Challenges Due to Operation of Turboshaft Engine with Synthetic Gas

Nikola Davidović
EDePro Company, Belgrade, Serbia
Email: anikola.davidovic@edepro.com

Aiman Elmahmodi, Predrag Miloš, and Ramadan Almadni
Faculty of Eng., UOT, Tripoli, Libya
EDePro Company, Belgrade, Serbia
LA'STAR, Tripoli, Libya
Email: elmahmodi@aerodept.edu.ly

***Abstract*—Synthetic gas is nowadays co-product of processes such as waste gasification and various industries waste gases. The logic idea is to use these gases as energy and to prevent atmospheric pollution. Idea to use gases from waste as a fuel for gas-turbine generator that producing electric power is very attractive engineering research project, but also challenging. In this paper the necessary modifications of an existing turbo-shaft engine combustion chamber in order to be capable to operate with synthetic gas were presented. It was experimentally proven that, this type of combustion chamber and atomizer of the gas turbine generator are very suitable for application with synthetic gas or with dual liquid and gaseous fuel operation. Tests shown excellent behavior and practically identical thermodynamic efficiency**

***Index Terms*—airblast atomizer, combustion chamber, stochiometric ratio, synthetic gas**

I. Introduction

Synthetic gas is nowadays co-product of processes such as waste gasification and processing biomass, coal and other potential fuels. Although composition depends on previous process, synthetic gas is generally mixture of hydrogen, carbon-monoxide and methane in different ratios. If we produce some benefit from such gas, it is obvious that we get something from the waste. Gas-turbine generator set is typical application for such gases, but also brings lot of problems to be solved: first of all most of gas-turbines are designed to work with kerosene or similar liquid fuels. This means that thermodynamic cycle parameters, combustion chamber air distribution, atomizers, turbine cross sections and fuel installation were chosen according to certain liquid fuel. In this paper is presented a modification of existing turbo-shaft engine combustion chamber in order to work with synthetic gas. The engine was selected according to mentioned problems: low pressure ratio and wide equivalence ratio combustion chamber. Changes were done in existing atomizers and engine was tested with simulating gas consisting of 50/50% CO and H_2 by volume. Gas was supplied to engine from tank under pressure of seven bars.

II. Engine Description

Engine designation is TM-40 developed by Laboratory for jet propulsion, Belgrade University [1]. It is turbo-shaft engine with radial compressor and turbine, and reverse flow annular combustion chamber with 12 airblast atomizers. Engine is capable to produce 40kW of power, which is connected to the generator rated for 15 kW. Working fuel is kerosene, diesel or gasoline while engine was also successfully tested with various liquid fuels such as palm oil, waste oil or ethanol. Engine design speed is 46000rpm, pressure ratio 2.75 and exit temperature 900K. Engine system consists of engine, fuel and oil installation, gear box, starter, generator and control unit. In order to simulate power consumption system, three heaters with power of 2.5, 3.5, and 8kW was loaded respectively. While liquid fuel is supplied with pump for synthetic gas. Gas control valve was made from existing pneumatic manual proportional valve and step motor with its own control [2].

III. Synthetic Gas Properties and Problems Related to Use it as a Fuel

Synthetic gas is nowadays co-product of processes such as waste gasification and various industry waste gases. The logic idea is to use these gases as energy and to prevent atmospheric pollution. To use such gases as a gas turbine fuel, generally there are few problems:

- Low heating value and different stochiometric ratio
- High contents of hydrogen
- Gaseous fuel installation
- As a consequence of low heating value, a fuel flow rate is increased.

Paradoxically, the latter problem would produce more power due to higher total engine flow rates [3]. Because processes are different it results in different composition i.e. properties of the gases so engine performances may

Manuscript received August 20, 2014; revised April 24, 2015.

doi: 10.18178/ijeee.4.1.43-46

vary from plant to plant [4], [5]. Gas turbines are designed to work efficiently with kerosene and similar hydrocarbon liquid fuels so introducing fuel with lower heating value and completely different mixture ratio needs adjusting of existing system if possible. High contents of hydrogen cause dangerous handling fuel type. Finally, to introduce gas into the engine pressure should be more than inside combustion chamber i.e. synthetic gas must be pressurized. In most of existing gas turbines it is very difficult because of high pressure ratio which is again used in design to work efficiently with kerosene fuel types.

