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Fuel-Water emulsion impact on miniature gas turbine pollutant emission

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Abstract. The innovative use of the Fuel-Water emulsion in a small gas turbine for distributed energy generation is proposed. The FWE in this situation is considered as a nonhomogeneous mix of water and fuel, where water is a dispersed phase in the continuous fuel phase with an addition of surfactants. The Fuel-Water emulsion has a great mainly due to two mechanisms: temperature reduction due to heat absorption by the water phase and enhanced homogeneity of the fuel-air mixture due to micro-explosion of the superheated water phase inside the emulsion droplet. Proposed paper presents theoretical background on Fuel-Water emulsion combustion mechanism. Finally initial results of numerical research of fuel-water emulsion injection to miniature gas turbine are presented. Theoretical predictions of NO_X pollutant emissions are compared with accuracy of the gas analyzer planned to be used during experimental research.

1 Introduction

Historically water injection into reciprocating engines was used as a mean to cool down an air/fuel mixture temperature and prevent knocking, which was the main limitation for increasing a compression ratio [1]. Modern reciprocating engines water delivery systems includes: direct water injection into the engine cylinder, water injection through the intake port, water injection into the exhaust pipe, oil-water emulsification and combustible gas humidification [2-4]. Currently water addition to reciprocating engines is used mainly for engine pollutant and noise reduction [5, 6]. The water absorbs part of the heat generated in the cylinder which reduces the flame peak temperature. As the oxides of nitrogen (NO_X) formation is exponentially dependent on the temperature [7], reduction in temperature helps to meet stringent emission regulations [8, 9].

Mechanism described above works also inside gas turbine, which can explain the popularity of this method in the case of stationary gas turbines. In case of direct water injection into combustion chamber, water is delivered directly through separate fuel nozzle circuit or through dedicated water nozzles located on combustor domeplate [10]. Water injection upstream combustor helps to atomize water by small droplets detachment from trailing edge of the swirler vanes [11]. Water or steam injection into compressor is also popular, as it provides more homogeneous water-air mixture. On the other hand it generates also some losses, because only part of the compressed air reaches combustor primary zone [12]. It has been proven that water is approx. 60% more effective than steam to achieve the same NO_X reduction levels [13].

Despite clear benefits, traditional water and steam injection systems into gas turbines have many disadvantages. It is clear that additional water/steam supply systems have to be installed, which is connected with increased capital and maintenance cost of the gas turbine. There is also high risk for hot section components corrosion. In order to prevent that a water has to purified using reverse osmosis and de-ionization phenomena. Finally, as the combustion temperature is reduced, increase in the carbon oxides (CO) and unburned hydrocarbons (UHC) is expected.

The use of Fuel-Water Emulsion (FWE) inside small gas turbines, for distributed energy generation, proposed in this article might be an interesting alternative to traditional systems of water injection. The system provides all of the benefits of the traditional water injection systems and eliminates most of the their drawbacks. The FWE is considered as a nonhomogeneous mix of water and fuel, where water is a dispersed phase in the continuous fuel phase. Most commonly FWE contains between 3% to 15% of water with about 1% to 2% of surfactant (fatty acid esters). The surfactant role in the FWE is to improve emulsion stability by forming a boundary surface around dispersed water droplets and preventing them to join back together [14]. Since fuel-water mixture is prepared in advance, therefore no separate water tanks or delivery system is required. In addition, in the FWE water droplets are surrounded by the fuel, which prevents direct contact of the hot section components with the water, thus reducing corrosion risk.

Another notable advantage of the Fuel-Water Emulsion use are puffing and micro-explosion phenomena observed in number of research [15, 16]. It has been noticed that during the temperature increase in fuel-water emulsion injected into combustion chamber, causes rapid expansion of the vapour inside the droplet. This can lead to either to partial breakup of the droplet

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caused by vapor blowing out of droplet surface called “puffing” or to total disintegration of the droplet called ”micro-explosion”. Both phenomena lead to better atomization and intensified mixing of the fuel with the air inside combustion chamber [17]. Number of studies of droplet micro-explosion show that the size and distribution of emulsion water droplets inside the parent diesel droplet has a great impact on micro-explosion [18-24].

