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Combustion and Emissions Performance of Syngas Fuels Derived from Palm Kernel Shell and Polyethylene (PE) Waste via Catalytic Steam Gasification

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***Abstract*—**Computational fluid dynamics analysis of the burning of syngas fuels derived from biomass and plastic solid waste mixture through gasification process is presented in this paper. The syngas fuel is burned in gas turbine can combustor. Gas turbine can combustor with swirl is designed to burn the fuel efficiently and reduce the emissions. The main objective is to test the impact of the alternative syngas fuel compositions and lower heating value on the combustion performance and emissions. The syngas fuel is produced by blending palm kernel shell (PKS) with polyethylene (PE) waste via catalytic steam gasification (fluidized bed reactor). High hydrogen content syngas fuel was obtained by mixing 30% PE waste with PKS. The syngas composition obtained through the gasification process is 76.2% H2, 8.53% CO, 4.39% CO2 and 10.90% CH4. The lower heating value of the syngas fuel is LHV = 15.98 MJ/m^3. Three fuels were tested in this study natural gas (100%CH4), syngas fuel and pure hydrogen (100% H_2). The power from the combustor was kept constant for all the fuels tested in this study. The effect of syngas fuel composition and lower heating value on the flame shape, gas temperature, mass of carbon dioxide (CO_2) and nitrogen oxides (NO_X) per unit of energy generation is presented in this paper. The results show an increase of the peak flame temperature and NO mass fractions for the syngas and hydrogen fuels compared to natural gas fuel combustion. Lower average CO2 emissions at the exit of the combustor are obtained for the syngas compared to the natural gas fuel.

***Keywords*—**CFD, Combustion, Emissions, Gas Turbine Combustor, Gasification, Solid Waste, Syngas and Waste to Energy.

I. Introduction

GAS turbines are designed primarily to be fueled with natural gas (consisting primarily of methane) and supplying them with alternative fuels such as syngas (fuel gas from biomass, coal and waste gasification) and biogas (renewable natural gas produced from anaerobic digester) presents certain challenges that must be addressed. How can we burn efficiently renewable and alternative fuels (syngas and biogas fuel) with different chemical compositions and heating values in gas turbine combustors designed for natural gas? The lower heating values of alternatives fuels such as syngas and biogas are much lower than heating value of natural gas. The natural gas is made mainly of methane (CH4), syngas fuel contains methane (CH4), carbon dioxide (CO2), carbon monoxide (CO), hydrogen (H2), nitrogen (N2) and water (H2O), and biogas contains mainly methane (CH4) and carbon dioxide (CO2). In order to meet these challenges, we need to understand the physical and chemical processes of syngas and biogas combustion. Information regarding flame shape, flame speed, gas temperatures and pollutant emissions such as NO_X and CO_2 for a range of alternative fuels compositions and heating values are needed for the design of gas turbine combustors.

Several studies can be found in the literature on syngas fuel combustion. Giles et al. [1] and Ghenai et al [2] performed a numerical investigation on the effects of syngas composition and diluents on the structure and emission characteristics of syngas diffusion flame. Lean premixed combustion of hydrogen–syngas/methane fuel mixtures was investigated experimentally by [3]. Experimental study on the fundamental impact of firing syngas in gas turbines was performed by [4]. The results show that volume fraction of hydrogen content in syngas fuel significantly impact the life of hot sections as a result of higher flame temperature for hydrogen rich fuels and also the moisture content of combustion products. The challenges of fuel diversity while maintaining superior environmental performance of gas turbine engines was addressed by [5]. They reviewed the combustion design flexibility that allows the use of a broad spectrum of gas and liquid fuel including emerging synthetic choices. Gases include ultra-low heating value process gas, syngas, ultra-high hydrogen or higher heating capability fuels. The integration of heavy-duty gas turbine technology with synthetic fuel gas processes using low-value feed stocks in global power generation marketplace was covered by [6]. In this paper they summarized the experience gained from several syngas projects and lessons learned that continue to foster cost reductions and improve the operational reliability of gas turbine. They concluded that further improvements in system performance and plant design are needed in the future.