All data are percentage by volume. Syn-Gas comes from facility practically at atmospheric pressure and temperature. Further gas preparation for gas turbine should be connected to filtering and pressurizing and it was not concerned in this investigation. In order to simulate such gas we simplified composition to be (H2=50%, and CO=50%). Heating value and gas constant of such mixture is calculated as:

$$\rho_{H_2} = \frac{P \cdot V}{R_u / M_{H_2} \cdot T} \cdot 0.5 = \frac{P \cdot V}{R_u \cdot T} \cdot 0.5 \cdot M_{H_2}$$
$$\rho_{CO} = \frac{P \cdot V}{R_u / M_{CO} \cdot T} \cdot 0.5 = \frac{P \cdot V}{R_u \cdot T} \cdot 0.5 \cdot M_{CO} \quad (1)$$

So:

$$PM_{H_2} = \frac{\rho_{H_2}}{\rho_{H_2} + \rho_{CO}} = \frac{M_{H_2}}{M_{H_2} + M_{CO}} = 0.0667$$
$$PM_{CO} = \frac{\rho_{CO}}{\rho_{H_2} + \rho_{CO}} = \frac{M_{CO}}{M_{H_2} + M_{CO}} = 0.9333 \quad (2)$$

Now heating value and gas constant are calculated:

$$H_m = PM_{H_2} \cdot H_{H_2} + PM_{CO} \cdot H_{CO} = 17.4 \, MJ/kg$$
$$R_m = PM_{H_2} \cdot R_{H_2} + PM_{CO} \cdot R_{CO} = 554.4 \, J/kg \cdot K \quad (3)$$

Comparing to kerosene this mixture has almost 2.5 times lower heating value which means that mass flow rate should 2.5 times bigger to get the same energy. Also, because of hydrogen mixture has big gas constant i.e. approximately two times lower density comparing to the air. Both of these conclusions lead to the requirement for the enough big opening for gas injector. Although temperatures with syn-gas are higher in existing combustion chamber mixture will always be leaner for 1.44 times.

IV. Original and Modified Atomizer

Original airblast atomizer is shown at the Fig. 1. This type of atomizer uses air kinetic energy to atomize fuel into fine droplets. There are twelve atomizers in engine combustion chamber arranged in tangential direction thus producing swirling flow and igniting each other i.e. producing stability. Atomizer is suitable for practically all known liquid fuels [6]. It was of primary importance not to change air excess coefficient in atomizer because of stability and ignition, having in mind importance of primary zone [7]. Original combustion chamber is shown in Fig. 2 [1].

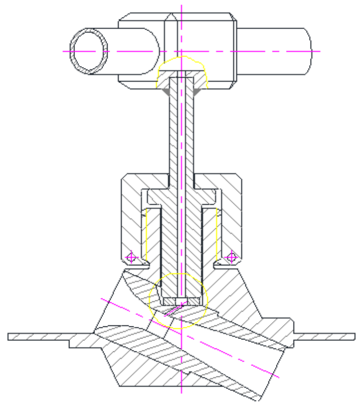

Figure 1. Original airblast atomizer assembly

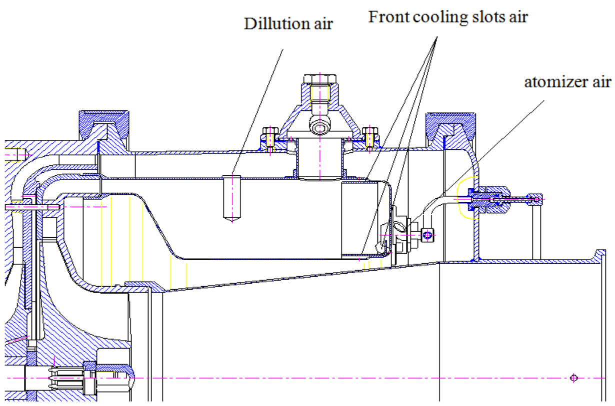

Figure 2. Combustion chamber air holes, Atomizer 8.8%, Film cooling slots 39.7%, Dilution 51.5%