Impact of the FWE use in the turbine engine is investigated with the use of the polish production small gas turbine “GTM-120”. The kerosene propelled gas turbine operating parameters are documented in [25, 26]. In this research paper a Fuel-Water Emulsion containing 3% of water is studied. The emulsion used in the study was developed at Warsaw University of Technology (WUT). The composition of the emulsion was precisely developed and studied. Microscope picture of the actual emulsion is shown in Figure 1. The full stability period of 24 hours of undisturbed emulsion and up to 2 weeks stability after emulsion stirring have been achieved.

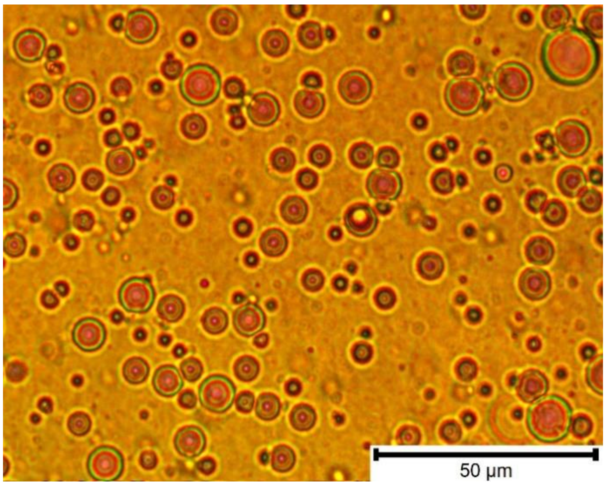

Fig. 1. Fuel-water emulsion microscope picture at 40x magnification.

The Computational Fluid Dynamics (CFD) model of reactive flow through the turbine is used in order to investigate the expected NO_X reduction levels. Finally, the comparison between numerical and baseline experimental data for the engine fueled with kerosene is discussed.

2 CFD model of reactive flow

The CFD models of the combustor chamber, fueled with standard fuel – kerosene and proposed fuel - emulsion containing 3% of water, were developed in order to find out what level of NO_X reduction is expected. This information was needed prior to experimental bench testing of the engine running on FWE to make sure that the gas analyzer accuracy allows to measure statistical difference in NO_X emissions.

The commercial CFD ANSYS Fluent code is used. Steady state engine operating conditions corresponding to 80k rpm are simulated. The geometry selected for numerical simulation consists of compressor diffuser, combustion chamber and nozzle. Tetrahedral mesh with 2.5M cells is used. Sensitivity study for the proposed mesh was performed in [27]. Boundary condition were taken from previous research [26]. The mass flow boundary condition was set at diffuser inlet. The values of mass flow for the simulated engine operating conditions were taken from experimental results [25]. The direction of air flow was determined by the solution of compressor velocity triangles for given rotational speed. Gauge pressure and total temperature at the inlet were adjusted iteratively to match experimental results for the static pressure and total temperature at diffuser outlet. The static pressure and total temperature were adjusted iteratively to match experimental results. Target mass flow and radial equilibrium pressure distribution were assumed at the test stand outlet, which was modeled with the use of pressure outlet boundary condition. The k-ε turbulence model with Scalable wall function was used. Convective heat transfer was calculated with the use of wall function. The Discrete Ordinates model was used for radiative heat transfer. Discrete Phase Model (DPM) was applied for modeling the injection, tracking and evaporation of fuel and water (only for emulsion case) droplets. Fuel-water emulsion parameters are taken directly from the microscopic study of the emulsion developed at WUT. Combustion was modeled as a non-premixed combustion model. The only difference between numeric models of kerosene combustion and emulsion combustion is water addition as separate DPM source to the combustion chamber through the fuel inlet for emulsion combustion model. The proposed emulsion combustion model aims only to account for an impact of water addition without simulating puffing or micro-explosion of the emulsion droplet. Such model is expected to provide the NO_X reduction, expected from water quenching phenomena. The obtained results are going to be compared against the actual NO_X emissions from the engine running on kerosene. That information will be used to decide if the gas analyzer accuracy is appropriate to show statistical difference of NO_X reduction between both fuels prior to running actual engine trials.