Syngas are renewable gaseous fuel derived from gasification of Biomass and solid waste. The syngas produced can be burned and used for different applications: (1) electricity generation, (2) heat and combined heat and power generation CHP, and (3) Transportation: internal combustion engines. The benefits of the using syngas are: (1) increase energy security: syngas offsets non-renewable resources (coal,

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oil, NG), (2) great potential for the production of syngas using a renewable energy sources, and (3) reduce emissions.

This study focus on the combustion performance and emissions of syngas fuels derived from Plasma gasification. The syngas are produced using plasma gasification of biomass and solid waste. The gasification is a process producing gas composed mostly of hydrogen and carbon monoxide. Plasma gasification can be used to control the produced syngas composition and lower heating value of the syngas by supplying the external energy for material gasification. The plasma gasification will also help to reduce the unwanted contaminant like tar, the carbon dioxide CO_2, methane CH_4 and higher hydrocarbon. High concentrations of hydrogen and carbon monoxides, and low concentrations of methane can be obtained for the syngas fuels using plasma gasification. The design of combustion systems using alternative fuels such as syngas fuel can take advantage of CFD analysis to optimize the efficiency of the combustion system with respect to the limitations of pollutants emission. The aim of this work is to analyze the fundamental impacts of firing syngas fuels in gas turbine combustor and predict the changes in the firing temperature and emissions with respect to natural gas or methane combustion.

II. Governing Equations

The mathematical equations describing the natural gas and syngas combustion are based on the equations of conservation of mass, momentum, energy, and supplementary equations for the turbulence, combustion and radiation. For turbulence modeling, the standard k-ε turbulence model is used in this study. The equations for the turbulent kinetic energy k and the dissipation rate of the turbulent kinetic energy ε are solved. For non-premixed (diffusion flame) combustion modeling, the mixture fraction/PDF model is used. The time averaged gas phase equations for steady turbulent non premixed combustion [2] are:

Continuity Equation

$$\frac{\partial \overline{\rho u_i}}{\partial x_i} = 0 \tag{1}$$

Momentum Equation

$$\frac{\partial \left(\overline{\rho u_i u_j}\right)}{\partial x_j} = -\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial \left(\overline{t_{ij}} + \overline{\tau_{ij}}\right)}{\partial x_j} \tag{2}$$

Turbulent Kinetic Energy Equation

$$\frac{\partial \left(\overline{\rho k u_j}\right)}{\partial x_j} = \frac{\partial \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \overline{k}}{\partial x_j}\right]}{\partial x_j} + G_k - \overline{\rho \varepsilon} \tag{3}$$

where $\sigma_k = 1$ and G_k is the production of the turbulent kinetic energy.

Dissipation of the Kinetic Energy

$$\frac{\partial \left(\overline{\rho \varepsilon u_j}\right)}{\partial x_j} = C_{\varepsilon 1}\frac{\overline{\varepsilon}}{k}G_k + \frac{\partial \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \overline{\varepsilon}}{\partial x_j}\right]}{\partial x_j} - C_{\varepsilon 2}\overline{\rho}\frac{\overline{\varepsilon^2}}{k} \tag{4}$$

where $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, and $\sigma_\varepsilon = 1.3$

Mixture Fraction f

In non-premixed combustion, fuel and oxidizer enter the reaction zone in distinct streams. The PDF/mixture fraction model is used for non-premixed combustion modeling. In this approach individual species transport equations are not solved. Instead, equation for the conserved scalar (f) is solved, and individual component concentrations are derived from the predicted mixture fraction distribution.

The mixture fraction equation is given by:

$$\frac{\partial \left(\overline{\rho f u_j}\right)}{\partial x_j} = \frac{\partial \left[\left(\frac{\mu_t}{\sigma_t}\right)\frac{\partial \overline{f}}{\partial x_j}\right]}{\partial x_j} + S_m \tag{5}$$

The mixture fraction, f, can be written in terms of elemental mass fraction as

$$f = \frac{Z_k - Z_{k,O}}{Z_{k,F} - Z_{k,O}} \tag{6}$$

where Z_k is the element mass fraction of some element k. Subscripts F and O denote fuel and oxidizer inlet stream values, respectively. For the mixture fraction approach, the equilibrium chemistry PDF model is used. The equilibrium system consists of 13 species (C, CH_4, CO, CO_2, H, H_2, H_2O, N_2, NO, O, O_2, OH, HO2). The chemistry is assumed to be fast enough to achieve equilibrium.

