapidly. In such cases the combustion is said to be mixing-limited, and the complex and often unknown chemical kinetics can be safely neglected. In this model, the chemical reaction is governed by large eddy mixing time scale. Combustion initiates whenever there is turbulence present in the flow. It does not need an ignition source to initiate the combustion. As the combustion of methane and ethane is non-premixed, the chemical species will burn at the moment they enter in the computation model. The model accommodates inlet diffusion and the diffusion energy source by using the stoichiometric chemical coefficients and rate exponents of methane and ethane reactions with oxygen as indicated in equations (1) and (2). The material and fluids are governed by methane-air and ethane-air mixture in case of Natural gas and in case of Turbine Exhaust Gas, it is air with molecular composition and fluid properties of flue gas. The boundary conditions of Natural gas and TEG are as indicated in Table 3.

Table 3. Boundary Conditions

Fluid	Boundary condition	Value	Temperature
Natural gas (NG)	Mass flow rate	0.002685 kg/s	300 K
Turbine gas Exhaust	Velocity	3.46 m/s	648 K

The mass flow of NG indicated is for the representative portion of the model. For the total duct burner cross section, by virtue of the symmetry boundary condition, the total mass flow rate of natural gas being modeled in combustion is 1.6 kg/s. Solution method for the model follows an iterative procedure where the pressure-velocity coupling of the Navier-Stokes equation is done by Semi-Implicit (SIMPLE) algorithm. The spatial discretization for Gradient and Pressure are Green-Gauss cell based and Standard respectively. For the other parameters namely momentum, turbulent kinetic energy, turbulent dissipation rate, Energy and species of methane, ethane, oxygen, carbon-di-oxide, water vapor and nitrogen, first order upwind is used.

4.2.Post-Processing and Inferences

Two configurations of models are iterated separately in FLUENT and contour plots are compared. For the converged solution of Case-1, the contours of methane species, oxygen species, temperature and velocity are as displayed in Figure7.,Figure 9., Figure 11. andFigure 13., respectively. For the converged solution of Case-2, the contours of methane species, oxygen species, temperature and velocity are as displayed in Figure8.,Figure 10., Figure 12., and Figure 14 respectively.

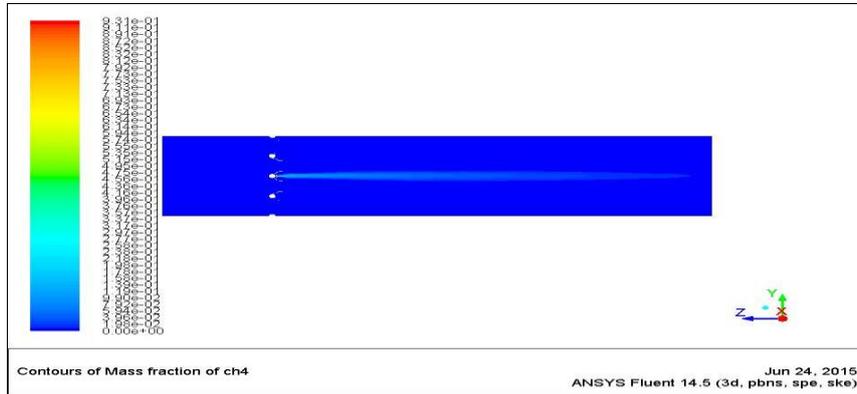


Figure 7. Methane Species Contour of Configuration-1

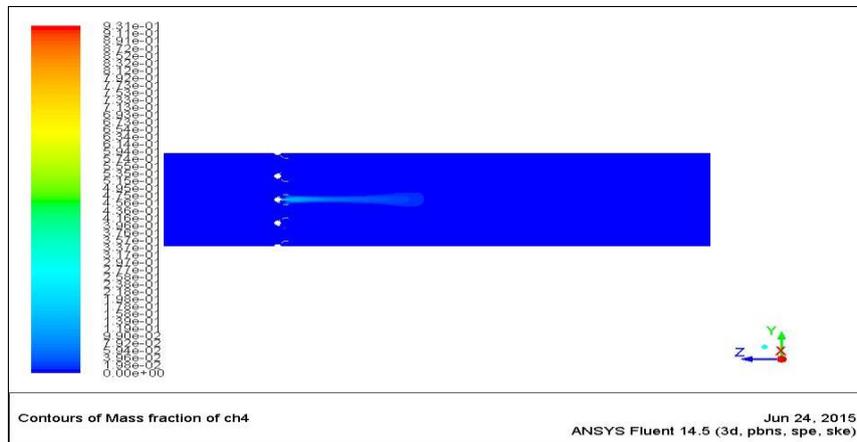


Figure 8. Methane Species Contour of Configuration-2

From Figure7., it is seen that in case of Configuration-1, the methane species move through the entire length of HRSG without participating entirely in combustion. Whereas, from Figure8., it is seen that in case of Configuration-2, the methane species actively participate in combustion and get reacted near the runner-front itself.