Thermal NO_X formation model was used to predict NO_X emissions from combustion chamber. It has to be stated that considered reactive flow is highly turbulent. In the highly turbulent flows significant fluctuations of the temperature and species concentration occurs. Since the relationships between temperature, species concentrations and NO_X formation rate are highly nonlinear, the time-average calculations of NO_X concentrations results in significant errors [28]. Much better results are obtained with Flamelet model which accounts for moderate chemical equilibrium. Simulation of the combustion process inside GE LM1600 gas turbine showed that Non-Premixed PDF model NO concentration relative error checks up to 80% comparing to approximately 10% when using the Flamelet model [29]. The best numerical tool for accurate NO_X formation modeling incorporated in ANSYS FLUENT is Decoupled Detailed Chemistry (DDC) models which decouples NO_X from flame calculations [28].

Authors understand that there is a significant room for numeric model of quantitative NO_X predictions improvement. However, the proposed numerical model is not going to be used directly to report quantitative results of NO_X productions. Results of both kerosene and emulsion combustion models are to be compared on "back-to-back" basis in order to find expected reduction of NO_X quantities. In addition, general conclusions about combustion with water addition are to be drawn. Future plans assumes Unsteady DDC model implementation to improve the quantitative results of NO_X concentrations towards experimental data.

Results of the numerical combustion numerical modeling are show in Figures 2-4. One can notice that in case of baseline kerosene combustion model, heat up of the kerosene liquid occurs inside the evaporating tubes (Figure 2a). Full evaporation and subsequent formation of the combustible mixture occurs at the evaporating tubes outlet. Mixture is ignited at the moment in which it mixes with hot combustion products in the combustor primary zone. On the other hand for the FEW combustion case the fuel evaporates inside evaporating tube (Figure 2b) and ignites almost immediately due to contact with hot surface of the tubes. The difference in the combustion beginning between the models can be clearly noticed on Figure 3.

The high temperature of the combustion process impacts the NO production rate and mole fraction which can be observed in Figure 4. One can easily observe that NO high concentration regions of the combustion chamber corresponds with the highest temperature area. The high NO mol fraction regions have been significantly reduced inside combustion chamber fueled with FEW (based on comparison of Figures 4a and 4b).

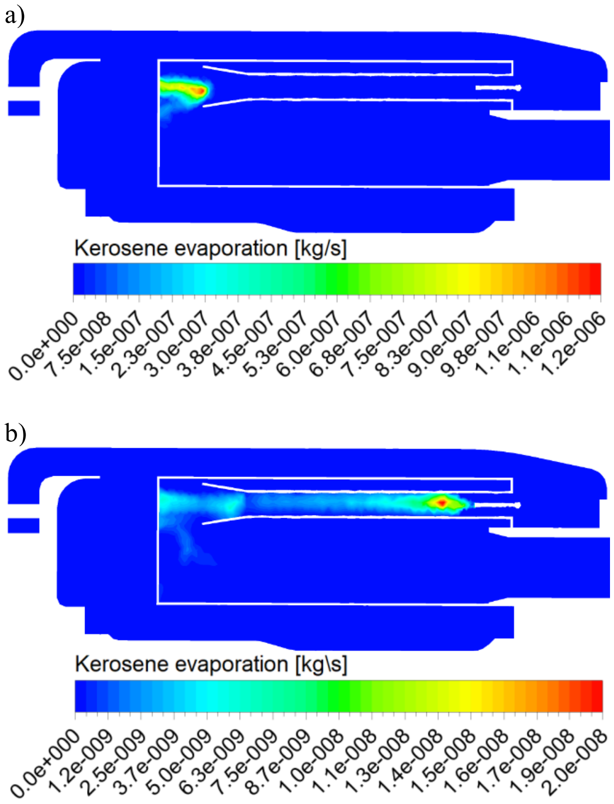

Fig. 2. Kerosene evaporation rate: a) engine running on kerosene, b) engine running on FEW.