Energy Equation

$$\frac{\partial \left(\overline{(\rho E + p)uj}\right)}{\partial x_j} = \frac{\partial \left[\left(k_{eff}\right)\frac{\partial \overline{T}}{\partial x_j} - \sum_j h_j J_j + \left(\overline{\tau}_{eff} u_j\right)\right]}{\partial x_j} + S_h \tag{7}$$

where E is the total energy ($E = h - p/\rho + v^2/2$ where h is the sensible enthalpy), k_{eff} is the effective conductivity ($k + k_t$: laminar and turbulent thermal conductivity), J_j is the diffusion flux of species j, and S_h is the term source that includes the heat of chemical reaction, radiation and any other volumetric heat sources.

Equation for the P-1 Radiation Model - Radiation Flux Equation

The P-1 radiation model is used in this study to simulate the radiation from the flame. The radiation model is based on the expansion of the radiation intensity into an orthogonal series of spherical harmonics [7], [8]. The P-1 radiation model is the simplest case of the P-N model. If only four terms in the series are used, the following equation is obtained for the radiation flux:

$$q_r = -\frac{1}{3(a+\sigma_s) - C\sigma_s}\nabla G \tag{8}$$

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where a is the absorption coefficient, σ_S is the scattering coefficient, G is the incident radiation, and C is the linear-anisotropic phase function coefficient [7], [8].

The finite volume method and the first order upwind method were used to solve the governing equations. The solution procedure for a single-mixture-fraction system was to: (1) complete the calculation of the PDF look-up tables first, (2) start the reacting flow simulation to determine the flow files and predict the spatial distribution of the mixture fraction, (3) continue the reacting flow simulation until a convergence solution was achieved, and (4) determine the corresponding values of the temperature and individual chemical species mass fractions from the look-up tables. The convergence criteria were set to 10^{-3} for the continuity, momentum, turbulent kinetic energy, dissipation rate of the turbulent kinetic energy, and the mixture fraction. For the energy and the radiation equations, the convergence criteria were set to 10^{-6}.

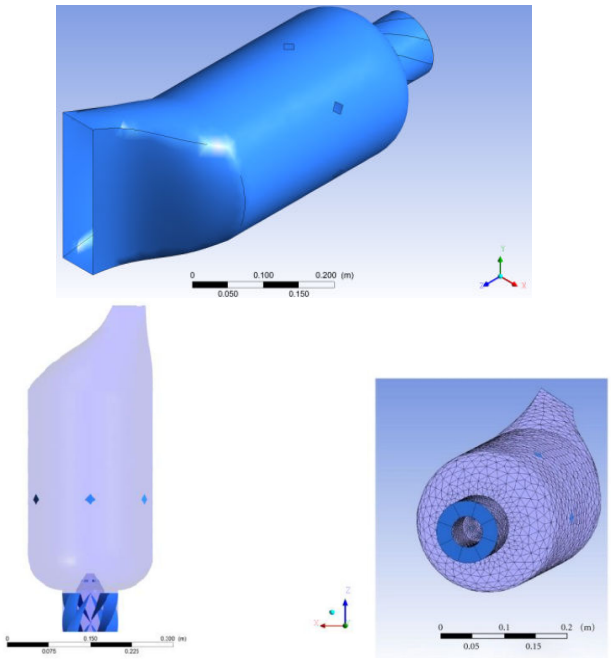


Fig. 1 Combustor Geometry Model and Mesh

TABLE I
FUEL AND AIR INJECTION CONDITIONS

Fuel and Air Injection Conditions and Combustor Power	Natural Gas	Syngas 30%PE + PKS	Hydrogen
Primary air velocity (m/s)	10	10	10
Secondary air velocity	6	6	6
Fuel velocity (m/s)	20.3	47	75.11
LHV (MJ/m^3)	37	15.98	10
Combustor Power (kW)	60	60	60