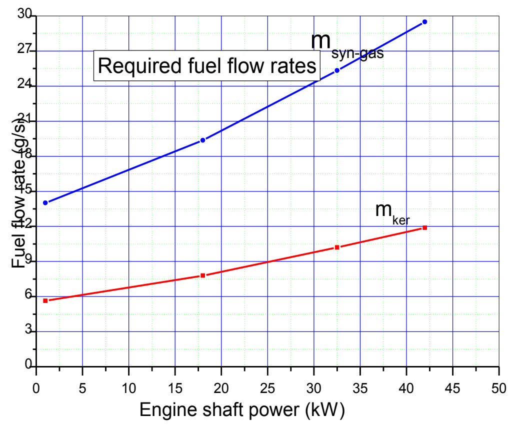

Figure 3. Engine required fuel flow rate for engine design speed of 46000rpm

Required fuel flow rates as a function of engine power are shown at the Fig. 3. Required kerosene flow is used from engine previous tests while syn-gas flow is calculated according to the heating value. Modified airblast atomizers were tested with air, means that both flows were simulated with laboratory air flow, because syn-gas not available at the moment. This air test, gives enough engineering data. The air test was performed with following procedure:

- Air for airblast atomizer was supplied under constant gauge pressure.
- Air substituting syn-gas was supplied independently through syn-gas pipe.
- Both flows were measured through its own throat
- Position of gas pipe to atomizer inlet was measured with x=0 and x=2.5mm.

Modified atomizer has a pipe of 2mm diameter and hole of 1.5mm positioned axially at inlet as shown at the Fig. 4. Modified atomizer test results are shown at the Fig. 5.

Finally comparison of equivalence ratio of proposed injector using syn-gas and propane as fuel to original atomizer using kerosene is shown at the Fig. 6. Data for kerosene are used from known measured values, while for syn-gas and propane is calculated according to their heating values.

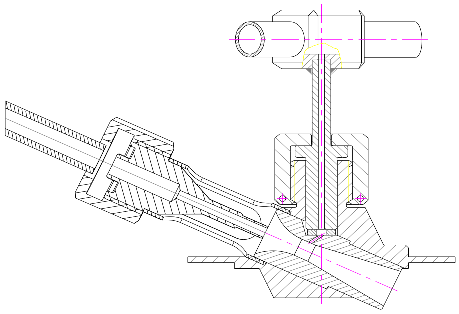

Figure 4. Modified airblast atomizer assembly

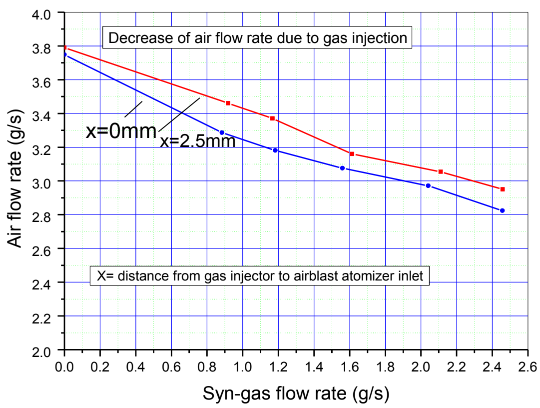

Figure 5. Decrease of air flow rate due to simulating gas injection

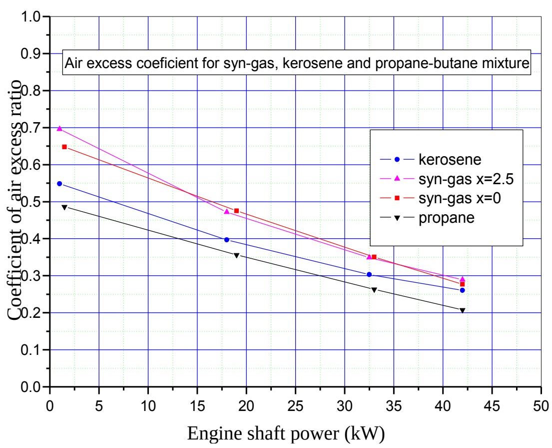

Figure 6. Coefficient of air excess in atomizer for different fuels

V. Test with Syn-Gas

Engine tests were performed in order to verify atomizer modification. Measured values were engine rpm, liquid fuel flow, syn-gas flow, exit temperature, fuel pump control voltage and gas valve control signal. Control unit was writing data for engine rpm, fuel pump control voltage and gas control valve signal, while other values were read from flow meters and displays. Gasoline is used as a liquid fuel, while turbo oil grade 32 was used to lubricate and cool bearings and gearbox.

