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Effect of ammonia fuel fraction on the exergetic performance of a gas turbine

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Abstract

Decreasing of fossil fuels and increasing global warming lead researchers to find cheap and environmentally friendly alternative energy sources. In this regard, ammonia (NH_3) is a widely used feedstock. This carbon free fuel can be combusted in gas turbines or internal combustion engines, producing only nitrogen and water vapor. Nevertheless, ammonia is hard to burn because of low laminar burning velocity. In this paper, the effect of ammonia fuel fraction on the exergetic performance of a Turbec T100 micro gas turbine is investigated. Three different fuels are considered to operate the gas turbine: (i) natural gas (100%CH_4), (ii) natural gas blend with %10 ammonia fraction (10%CH_4-90%NH_3) and (iii) natural gas blend with %20 ammonia fraction (20%CH_4-80%NH_3). The operating data of the micro turbine is obtained from the literature and the micro turbine is modelled with EBSILON software. It is found that %20 ammonia fraction is more environmentally benign compared to %10 ammonia fraction and natural gas fuels. The exergetic sustainability indicators are also determined as 3.168, 2.864 and 3.7 for the natural gas, 10% ammonia blend and 20% ammonia blend combustions, respectively. So, the controlling of ammonia fraction is important to sustain exergy efficiency of the micro turbine. More detailed combustion and environmental analyses are also necessary for better evaluation of environmental effects on the micro turbine during ammonia and natural gas combustions.

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Keywords: Ammonia; Efficiency; Fuel fraction; Gas turbine; Natural gas; Sustainability indicator

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1. Introduction

The carbon dioxide emission problems of fossil fuels have been increasing day after day and the search for alternative fuels becomes important challenge for societies. In this regard, ammonia is a widely used feedstock which includes carbon free content and provides potential for decreasing environmental effects of thermal processes. When it is combusted with air, it is possible to exhaust only water vapor and nitrogen gas if it is produced in a sustainable way, despite the challenges in combustion of it [1].

Ammonia is widely used in the agricultural sector. In 2015, 146 million tones ammonia have been produced [1]. Ammonia transport is safer and easier than other fuels such as hydrogen and methanol. Because, the ignition limits of ammonia are narrower than those of fuels. The auto ignition temperature is 571°C in hydrogen, 470°C in methanol and 651°C in ammonia. Ahlgren [2] studied on the power density of various fuels. It was found that nuclear-generated ammonia could be an alternative to the hydrocarbon based fuels and positively affected the global warming. Also, the ammonia and methanol were found more advantageous than propane, methane and hydrogen fuels [3-5].

Ammonia has a low laminar burning rate as 0.015 m/s and the minimum energy required for ignition as 8 MJ. These properties are better for the gas form of the amonnia. It is disadvantageous for ammonia to be obtained from hydrocarbon (CH_4) fuel in Haber-Bosh synthesis. However, alternative sources such as sun, wind, and biomass can reduce the negative effects of this situation.

The project developed by the Solar Division of the University of California, which were the first to use ammonia in a gas turbine engine, had resulted that ammonia could be replaced with hydrocarbon fuels in gas turbines [6]. Verkamp [7] studied the use of ammonia in a gas turbine. It was found that the decomposition of ammonia and the addition of nitrogen monoxide/acetylene to the reactants increased the flame stability. Bian et al. [8,9], Vandooren et al. [10] and Vandooren [11] had proposed various combustion models for ammonia. Also, the effects of feeding ammonia and nitrogen monoxide on the hydrogen-oxygen-argon mixture had been investigated. Meyer et al. [12] and Kumar and Meyer [13] experimentally examined the combustion performance and combustion-generated emissions of hydrogen, ammonia, and methane ammonia mixtures in a combustion chamber using a swirl. Duynslaegher et al. [14] worked on a numerical simulation for an internal combustion engine of the ammonia and air mixture. It was determined that the nitrogen oxides formation in emissions could be reduced with rich mixture and high inlet pressure at constant temperature. Finally, Kurata et al. [15] experimentally investigated an ammonia-kerosene-methane burning gas turbine. It was concluded that the ammonia fraction in the fuel could reduce the CO_2 emissions while obtaining satisfactory power comparing to single kerosene and methane burning.