III. Swirl Can Combustor

The basic geometry of the gas turbine can combustor is shown in Fig. 1. The size of the combustor is 590 mm in the z direction, 250 mm in the y direction and 230 mm in the x direction. The primary inlet air is guided by vanes to give the air a swirling velocity component (See Fig. 1). The boundary conditions of the primary air are: the injection velocity is 10 m/s, the temperature is 300 K, the turbulence intensity is 10%, mixture fraction f = 0 and the injection diameter is 85 mm. The fuel is injected through six fuel inlets in the swirling primary air flow (near the vanes region - see Fig. 1). The boundary conditions of the fuel are: the fuel velocity or the volume flow rate (see Table I) were varied to keep the same combustor power P = 60 kW for the four fuels tested in this study (note the syngas with low lower heating value has high fuel velocity of volume rate rate), the fuel temperature is 300 K, the turbulence intensity is 10%, mixture fraction f = 1 and the injector diameter is 4.2 mm. The secondary air or dilution air is injected at 0.1 meters from the fuel injector to control the flame temperature and NOx emissions. The secondary air is injected in the combustion chamber though six side air inlets each with a diameter of 16 mm (see Fig. 1). The boundary conditions of the secondary air are: the injection velocity is 6 m/s, the temperature is 300 K, the turbulence intensity is 10%, mixture fraction f = 0 and the injection diameter is 16 mm. The can combustor outlet has a rectangular shape (see Fig. 1) with an area of 0.0150 m^2. A quality mesh was generated for the can combustor (see Fig. 1). The mesh consists of 106,651 cells or elements (74189 tetrahedra, 30489 wedges, and 1989 pyramids), 234368 faces and 31433 nodes. The grid quality was checked and the results showed a maximum cell squish of 0.94, maximum cell skewness of 0.99 and a maximum aspect ratio of 83.17.

IV. Syngas Fuel Composition and Lower Heating Value

The syngas compositions and lower heating values are shown in Table II. The syngas is produced using catalytic steam gasification [10]. Fluidized bed gasifier was used to convert the biomass (PKS: Palm Kernel Shell from palm oil) and solid waste (PE: high density polyethylene HDPE plastic waste) mixture feedstock to syngas. The proximate and ultimate analysis of biomass feedstock (PKS) are: Proximate analysis is moisture content 12% (wt), volatile matter 30.53%, fixed carbon 48.50%, and ash 8.97%; and the ultimate analysis is C = 49.23%, H = 5.04%, O = 44.94%, N = 0.74%, S = 0.05%. The density and high heating value of the PKS are 733 kg/m^3 and 24.97 MJ/kg. For the PE waste, the proximate analysis is 99.67% volatile matter and 0.33 ash; and the ultimate analysis is C = 85.71%, H = 14.29%. The density and high heating value of the PE are 1194 kg/m^3 and 45.98 MJ/kg. The feedstock was mixed with commercial Ni catalyst in the gasification process [10]. Table II shows that the syngas produced using PKS and 30% of PE feedstock mixture has high hydrogen content (76.28%) and high lower heating value (15.98 MJ/m^3). Blending PE waste with Biomass PKS favors enhancement of hydrogen production. Other techniques such as plasma gasification of biomass and solid waste can be used to produce good quality syngas fuels [9]. Plasma gasification can be used to control the produced syngas composition and lower heating value of the syngas by supplying the external energy (high energy in short time) for material gasification.

The plasma gasification will also help to reduce the unwanted contaminant like tar, the carbon dioxide CO_2, methane CH_4 and higher hydrocarbon [9].

TABLE II
FUEL COMPOSITIONS AND LOWER HEATING VALUES

Fuel Compositions and Lower Heating Value %	Natural Gas	Syngas 1 30%PE + PKS	Hydrogen
Hydrogen H_2 %	0	76.28	100
Carbon monoxide CO %	0	8.53	0
Carbon dioxide CO_2 %	0	4.39	0
Methane CH_4 %	97	10.88	0
Ethane C_2H_6 %	3	0	0
LHV (MJ/m^3)	37	15.98	10