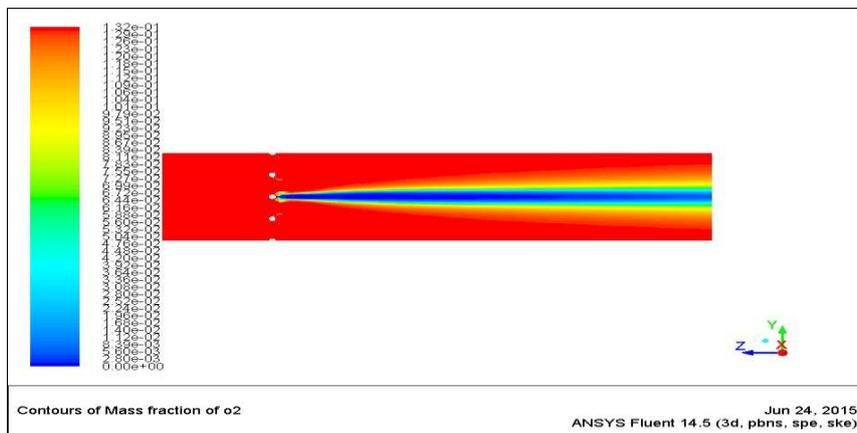


Figure9. Oxygen Species Contour of Configuration-1

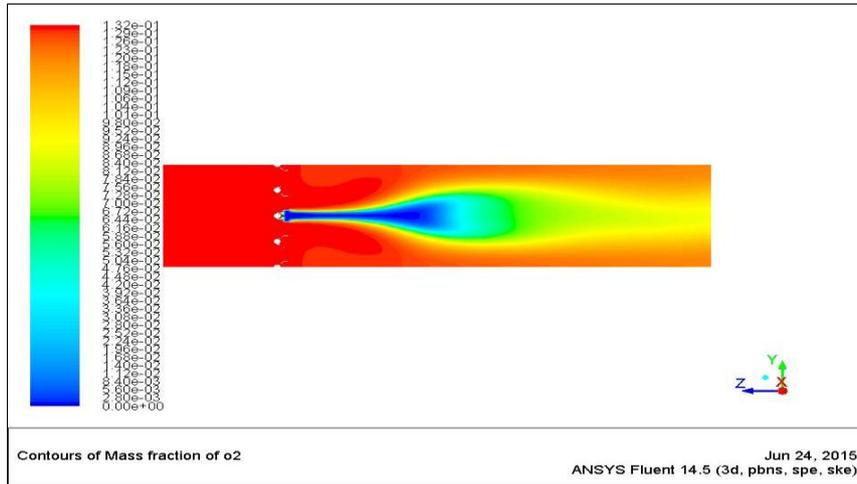


Figure 10. Oxygen Species Contour of Configuration-2

For Configuration-1, as it can be seen in Figure9., the higher concentration of oxygen species escape through the gaps in dummy runners. Whereas for Configuration-2, as seen in Figure 10., where the higher concentration of oxygen species is re-directed by the block plates in dummy runners to the vicinity of flame.

Though the combustion of ethane is also modeled, the contours of ethane species are not compared. Being only 1.29% of the total natural gas composition, the dissipation rate of ethane is very meagre, that the contours do not give significant difference on the overall combustion dynamics.

