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Numerical combustion of aluminum nano particles in gas turbine engine

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ABSTRACT

Scarcity of fossil fuel resources and the pollution caused by the carbon fuels increases the necessity for an alternative fuel in recent years. Metal powders used as a fuel additive to accelerate the combustion of solid rocket motors. In this article a numerical study is conducted on a CAN type combustion chamber of a gas turbine engine with and without casing, which uses aluminum aerosol (Aluminum Nano-particle mixed with air) as a fuel. A 3-D computational flow domain is modeled in CAD and the combustion inside the chamber is simulated using CFD. The combustion flow is solved using RANS k- Ɛ turbulence model and the species transport equations are used for modeling chemical reaction during combustion. The aluminum (Al) Nano particle in the fuel stream reacts with oxygen (O_2) inside the combustion chamber and releases enormous heat, which increases the combustion efficiency of the gas turbine engine. Byproduct of combustion contains only aluminum oxide and there is no carbon dioxide, carbon monoxide and other polluting gases, which is mainly due to the absence of carbon and other impurities in the fuel. Even after the reduction of greenhouse gases, still NO_x is produced at high temperature. The simulation result shows very high temperature inside the chamber during combustion, which could possibly damage combustion chamber and turbine. The temperature near the wall and the outlet are diluted by increasing the mass flow rate of air in primary, secondary and tertiary inlet of combustion chamber without casing.

KEY WORDS: Metal fuel, Aluminum Nano particles, Aluminum aerosol, gas turbine engine, can combustion chamber, species transport, Aluminum oxide.

1. INTRODUCTION

Both industrial and aircraft gas turbine engines use hydrocarbon fuels. Usage of fossil fuel leads to inevitable shortage of fuel resources due to over consumption, the atmosphere gets polluted by the combustion byproducts such as CO, CO_2, NO_X etc..., Therefore need for an alternative fuel is also inevitable. These alternative fuels should be eco-friendly and renewable resources, which could be recycled and used again and again. Gupta and Rehman (2010), reviewed bio-fuels such as bio-diesel, bio-ethanol, Vegetable oil, pyrolysis oil, Jatropha oil, and hydrogen can be used as fuel in gas turbine engine and recommended the suitability and modifications of existing systems. Cavarzere (2014), have conducted experiment on micro gas turbine fed by straight vegetable oil and blend of diesel with vegetable oil. Rehman and Phalke (2011), has been reported the combustion performance, feasibility and emission characteristics of diesel fuel blended with Jatropha. Mendez (2014), has conducted a comparative study for pure Jet A, butanol and blended butanol, the result shows much fewer pollutants for butanol and blended butanol comparisons to Jet A. Krieger (2015), has controlled the pollution caused by the gas turbine engine fed with Oxy-fuel, using carbon capture storage system. Liu (2012), numerically studied the thermodynamics and combustion Characteristics of Oxy fuel combustion, flame is stable and emission of an un brunt intermediate is low for certain range of oxygen/diluents ratio. Kutne (2011), studied reliability of Oxy fuel combustion experimentally, using methane as fuel in model gas turbine combustor.

Metal fuels are one among the alternative fuel resources, which is used as additives in some liquid fuels and solid fuels to accelerate the combustion and to reduce the emission. Especially aluminum powders are used as additive in solid propellants. Yanan (2011), investigated micro explosion behavior of micro and nano Al particles in fuel droplets. Sundram (2016), proposed a general theory of ignition for nano and micro Al particles. Escot (2007), experimentally studied ignition and burning time of Al particles coated and uncoated with nickel. Washburn (2010), investigated the effect of oxidizer concentration, pressure and particle diameter of al particles. Sundaram and Yang (2014), reported combustion characteristics of micro al particles with water and hydrogen peroxide. Javed (2014), show accelerated combustion while using aluminum Nano powders with kerosene than pure kerosene. Rai and Park studied the oxidation mechanism of nano al particles. Auman (1995), were found the activation energy and oxidation behavior of ultra-fine Al particles. Wu (2010), were conducted an experiment to determine the relation between al particle diameter with explosion pressure, rate of pressure rise and ignition energy.