V. RESULTS

The combustion of natural gas and syngas fuels in gas turbine can combustor is presented in this paper. The effects of the variability in the syngas fuel composition and lower heating value on the combustion performance and emission are investigated. The composition of the syngas fuels and the lower heating values are shown in Table II. The range of constituents volume fractions for the selected syngas fuel are (1) Hydrogen 76.28%, (2) carbon monoxide (CO) = 8.53%, (3) carbon dioxide (CO_2) = 4.39%, and (4) methane (CH_4) = 10.88%. The hydrogen to carbon monoxide fraction for the syngas fuel is 8.94. The lower heating value of the natural gas fuel is 2.32 times the heating values of the syngas fuel. The syngas volume flow rate of the syngas was increased by 2.32 compared to the natural gas volume flow rate to keep the same power from the combustor as shown in Table I. The contours of the gas temperature for the combustion of natural gas and syngas fuel in gas turbine can combustor are shown in Fig. 2. The combustion of natural gas fuel shows a maximum gas temperature of 2150°K. The predicted gas temperature for the natural gas fuel was compared to the adiabatic flame temperature. The theoretical flame temperature at atmospheric conditions (1 bar and 20°C) is about 2200°K. The predicted maximum temperature inside the can combustor compare well with the theoretical adiabatic flame temperature. The natural gas fuel combustion shows a peak gas temperature in the primary reaction zone. The fuel from the six injectors is first mixed in the swirling air before burning in the primary reaction zone. After the primary reaction zone, the gas temperature decreases due to the dilution of the flame with secondary air flow. Fig. 3 shows the velocity vectors and the recirculation zones in the primary reaction zone. The primary air is injected in the z direction with an initial velocity of 10 m/s. The primary air is accelerated to 20 m/s at the entrance of the combustors due to the presence of swirlers vanes [2]. Recirculation regions are produced in the fuel injection region. A good air fuel mixing is obtained in the primary reaction zone as shown in Fig. 3. This will help to burn the fuel efficiently and reduce the emissions from the combustor. Fig. 4 shows the contours (x-y plane) of the velocity swirling strength. Recirculation regions with strong swirling strength are shown at the entrance regions near the fuel injection. The contours show that the velocity swirling strength decreases downstream with the increase of the axial distance Z. The velocity swirling strength contours shows annulus region with high swirling strength in the primary reaction zone.

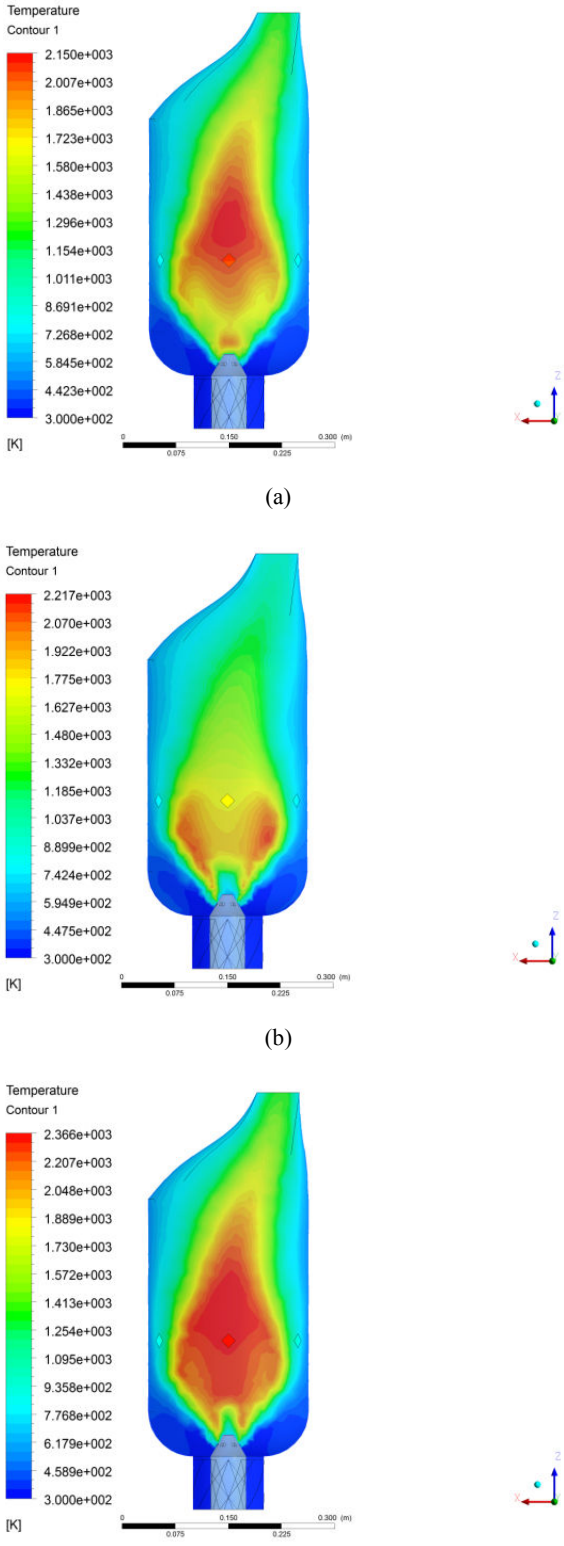


Fig. 2 Contours of Temperature (a) Natural gas, (b) Syngas (PKS+30%PE) and (c) Hydrogen