This study focuses on the effect of ammonia fuel fraction (natural gas (100%CH_4), (ii) natural gas blend with %10 ammonia fraction (10%CH_4-90%NH_3) and (iii) natural gas blend with %20 ammonia fraction (20%CH_4-80%NH_3)) on the performance of a gas Turbec T100 micro gas turbine and its equipment in terms of thermodynamics. The sustainability indicators and improvement potentials are investigated for three different fuel combustion in the micro gas turbine.

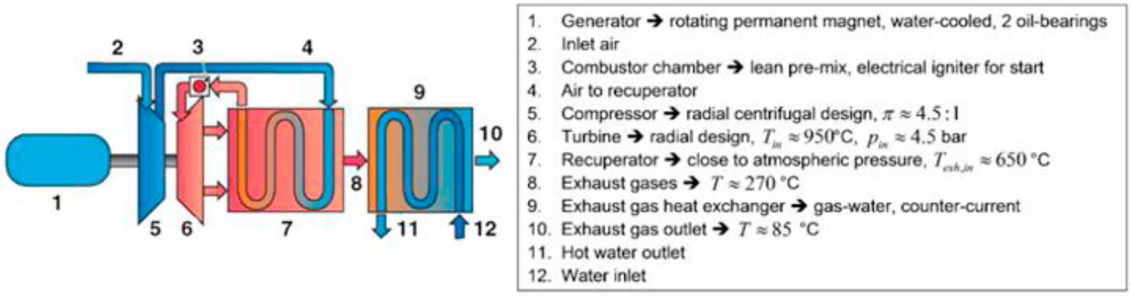

Fig. 1. Schematic layout of the micro turbine system [16,17].

2. System Description and Analysis

Micro turbines are gas turbines that produce power approximately between 10 kW and 200 kW. However, regular gas turbines are marketed as 40MW-50 MW engines [16]. First, a short description of the micro turbine is given, then the simulation of the system is explained. The schematic layout of the micro turbine system is given in Figure 1.

A Turbec T100 modelled micro turbine is used in this study and it originally consists of centrifugal compressor, radial turbine, recuperator, single can combustor, exhaust gas heat exchanger and generator. In this micro turbine, the cooling air is used to decrease turbine inlet temperature. The micro turbine data set is obtained from the literature [17-19] and tabulated in Table 1. Table 1 shows data for T100 micro turbine operating at full power load around 100 kW.

Table 1. Micro turbine data set [17-19].

Parameters	**Unit**	**Data**	**Parameters**	**Unit**	**Data**
Turbine			*Others*		
Isentropic efficiency	-	0.841	Ambient temperature	K	277.55
$T_{\text{in turbine}}$	K	1189.35	Ambient pressure	bar	1.0092
$T_{\text{max in turbine}}$	K	1273.15	Ambient relative humidity	-	0.63
$T_{\text{out turbine}}$	K	894.45	$\dot{m}_{\text{air}}$	kg/s	0.884
$P_{\text{in turbine}}$	bar	4.18	$T_{\text{natural gas}}$	K	353.15
$P_{\text{out turbine}}$	bar	1.0092	$P_{\text{natural gas}}$	bar	5
Compressor			$\dot{m}_{\text{fuel}}$	kg/s	0.0083
Isentropic efficiency	-	0.76	$P_{\text{cooling air}}$	bar	4.5
Pressure ratio	-	4.5	$\Delta P_{\text{heat exchanger}}$	bar	0.207

The Turbec T100 micro turbine is originally operated with natural gas. The composition of the natural gas is given in Table 2. The advantage of this micro turbine is that it is capable of burning different fuels such as diesel, LPG or biomass (as long as the calorific value is higher than 4 kWh/Nm^3) [17].

Table 2. Composition of the natural gas [17].

Name	**Chemical formula**	**% Mole**
Methane	CH_4	88.36
Ethane	C_2H_6	8.49
Propane	C_3H_8	0.35
Carbon dioxide	CO_2	2.03
Nitrogen	N_2	0.77
Total	-	100

The Turbec T100 micro turbine is modelled with natural gas combustion in EBSILON software [20]. The EBSILON model of Turbec T100 micro turbine with natural gas combustion is shown in Figure 2.