Huang (2009), theoretically studied the burning characteristics, equivalence ratio, particle size and chemical kinetics. Sundaram and Yang (2014), studied flame propagation; temperature distribution and burning rate for aluminum Nano particles mixed with ice (ALICE) both theoretically and experimentally. In gas turbine engine fuels such as jet-A, jet-B and aviation gas are used. Using solid fuels in gas turbine engine pose challenge to control the fuel flow, leads to uncontrollable combustion. In this work a study has been conducted on can type gas turbine engine using Aluminum Nano powder as fuel. The Aluminum Nano powder is mixed with air to control the fuel flow rate of combustion.

Problem definitions: Aluminum particles are used as fuel additives or catalyst to accelerate the combustion of solid propellant in solid rocket motor. Aluminum has the potential to be used as a fuel in gas turbine engine. Even if it is used as a fuel in gas turbines, controlling the fuel flow rate to control the combustion will be difficult because of it solid form. But controlling the aluminum aerosol (Aluminum Nano particle mixed with air) will be easy. The fine mixture of Aluminum Nano particle with air can be used as fuel. Generally Aluminum does not react with air in room temperature due to oxide layer on the top of aluminum; it requires high temperature to react with air. When aluminum heated with air at high temperature nearly 2350k, the aluminum oxide layer on the top of the aluminum gets melt and reacts with oxygen produce enormous amount of heat energy. The size of aluminum particle get reduces from micro to Nano the reacting temperature also gets reduced from 2350k to 900k. This Aluminum Nano particle can react with oxygen at temperature lower than 900k, therefore Nano particles ignited by spark. Subsequently, in this numerical simulation the Aluminum Nano particles are mixed with air in the mass ratio of 75:25 respectively. This mixture is used as fuel in can type combustion chamber.

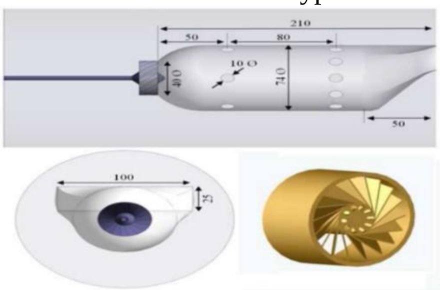

Figure.1. Geometry of the combustion chamber

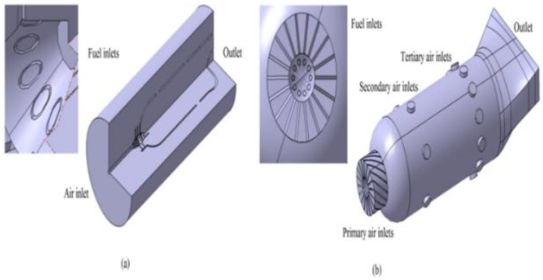

Figure.2. Flow domains with and without casing

In this numerical simulation there are two flow domains were modeled as per the dimension shown in fig.1. and explained in detail. A cylindrical combustion chamber has swirler at front and rectangular nozzle at back. The swirler composed of 18 blades twisted at 45^0 for flame stabilization. The chamber has two rows of dilution holes having diameter of 10mm each. In first row there are 6 dilution holes and in second row there are 12 dilution holes. The cylindrical portion of chamber has 74mm in diameter and end with rectangular nozzle of 100mm width and 25mm height. These models were modeled with and without casing as shown in Fig.2.

Numerical modeling: The flow domain of the combustion chamber and casing is modeled in CAD as per the dimension and the description given above. The combustion is simulated in CFD which is based on finite volume method. Combustion process consist of turbulence flow properties to ensure the right mixture of air with fuel and combustion phenomenon such as mass fraction, reaction etc..., to make sure proper complete combustion.