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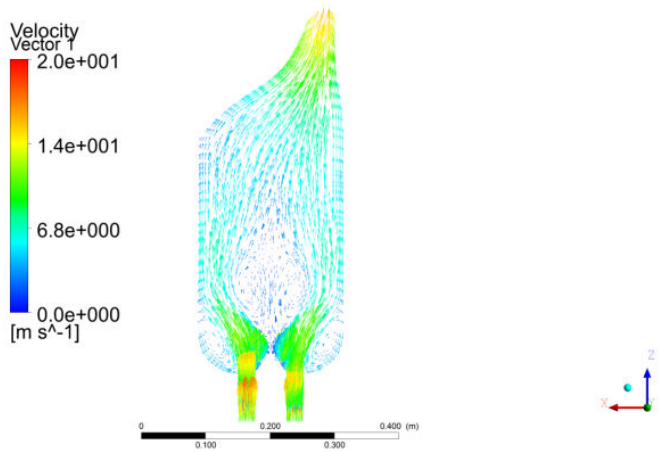


Fig. 3 Velocity Vectors colored by the velocity magnitude in the x-z plane – Combustion of natural gas

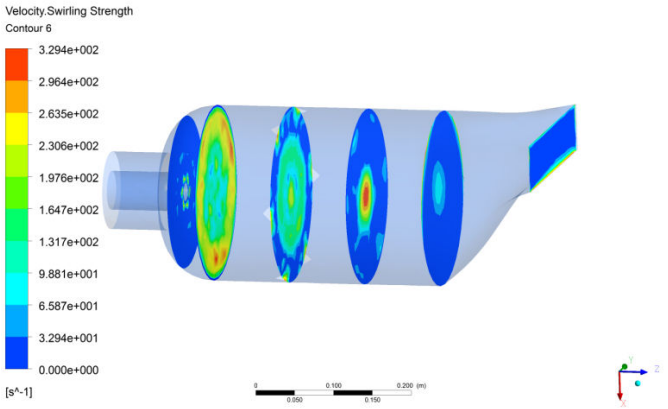
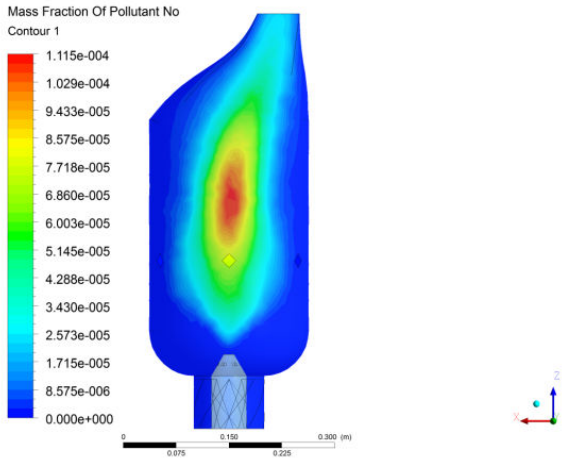