The chemical compositions of the exhaust gases after the combustion process are calculated by using the GASEQ software. Within GASEQ software, the chemical species calculation is performed through the resolution of the free energy equation for n species as follows [21]:

$$\frac{G}{RT} = \sum_{i=1}^{nSP}\left(\frac{x_i {G_i}^0}{RT} + x_i ln\frac{x_i}{\sum x_i} + x_i lnP\right) \tag{1}$$

The combustion equation for the methane is given by the following equation.

$$CH_4 + (0.009349Ar + 0.0002632CO_2 + 0.781N_2 + 0.2094O_2) \rightarrow$$
$$0.000285Ar + 0.000508CO_2 + 0.023841N_2 + 0.005429O_2 + 0.000939H_2O + 0.00002NO_2 \tag{2}$$

After successfully simulation of Turbec T100 micro turbine, ammonia is introduced into simulation environment. It is assumed that the mass fraction of the fuel consists of ammonia and natural gas blends. The gas turbine performance is evaluated at the same power output for different fuel blends. The exergy analysis is performed to evaluate the system performance. The mass balance equation can be expressed by;

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3}$$

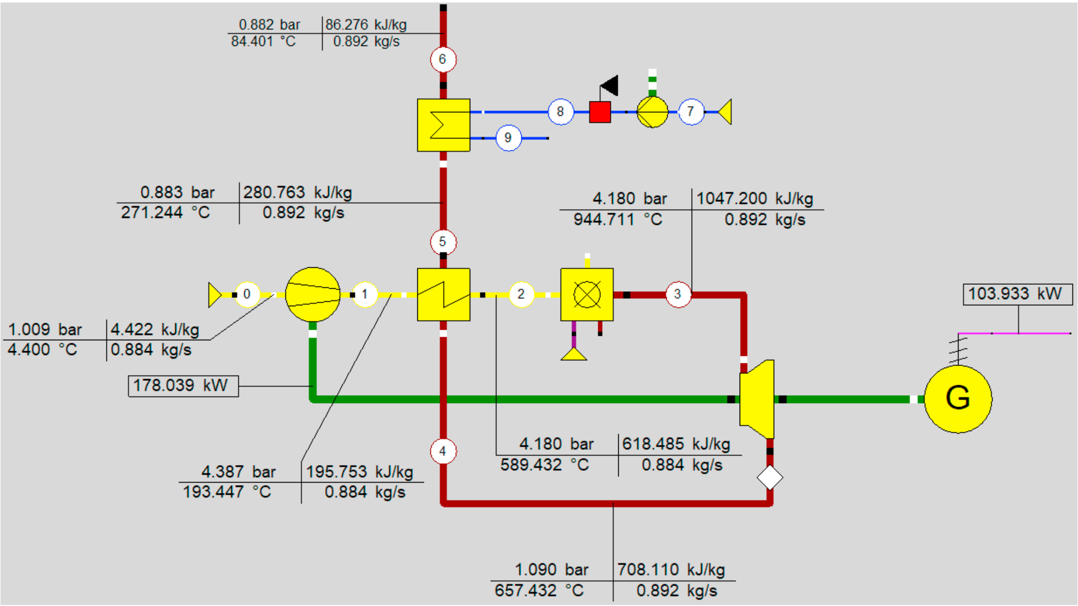

Fig.2. EBSILON model of Turbec T100 micro turbine with natural gas combustion (*yellow line represents air flow, brown line represents flue gas flow, blue line represents water, content, green line represents power*).

The general energy balance can be expressed as follows:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{4}$$

For steady state flow, the first law of thermodynamics can be written as described below where $\dot{Q}$ represents heat rate and $\dot{W}$ represents work rate.

$$\sum (h + ke + pe)_{in}\, \dot{m}_{in} - \sum (h + ke + pe)_{out}\, \dot{m}_{out} + \dot{Q} - \dot{W} = 0 \tag{5}$$

$$\sum (h)_{in}\, \dot{m}_{in} - \sum (h)_{out}\, \dot{m}_{out} + \dot{Q} - \dot{W} = 0 \tag{6}$$

$$\bar{h}_m = \sum_{i=1}^{k} x_i \bar{h}_i \tag{7}$$

$$\bar{s}_m = \sum_{i=1}^{k} x_i \bar{s}_i \tag{8}$$

$$\bar{s}_i(T_i, P_i) = \bar{s}_i{}^{o}(T_i) - \bar{R} ln \frac{x_i P_i}{P_{ref}} \tag{9}$$