In this simulation the turbulence flow is modeled using Reynolds Average Navier Stroke k- Ɛ turbulence model, in order to obtain proper turbulence of airflow to mix with fuel. The approach which is used in here is most economic for computing complex turbulence flows such as combustion. Especially the RNG K- Ɛ turbulence model in RANS is commonly used for swirling flows and accuracy is enhanced. In this simulation swirler is used to produce the swirling flow for flame stabilization, so the RNG K - Ɛ turbulence model is appropriate model for this simulation. The RNG K - Ɛ transport equations are given by Eq. 1&2.

$$\frac{\partial}{\partial t}(\rho K) + \frac{\partial}{\partial x_j}(\rho K u_j) = \frac{\partial}{\partial x_j}\left[\sigma_k \mu_{eff} \frac{\partial k}{\partial x_j}\right] + G_K + G_b - \rho\varepsilon - Y_M + S_K \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \mathcal{E}) + \frac{\partial}{\partial x_j}(\rho \mathcal{E} u_j) = \frac{\partial}{\partial x_j}\left[\sigma_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_K + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\mathcal{E}^2}{k} - R_\varepsilon + S_\varepsilon \quad (2)$$

In these equations K and Ɛ represents turbulent kinetic energy and dissipation rate respectively, G_k and G_b indicates the generation of kinetic energy caused by velocity gradient and buoyancy, S_ε and S_K are user define source terms. Y_M represents the contribution of variable dilatation in compressible turbulence to the overall dissipation rate. σ_k and σ_ε are prandtl number for K and Ɛ.

Combustion is a chemical process between two or more reactants; as a result, amount of heat energy is released along with by products. In order to obtain proper complete combustion the chemical species and their reactions along with their combustion phenomenon must be defined. The species transport is used to model the mixing, transport and combustion reaction between aluminum nano particles with air. Eddy dissipation turbulence - chemistry interaction model is used in this volumetric chemical reaction. The transport equation for species transport model is given by Eq. 3.

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla.(\rho \vec{v} Y_i) = -\nabla.\vec{J_i} + R_i + S_i \quad (3)$$

In the above equation Y_i shows the local mass fraction each species, $R_i$is the net rate of production of species i by chemical reaction, S_i is the rate of creation by addition from the dispersed phase.

Chemical Reaction Mechanisms: An endothermic reaction takes place between aluminum nano particle and air. These two species comes to contact at temperature nearly 900k combustion take place according to the following reaction equation 4. The materials are defined according to the table 1.

$$4Al + 3O_2 \Delta H^{= -1675.7\ KJ/mol} \longrightarrow 2Al_2O_3 \quad (4)$$

As show in the chemical reaction the four moles of aluminum nano particles react with three moles of diatomic oxygen present in air form two moles of aluminum oxide or also known as alumina. During this reaction change in enthalpy (ΔH) is -1675.7 KJ/ mol; the negative sign indicates the heat energy is released.

Table.1. Material properties

Name	Aluminum (Al)	Aluminum oxide (Al_2O_3)
Density (kg/m^3)	2700	3950
Specific heat (J/kg k)	904	880
Thermal conductivity (W/m k)	235	30
Molecular weight (kg/kmol)	26.98	101.96
Standard Enthalpy (J/kmol)	0	-1675.7 e6
Standard Entropy (J/kmol k)	28300	50920

Table.2. Boundary condition for the model with casing

	Oxidizer		Fuel Mixture		
	O_2	N_2	Al	O_2	N_2
Mass flow rate (kg/s)	0.085		0.00217		
Temperature (k)	300		300		
Turbulence intensity (%)	10		5		
Turbulence length (m)	0.01		0.001		
Volumetric fraction	0.21	0.79	0.75	0.1975	0.0525

Table.3. Boundary conditions for the model without casing

		Oxidizer		Fuel Mixture		
		O_2	N_2	Al	O_2	N_2
Mass flow rate (kg/s)	Primary air inlets	0.051		0.00217		
	Secondary air inlets	0.017				
	Tertiary air inlets	0.017				
Temperature (k)		300		300		
Turbulence intensity (%)		10		5		
Turbulence length (m)		0.01		0.001		
Volumetric fraction		0.21	0.79	0.75	0.1975	0.0525

The boundary condition of the system should reflect the real time condition. It is assume that the simulation of combustion taking place in atmospheric condition. Using some external source the air is driven in to the combustion chamber through air inlet on the casing and mixture fuel is then injected to the combustion chamber through fuel holes according to the condition given by the table.2. For the model without casing, total air mass flow rate is divided in 60%, 20%, 20% for Primary air inlets, Secondary air inlets and Tertiary air inlets respectively. The fuel mixture is then injected through fuel holes according to the condition given in table.3.