Fig. 4 Velocity Swirling Strength – Combustion of natural gas

The static temperature contours (see Fig. 2) in the x-z plane show that the gas temperature inside the can combustor increase slightly for the syngas and hydrogen fuels compared to the natural gas fuel. The maximum flame temperature increases by 3% for the syngas and 10% for the hydrogen fuels compared to the maximum flame temperature for natural gas combustion. The presence of high hydrogen fuel concentrations (H2 = 76.28% and H2/C0 = 8.94) and low carbon dioxide concentration (CO2 = 4.39%) in the syngas fuel are responsible for the slightly increase of the flame temperature. The dilution of hydrocarbon syngas fuel (H_2 and CO) with carbon dioxide (CO_2) usually reduces the flame temperature. The carbon dioxide CO_2 and other inert gas such as nitrogen N_2 in the fuel will absorb the heat from the combustion process (they are flame inhibitors) and reduce the flame temperature. The presence of carbon dioxide and nitrogen in the syngas fuel will reduce the burning velocity [8] of the flame, the burning rate and will affect the flame shape. Syngas syngas-air mixtures combustion produce lower gas temperature inside the combustor compared to natural gas fuel if the amount of hydrogen in the syngas decreases and the concentration of CO2 in the fuel increases. The gas temperature for syngas fuel combustion depends on the carbon dioxide and other inert gas volume fractions. The peak gas temperature decreases as the CO_2 volume fractions in the fuel increases and the lower heating values decreases.

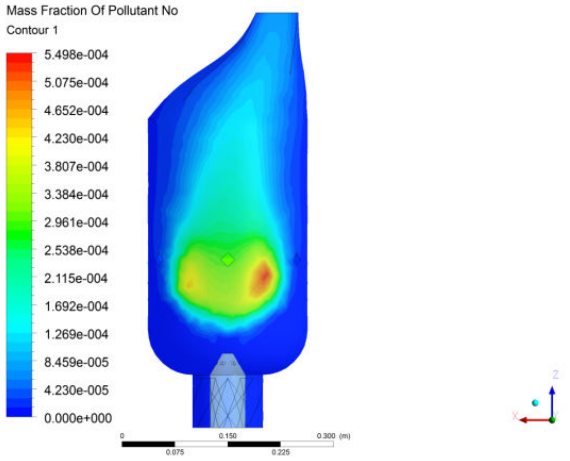
The NOx emissions from natural and syngas gas fuel combustion were also calculated in this study. The NO_X concentrations emitted from combustion systems are generally low. The NO_X chemistry has negligible influence on the predicted flow field, temperature, and major combustion product concentrations. The NO_X model used in this study was a postprocessor to the main combustion calculation. First the reacting flows are simulated without NO_X emissions until the convergence of the main combustion calculation was obtained; after that the desired NO_X models were enabled to predict the NO_X emissions. The contours of NO mass fraction inside the can combustor are shown in Fig. 5. Like the flame temperature contours, the NO mass fraction inside the combustor increases when the baseline fuel (natural gas) is replaced with syngas and hydrogen fuels. The thermal NO_X emission is function of the gas temperature. Higher is the temperature, higher is the NO_X mass fractions. The presence of high hydrogen concentrations and low concentration of non- combustible constituents in the syngas such as carbon dioxides is responsible for the increase of the flame temperature and consequently the NO mass fractions.

The effect of syngas fuel compositions and lower heating values on the combustion and emissions characteristics at the exit of the combustor was also determined in this study. The average NO mass fractions, and CO_2 mass fractions at the exit of the combustor were determined. The average NO mass fractions for the natural, syngas and hydrogen fuels at the exit of the combustor are shown in Fig. 6. Lower average NO mass fractions are obtained during natural fuel combustion. Syngas and hydrogen combustion shows higher NO mass fractions compared to natural gas fuel combustion. Fig. 7 shows the average CO2 mass fraction at the exit from the combustor. The syngas fuel derived from the gasification of palm kernel shell (PKS) with 30% polyethylene (PE) waste shows low CO_2 mass fraction at the exit of the combustor compared to natural gas fuel combustion.

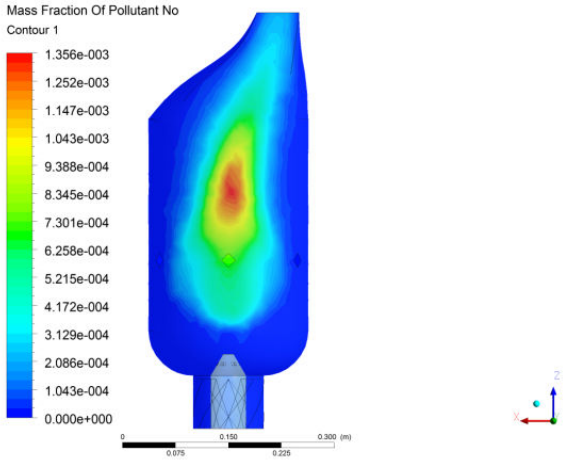


(a)