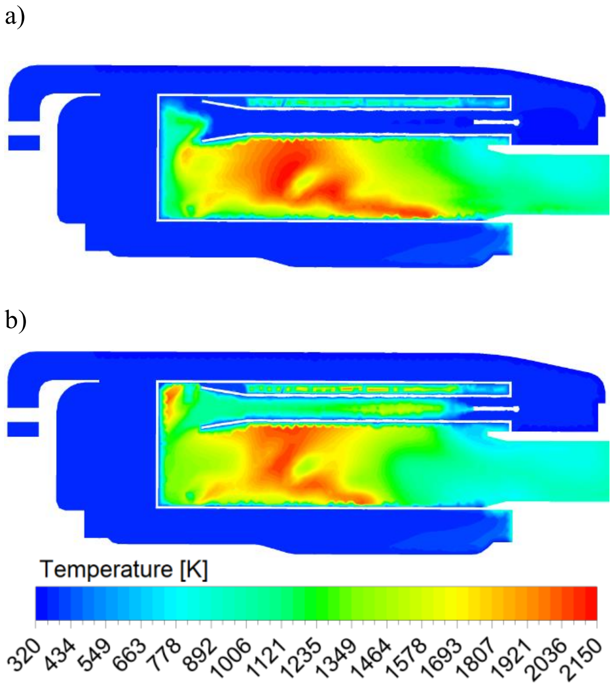

Fig. 3. Temperature: a) engine running on kerosene, b) engine running on FWE.

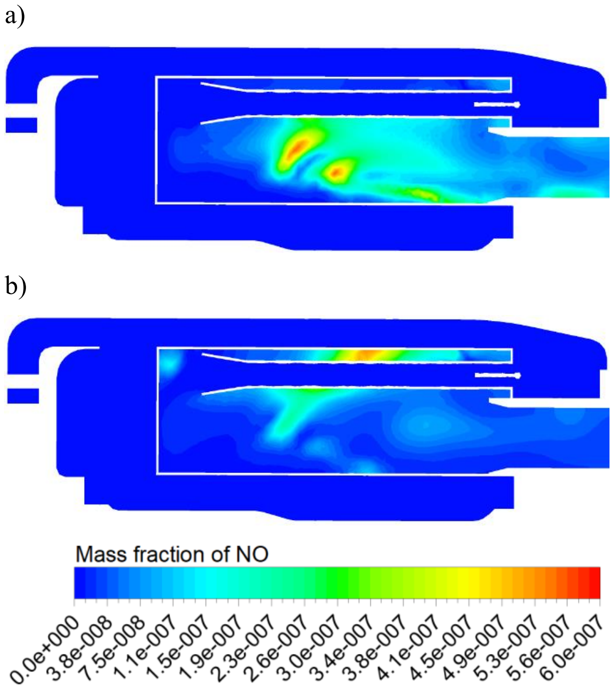

Fig. 4. Mass fraction of NO: a) engine running on kerosene, b) engine running on FWE.

Finally based on the numerical results the NO concentration (which is the main NO_X component in hot combustion gasses) produced by the engine running on kerosene checks 256 ppm compared to 186 ppm produced by the engine running on the FWE. Clearly the quantitative results of NO production are overestimated when comparing to experimental data given in [25, 26]. As explained above, qualitative results are not the aim of the proposed numerical model. Proposed data shows that