Air flow, gasoline flow rate and exit temperature data for gasoline are given in Table I. These data are from previously measured engine data, while syn-gas data are from performed tests.

TABLE I. Comparison of Fuel Flows with Power for 42000rpm

	m_{air} [g/s]	$m_{gasoline}$ [g/s]	m_{syn} [g/s]	T_{ex} [K] Gasoline/syngas
Idle	480	4.6	11.5	690/650
Power 14 kW	440	6.6	16.5	840/820

VI. Result and Comments

According to Fig. 5 air flow is decreasing from 3.75 to 2.82g/s per atomizer when syn-gas is injection from 0 to full power flow i.e. atomizer is naturally adjusting equivalence ratio by giving 33% of required 44% to have the same as with kerosene. Differences are bigger at idle but combustion chamber and engine are not showing any instability or efficiency problem.

Very small difference is made by changing the position of gas injector about 5% i.e. choice will be according to assembling requirements.

When considering atomizer equivalence ratio for syn-gas and kerosene from 18% difference at idle practically there is no difference at full power. It is interesting to compare with propane or similar gas as methane: in that case mixture is more reach then with kerosene 7% at idle and 20% at full power.

Engine test fuel flow rates shows a bit smaller efficiency of combustion chamber with syn-gas because syn-gas flow is bigger for 0.69% for the same thermal power, while total engine flow rate is bigger for 1.4% for idle and 2.2% for 14kW. So, efficiency was lower for 2%, and 2.9% for idle and 14kW operation respectively. The reason for that is probably higher level of velocities in primary zone.

VII. Conclusion

The experimental investigation shows that, the existing type of combustion chamber and atomizer are very suitably for application with synthetic gas or with dual liquid and gaseous fuel operation. And measured exit temperatures where practically the same as with kerosene (Table I), which means for such composition no special materials should be used. It should be noted that such statement is consequence of shifted temperature and coefficient of air excess curve from Fig. 5, air flow rate is considered the same in case of syn-gas and kerosene, syn-gas flow rate is bigger 43.2/17.4 times because of lower heating value while stochiometric ratio of syn-gas to kerosene stands as 4.15/14.77; as a result syn-gas engine operation will always be 1.44 times leaner then with kerosene, compensating higher adiabatic temperatures of air/syn-gas mixture. Test was using pressurized gas mixture. In real conditions gas mixture, which is typically comes at atmospheric pressure, must be pressurized and that will decrease overall system efficiency. Engine used for demonstration is of low pressure ratio (2.75) which affects thermodynamic efficiency but in application with such gases low pressure ratio is more than welcome because power for gas pressurization should be taken into account for overall efficiency. Practically there are not so many gas-turbines operating with synthetic gases, especially small gas turbines [8]. Main reason is that engineers are always trying to adopt existing engines designed for use with liquid fuel, which is sometimes is not possible. If so, syn-gas pressurization or completely new combustion chamber must be considered, causing undesired expenses. Another logic reason is of commercial type: big companies do not have clear commercial reason to enter into such a field giving opportunity to smaller more elastic companies to grab the part of this market. More detailed considerations about modification made in this paper can be found in [9].