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0 \tag{10}$$

$$\dot{E}x = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{11}$$

$$\dot{E}x_{ph} = \dot{m}\{(h - h_0) - T_0(s - s_0)\} \tag{12}$$

The chemical exergy of gas mixture is found by [22];

$$\dot{E}x_{ch,m} = \dot{n}\{\sum x_k \bar{e}^{ch} + \bar{R}T_0 \sum x_k \, ln x_k\} \tag{13}$$

The chemical exergy of fuel is determined by

$$\dot{E}x_{ch,f} = \dot{n}(\sum x_k \bar{e}^{ch}) \tag{14}$$

The exergy balance of a system is written as:

$$\dot{E}x_{in} - \dot{E}x_{out} = \dot{E}x_D \tag{15}$$

The exergy destructions in the heat exchangers and air preheater can be calculated as follows [23]:

$$T_a = \frac{\dot{H}_{out} - \dot{H}_{in}}{\dot{S}_{out} - \dot{S}_{in}} \tag{16}$$

$$\dot{E}x_{D,HE} = T_0 \dot{Q} \frac{T_{ha} - T_{ca}}{T_{ha} T_{ca}} \tag{17}$$

The exergy loss can be calculated according to following equation:

$$\dot{E}x_{loss,out} = \dot{E}x_{ch,out} + \dot{E}x_{ph,out} \tag{18}$$

The exergy parameters are calculated according to following equations:

$$IP = (1 - n_{ex,eff})(\dot{E}x_{in} - \dot{E}x_{out}) \tag{19}$$

where IP is improvement potential and $n_{ex,eff}$ is exergy efficiency as follows:

$$n_{ex,eff} = \frac{\dot{E}x_{useful,out}}{\dot{E}x_{in}} \tag{20}$$

Relative irreversibility (X_k) is expressed by;

$$X_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{D,tot}} \tag{21}$$

Waste exergy ratio (r_{we}) can be explained as;

$$r_{we} = \frac{total\ waste\ exergy\ out}{total\ exergy\ inlet} \tag{22}$$

$$total\ waste\ exergy\ out = total\ exergy\ inlet - useful\ exergy\ out \tag{23}$$

Environmental effect factor (r_{eef}) is found from

$$r_{eef} = \frac{r_{we}}{n_{ex}} \tag{24}$$

Exergetic sustainability index (θ_{esi}) is calculated as follows:

$$\theta_{esi} = \frac{1}{r_{eef}} \tag{25}$$

3. Results and Discussion

The exergetic sustainability parameters are obtained for three different fuel options: (i) natural gas, (ii) natural gas blend with %10 ammonia fraction and (iii) natural gas blend with %20 ammonia fraction. Figure 3 shows the improvement potential comparisons of the micro turbine equipment for 100%CH_4, 10%CH_4-90%NH_3 blend and 20%CH_4-80%NH_3 blend.

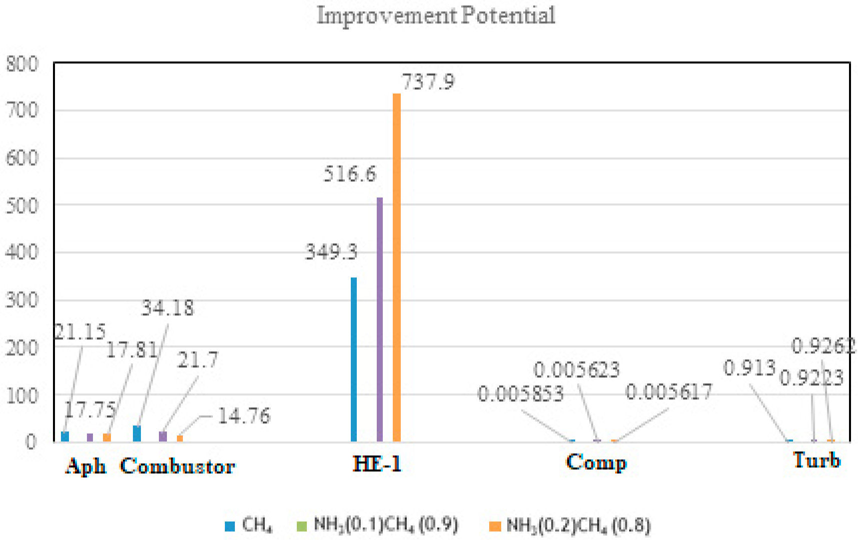

Fig.3. Improvement potential comparisons of the micro turbine equipment for 100%CH_4, 10%CH_4-90%NH_3 and 20%CH_4-80%NH_3 fuels.