3. RESULTS AND DISCUSSION

The reaction begins when fuel enters the combustion chamber through fuel holes on the conical hub, as shown in fig.3. In the beginning fuel react with air enters through swirler. The remaining air enters through the secondary and tertiary dilution holes to complete combustion and to reduce chamber temperature. The contour explains the temperature variation on the chamber. Temperature near the core is about 5000k in both models. Temperature near the wall and outlet is very high nearly 4000k as shown in fig.3(a), which could melt the combustion chamber and turbine blades. In order to prevent the combustion chamber and turbine blade from melting, the temperature must be reduced. This is achieved by increasing the air mass flow rate through secondary and tertiary inlets.

The model without casing shows very high temperature near the core and moderate temperature near the wall and the outlet. As discussed above the air mass flow rate is increased in the model without casing, so ultimately the temperature gets reduced as shown in fig.3(b).

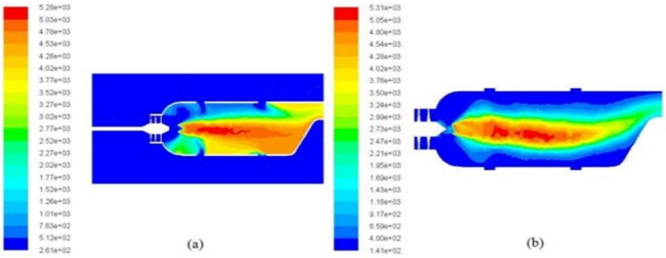

Figure.3. Combustion temperature contour

During the combustion of hydrocarbon fuel pollutant such as co, co_2, and No_x are formed. In this combustion due to the absence of carbon and other impurities only No_x will form at high temperature. The following contours show the mass fraction of No_x formed inside the chambers. Model with casing shows mass fraction of 0.0867, while the model without casing shows 0.13. The mass fraction of model with casing is lower than the model without casing.

The dilution of temperature is achieved by increasing the mass flow rate of air, the increase in air mass flow in the model without casing produce little higher mass fraction of No_x when compare to the model with casing as shown in fig.4.

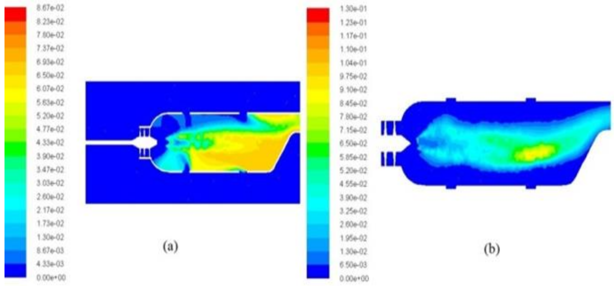

Figure.4. Mass fraction contour of No_x

4. CONCLUSIONS

Numerical combustion analysis of Aluminum Nano particle mixed with air releases intense heat energy. Usage of Aluminum Nano particles leads to high turbine inlet temperature and there by thermal efficiency of combustion is increased. The formation of pollutants such co, co_2, so_x and other un burnt hydrocarbons are reduced due to the absence of carbon and other impurities on the fuel. The formation of No_x is increased significantly as a result of high temperature.

Very high temperature inside the chamber leads to damage of combustion chamber and turbine blades. The temperature can be reduce by increasing airflow inside the chamber, large rate of air flow at high temperature inside the combustion chamber causes further increment in No_x. The reduction of No_x and high turbine inlet temperature will be focused on further works.

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