Appendix Nomenclature

H	Heating value (MJ/kg)
M	Molecular mass (kg/kmol)
m_{ker}	Kerosene mass flow rate (g/s)
m_{syn}	Syn-gas mass flow rate (g/s)
P	Pressure (Pa)
PM	Mass fraction
R_u	Universal gas constant 8314 J/kgK
R	Gas constant (J/kgK)
Syn-gas	Synthetic gas
T	Temperature (K)
V	Volume (m^3)
ρ	Density
Suffixes	
H_2	Hydrogen
CO	Carbon monoxide
m	Mixture

References

[1] B. Jojić, V. Milosavljević, Đ. Blagojević, V. Fotev, and P. Milojković, "Glavni projekat motora TM40," Technical Report, Mechanical Engineering Dept., Beograd University, 1984.

[2] D. Dini, "Modification of fuel control system of gas turbine engine from kerosene to hydrogen," in *Proc. RTO-AVT Symposium*, Lisbon, Portugal, Oct. 12-16, 1998.

[3] M. S. Johnson, "Prediction of gas-turbine on- and off-design performance when firing on coal derived syn-gas," *Transactions of ASME*, vol. 114, Apr. 1992.

[4] J. Wu, P. Brown, I. Diakhunchak, A. Gulati, M. Lenze, and B. Koestlin, "Advanced gas turbine combustion system for high hydrogen fuels," in *Proc. GT2007, ASME Turbo Expo*, Montreal, Canada, 2007.

[5] J. Zhang, L. Ma, Z. Li, and W. Ni, "Modeling an air-cooled gas turbine of the integrated gasification combined cycle in Aspen plus," in *Proc. International Conference on Future Electrical Power and Energy Systems*, 2012.

[6] M. Adžić, "Effects of changes jet fuel quality on gas turbine performance and emissions, fuels and lubricants," *Journal of Fuels and Lubricants*, vol. 28, no. 5-6, pp. 233-244, 1989.

[7] N. Davidović, "Mathematical model of turbojet engine combustion chamber primary zone," *FME Transactions*, vol. 35, pp. 29-34, 2007.

[8] *Development of Micro-Turbine Plant to Run on Gasifier Producer Gas*, Biomas Engineering Ltd., 2004.

[9] N. Davidović, P. Miloš, A. Elmahmodi, M. Miloš, B. Jojić, and I. Todić, "Modification of existing turboshaft engine in order to operate on synthetic gas," *FME Transactions*, vol. 42, no. 2, pp. 112-117, 2014.

Nikola Davidović was born on 22.10.1971, in Kragujevac, Serbia. He graduated as mechanical engineer at 1996. He obtained Master of Science in March 2000, and in October 2003 defended his PhD thesis "Contribution to research of central vaporizer of annular combustion chamber of turbojet" at Faculty for Mechanical Engineering, University of Belgrade.

He started to work in EDePro Company as a research engineer in the field of air-breathing and rocket propulsion, aerodynamic and flight dynamic of unguided rockets. He participated in many projects dealing with development and testing of propulsion systems. His main research interests are propulsion systems and turbo-machinery. Up to year 2010, he was working as Research-Assistant at Faculty for Mechanical Engineering and full-time and part-time in EDePro Company, from year 2010 till present full-time in EDePro Company and part-time at Faculty for Mechanical Engineering.

Dr. Nikola, achieved award from UPM (University Putra Malaysia) for the best paper presented in conference of aerospace technology (AEROTECH-III-2009).

Aiman Elmahmodi was born on 23.09.1964 in Tripoli, Libya. He obtained his Ph.D. in Jet Propulsion form University of Belgrade Serbia in 2000, Master of Science in Thermodynamic and Fluid Mechanics from Strathclyde University Glasgow UK in 1993, and Bachelor (BSc.) in Mechanical Engineering from University of Tripoli in 1988.

He served as a Project Manager in Tripoli R&D Center in Engineering Department. His main research interests are propulsion systems and turbo-machinery. Currently he is an Associated Professor of propulsion and a member of staff at Aeronautical Engineering Department, Faculty of Engineering, University of Tripoli, and serving as part-time Research Engineer with EDePro Company Group, Belgrade, Serbia for design and qualify energy and power systems.

Dr. Aiman involved as a member in Advisory Board at Libyan Authority for Science, Technology and Research (LA STAR). E achieved awards From UPM (University Putra Malaysia) for the best paper presented in Conference of Aerospace Technology (AEROTECH-II-2007) and (AEROTECH-III-2009).