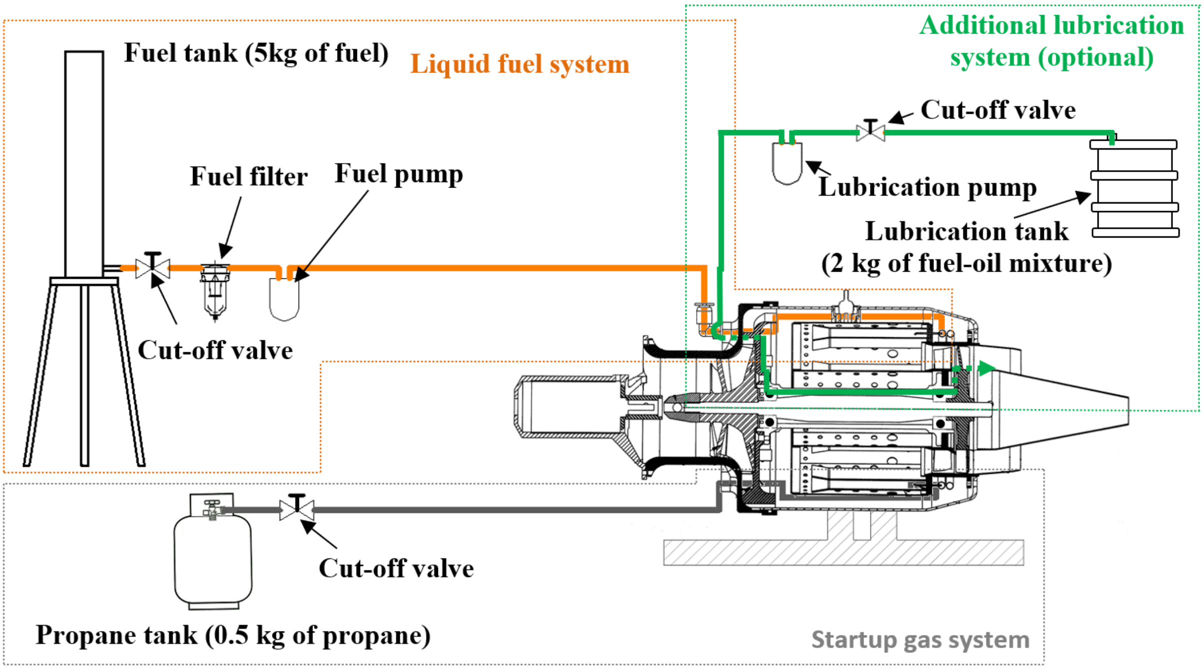

Fig. 5. Engine test bench supporting systems.

there is 27% of the NO emission reduction due to addition of the water. Based on the experimental data mean values of overall NO_X production levels are between 16 ppm (for 40k rpm) up to 27 ppm (for 120k rpm) with approximate linear dependence on the engine rotational speed. Assuming 27% of NO_X reduction due to water addition, the experimental results of the engine running on FWE containing 3% of water should show between 12 ppm up to 20 ppm of NO_X concentration, for 40k rpm and 120k rpm respectively, measured at the engine exhaust by the emission analyzer.

Above results shows that between 4 ppm to 7 ppm of NO_X concentration reduction is expected which, for engine rotational speeds above 40k rpm, is more than ±5 ppm of NO_X measurement accuracy by gas analyzer according to [30]. Based on above the proposed measuring technique and equipment is suitable to prove statistical difference between NO_X concentrations produced by engine operating on kerosene and FWE above 40k rpm of engine rotational speed.

3 Experimental research

Experimental research work to confirm results of the numerical predictions is to be carried on the GTM-120 miniature engine test bench developed in Institute of Heat Engineering, Warsaw University of Technology [25]. Test bench (Figure 5) consists of GTM-120 small jet turbine with ECU mounted on engine mount, fuel tank, exhaust gas analyzer, data acquisition card and PC with test bench software. Pressure and temperature sensors have been placed in all major engine sections. In the inlet section of the engine differential pressure sensor with static pressure sensor and type K thermocouple are installed. One static pressure sensor and one type K thermocouple are mounted at compressor and combustor outlet sections. At the engine outlet a type K thermocouple and gas analyzer probe are installed. Test bench is equipped with strain gauge Mavin NS-6 with WOBit WDT-1 strain gauge amplifier used to measure thrust force. Fuel tank is equipped with differential pressure sensor Dudek P400U used to measure fuel consumption. All sensors are connected to the National Instruments USB-6259 BNC card connected to PC with test bench software programmed in LabVIEW. Portable emission analyzer Testo 350 is used to measure engine exhaust gas composition.