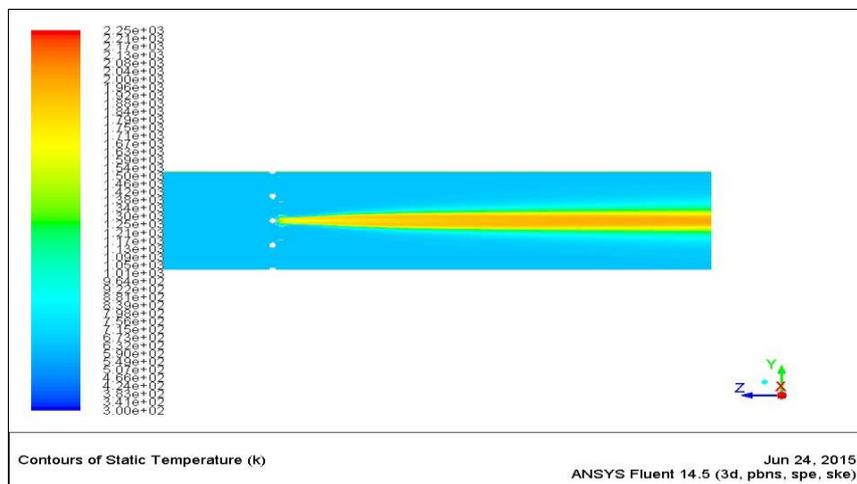


Figure11. Temperature Contour of Configuration-1

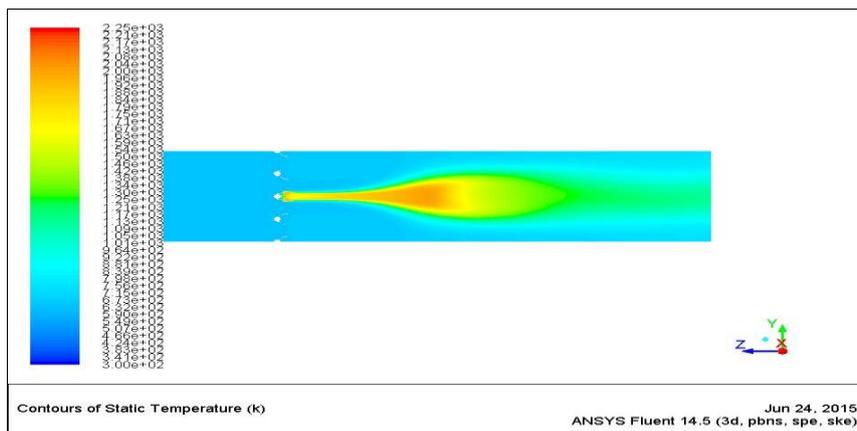


Figure 12. Temperature Contour of Configuration-2

In configuration-1, since the methane and oxygen species do not come in contact entirely, the resultant temperature profile in Figure 11., is a patch of high heat zone indicating that the reaction of methane and oxygen are never complete. Whereas in configuration-2, since the methane and oxygen species come in significant contact near the burner, the resultant temperature profile in Figure 12., is flame shaped comprising of high heat zone indicating that the reaction of methane and oxygen yields a complete combustion.

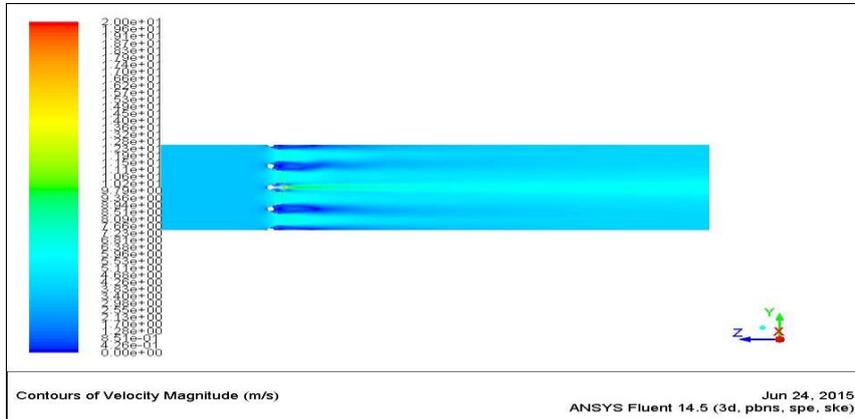


Figure13. Velocity Contour of Configuration-1

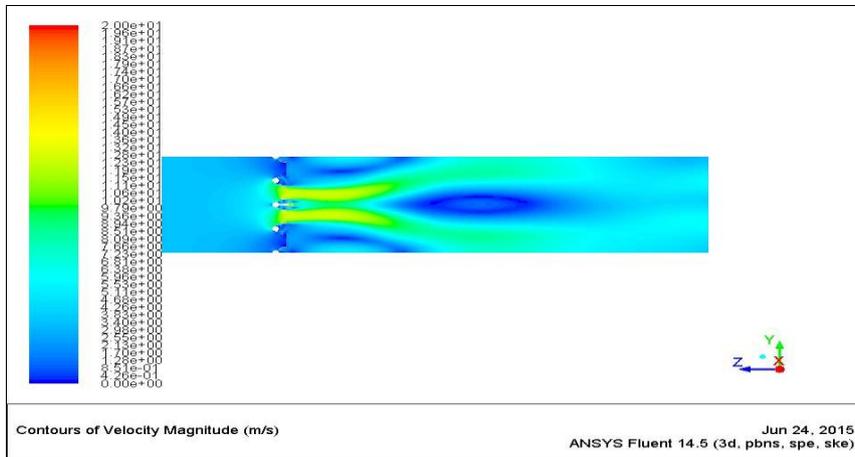


Figure14. Velocity Contour of Configuration-2

In configuration-1, the oxygen in TEG is carried away in the dummy runner gaps as seen in the TEG flow contour in Figure 13. Whereas in configuration-2, the oxygen in TEG is diverted towards the active runners by means of block plates as seen in the TEG flow contour in Figure 14.