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(b)



(c)

Fig. 5 Contours of NO mass fraction inside the can combustor (a) Natural gas, (b) Syngas (PKS+30%PE) and (c) Hydrogen

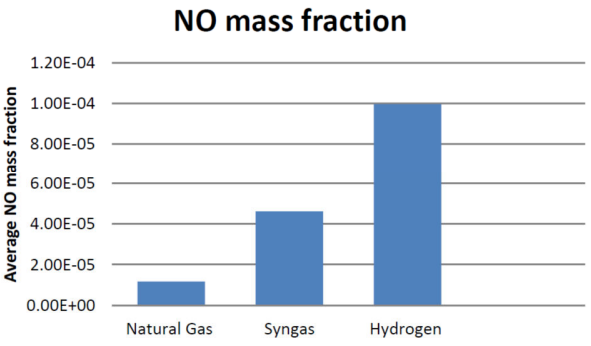


Fig. 6 Average NO mass fractions at the exit of the combustor

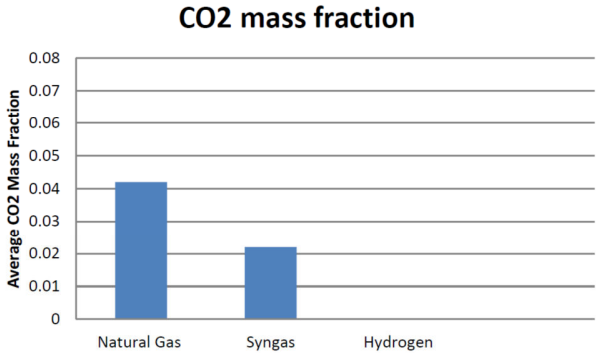


Fig. 7 Average CO_2 mass fractions at the exit of the combustor

VI. Conclusions

Three dimensional CFD analyses of natural gas, syngas and hydrogen fuels combustion in gas turbine can combustor is presented in this study. The syngas fuel is produced by blending palm kernel shell (PKS) with polyethylene (PE) waste via catalytic steam gasification (fluidized bed reactor). The syngas composition obtained through the gasification process is 76.2% H2, 8.53% CO, 4.39% CO2 and 10.90% CH4. The lower heating value of the syngas fuel is LHV = 15.98 MJ/m^3. The fuel flow rate was varied for different fuels to keep constant the power from the combustor (P = 60 kW). The k-epsilon model was used for turbulence modeling, mixture fractions/PDF model for non-premixed gas combustion, and P-1 for radiation modeling. The effect of the syngas fuel composition and lower heating value on flame shape, flame temperature, carbon dioxide (CO2), and nitrogen oxides (NOx) emissions was determined in this study:

The peak gas temperature for the syngas and hydrogen fuels increases compared to the natural fuel. The peak flame temperature for the syngas and hydrogen fuels increases respectively by 3% and 10% compared to the flame temperature of natural gas. For the syngas fuel, this temperature increase is due to the high hydrogen concentration and low carbon dioxide concentration in the fuel. The presence of high concentration of inert gas (CO_2) in the syngas fuels cools down the reaction by absorbing the energy from the combustion of hydrocarbon fuels.

The flame shape and the temperature distribution inside the can combustor depend on the H_2/CO ratio, the amount of inert gas (CO_2), and lower heating values of the syngas fuels. Shorter flame with high turbulent burning velocities and close to the fuel injection regions are obtained with syngas fuels with high hydrogen contents. The gas temperature increases with the hydrogen contents in the syngas fuels but the presence of high inert gas such as CO_2 reduces the flame temperature, the flame turbulent burning velocity, and the burning rate.

The NO mass fraction inside the combustor increases when the baseline fuel (natural gas) is replaced with syngas and hydrogen fuels. The thermal NO_X emission is function of the gas temperature. Higher is the gas temperature, higher is the NO_X mass fractions. The presence of high hydrogen concentrations and low concentration of non- combustible

constituents in the syngas such as carbon dioxides is responsible for the increase of the flame temperature and consequently the NO mass fractions.

The syngas fuel derived from the gasification of palm kernel shell (PKS) with 30% polyethylene (PE) waste shows low CO_2 mass fraction at the exit of the combustor compared to natural gas fuel combustion.

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