In addition to test bench components listed above, a separate lubrication system was developed (Figure 5). The main advantage of the GTM-120 engine is trust/weight ratio. A total-loss oil system is used in default configuration of the GTM-120 to reduce weight of the engine. In the original oil system a fuel with 5% of oil addition is used to lubricate and cool down two sets of ball bearings installed in the engine. Corrosive properties of water contained in FWE delivered to hot bearings were primary reason to design standalone lubrication system delivering an oil during engine operation. Additional lubrication system consists of lubrication pomp, separate lubrication liquid tank and flow restrictor (Figure 5). Flow restrictor assures that approximately 2.5% of main fuel flow is delivered to engine bearings, which is the same amount as for the default engine.

Predictions of experimental data based on [26, 27] and numerical model are shown in Figure 6. Experimental data was scaled down by 27%.

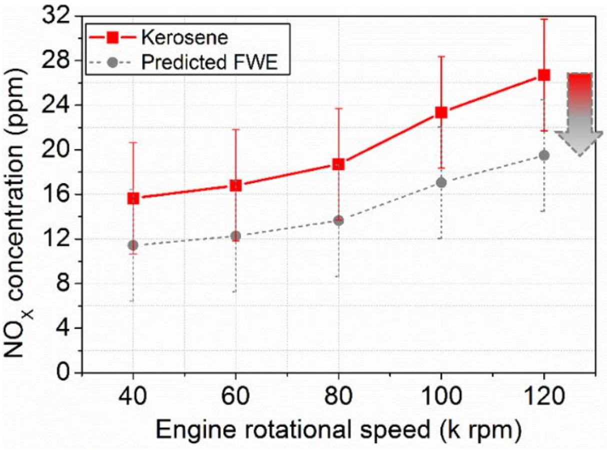

Fig. 6. Predicted NO$_X$ emissions from engine running on FWE.

4 Conclusions

Proposed, simple PDF numerical model of the kerosene and FWE combustion shows up to 27% of reduction in terms of NO concentration in hot combustion products at the small gas turbine combustor outlet. Large potential for the emissions reduction from miniature gas turbine can be explained by poor combustion efficiencies inside small combustion chambers. The results obtained from the model are used for “back-to-back” comparison of the kerosene and FEW combustion and to draw general conclusions on the water addition impact on combustion. More sophisticated, non-equilibrium, combustion models have to be incorporated in order to obtain more accurate absolute values of NO$_X$ emission results.

Predicted NO$_X$ emission reductions (up to 7 ppm) allows to claim that the gas analyzer accuracy (up to ±5ppm) which is going to be use in the experimental research allows to show statistical difference between both fuels. In addition the model shows that evaporation of liquid kerosene and ignition of the kerosene-air mixture accelerates when the water addition is used. According to model, the combustion can start in the evaporating tubes when FWE is used, whereas the evaporation and subsequent ignition of the combustible mixture takes place at the outlet of the evaporating tube for pure kerosene. The proposed equilibrium model does not account for chemical non-equilibrium due to aerodynamic straining of the flame by the turbulence. Base on above ore accurate model together with experimental data is needed to confirm the phenomena. Currently a Flamelet combustion model is developed to improve numerical NO$_X$ predictions and ongoing experimental research will be used to anchor numerical model and confirm whether combustion occurs inside evaporating tubes.

Numerical study proves that there is a high potential to reduce pollutant emissions from miniature gas turbines especially used in distributed energy generation systems where additional mass of the fuel does not adversely impact performance of the entire system. It is proposed to confirm the conclusions from the numerical model by using more sophisticated combustion modelling an investigating phenomena occurring inside the evaporating tubes during engine operation on FWE.

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