The biggest improvement potential in the system is found in the heat exchanger which is used to obtain warm water. The compressor, turbine and air preheater have almost identical improvement potentials in all cases. The combustor improvement potential decreases with the increasing ammonia mass fraction. Figure 4 shows the sustainability indicators of the micro turbine for 100%CH_4, 10%CH_4-90%NH_3 and 20%CH_4-80%NH_3 fuels.

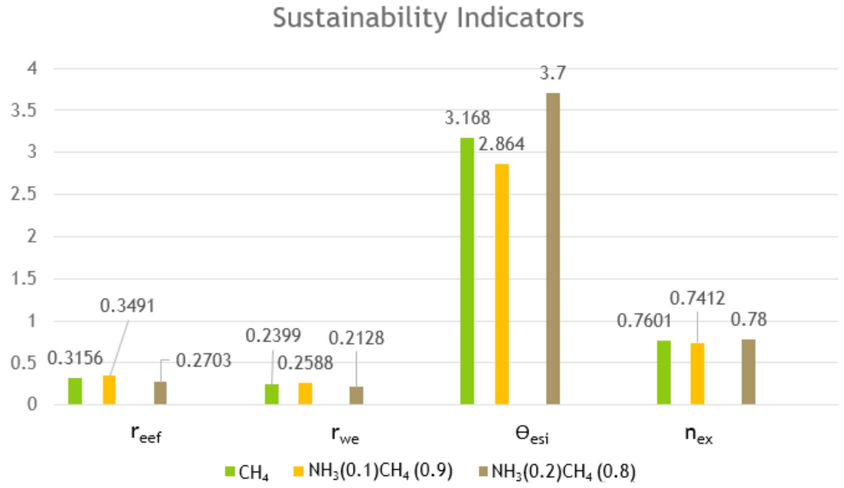

Fig.4. Sustainability indicators of the micro turbine for 100%CH_4, 10%CH_4-90%NH_3 and 20%CH_4-80%NH_3 fuels (r_{eef}=Environmental effect factor, r_{we}=Waste exergy ratio, Θ_{esi}=Exergetic sustainability index, n_{ex}=Exergy efficiency).

The environmental effect factor (r_{eef}) is increasing in %10 ammonia fuel option (10%CH_4-90%NH_3) comparing to natural gas (CH_4) fuel combustion. On the other hand, %20 ammonia fuel option (20%CH_4-80%NH_3) has the lowest environmental effect factor. Thus, %10 ammonia fuel option has the biggest effect on environment. The exergetic sustainability indicators are found as 3.168, 2.864 and 3.7 for the natural gas, 10% ammonia blend and 20% ammonia blend combustions, respectively. Accordingly, the exergetic sustainability indicator (Θ_{esi}) and exergy efficiency is increasing with %20 ammonia fuel option.

4. Conclusions

In this paper, the effect of ammonia fuel fraction on the exergetic performance of a Turbec T100 micro gas turbine is investigated. Three different fuels are considered to operate the gas turbine: (i) natural gas (100%CH_4), (ii) natural gas blend with %10 ammonia fraction (10%CH_4-90%NH_3) and (iii) natural gas blend with %20 ammonia fraction (20%CH_4-80%NH_3) fuels. The operating data of the micro turbine is collected from the literature and the micro turbine is modelled with EBSILON software. It is found that %20 ammonia fraction is more environmentally benign compared to %10 ammonia fraction and natural gas. Also, the controlling of ammonia fraction is important to sustain exergy efficiency of the micro turbine. More detailed combustion and environmental analyses are also necessary for better evaluation of environmental effects on the micro turbine during ammonia and natural gas combustions.

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