Further, the vector plots of velocity through the flame stabilizers of active runners are taken for comparison, to understand the flow patterns of TEG near the flame. Figure 15. & Figure 16. are the respective vector plots of Case-1 and Case-2.

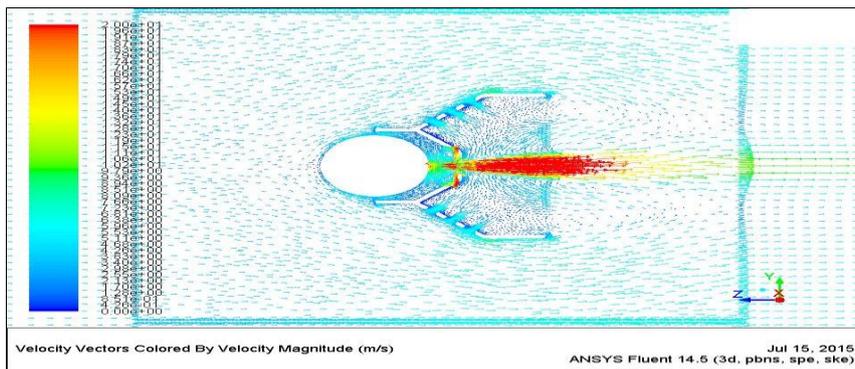


Figure 15. Velocity Vector of Configuration-1

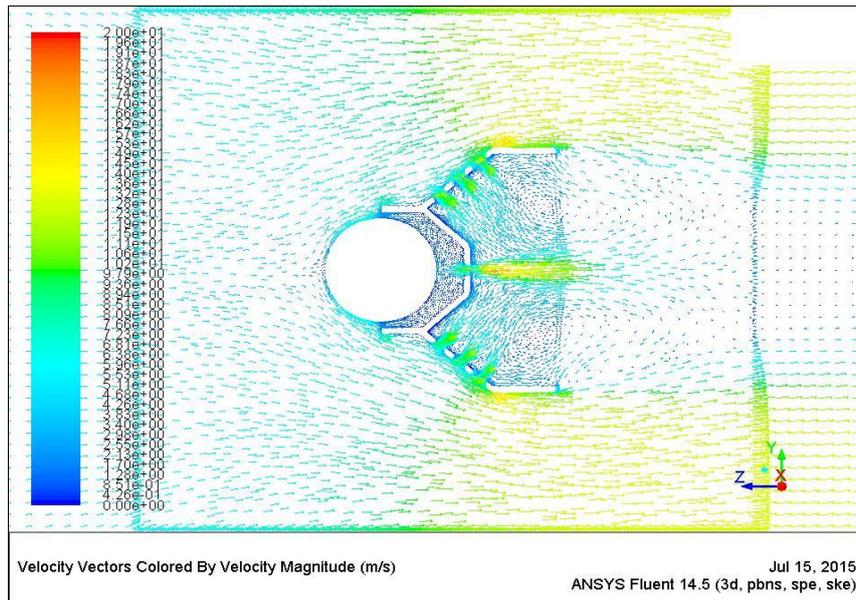


Figure16. Velocity Vector of Configuration-2

From the velocity vector plot in Figure 15., it can be seen that the TEG velocity near the flame front is very low and so the flame stability is very poor for configuration-1. Whereas from the velocity vector plot in Figure 16., it can be seen that the TEG velocity near the flame front is relatively higher and so the flame stability is greatly improved for configuration-2.

V. Conclusion

Hence it can be concluded that the block plates fixed to the flame stabilizers in between the dummy runners and the active runners give great flame stability for the combustion of natural gas. This stable complete combustion in the active gas runners achieved by the new block plates will help in improving the quality of combustion of duct burners in higher capacity HRSGs used in tandem with advanced class Gas Turbines behind Fr. 6FA. By way of complete burning of the hydrocarbons in natural gas, the emissions from incomplete combustion will go down and sustained heat output will be obtained enhancing the HRSG steam generation.

VI. Acknowledgement

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