MATHEMATICAL MODELING AND NUMERICAL SIMULATION OF PROCESSES INSIDE A TURBO-ENGINE THAT USES LANDFILL GAS

Valentin SILIVESTRU[1], Romulus PETCU[2], Valeriu VILAG[3],
Corina MANDIŞ[4], Dan ROBESCU[5]

În România, gazul de depozit, obţinut prin fermentarea materialului organic din gunoaiele menajere, se arde direct la locul de producţie fără o utilizare energetica. Se impune astfel adoptarea unor soluţii de valorificare energetică. Pe de altă parte, se ştie ca motoarele de aviaţie, după epuizarea numărului de ore de zbor nu se mai folosesc (exista riscuri de defectare), cu toate ca acestea sunt încă funcţionale. Pentru a da o utilizare economică acestor motoare, care mai au încă un număr mare de ore de funcţionare, se propune prin lucrarea de faţă, adaptarea şi modificarea lor pentru a putea fi valorificat gazul de depozit în cadrul unei instalaţii de cogenerare.

In Romania, the landfill gas, obtained through fermentation of organic matter contained in waste materials, is burned without an energetic utilization. This fact imposes the adoption of solutions for the energetic capitalization of these gases. On the other hand it is known that the engines used in aviation, after the exhaustion of flight hours, are no longer used (because of the risk of failure), although they are still functional. To give an economical utilization for these engines, which still have a large resource of functionality, their adaptation and modification is proposed in this paper in order to be used in cogeneration systems that uses the landfill gases as fuel.

Keywords: combustion, simulation, gas turbines, combustor chamber, landfill gas

1. Introduction

This research resulted from the necessity of ecologization of urban landfills from Romania, by capitalizing the landfill gases obtained from fermentation of the biodegradable organic matter contained in wastes. The sources of biogas are known for a long time, but the exploitations of biogas have developed since the end of ’70, as a result of the second energetic crisis. The basic

[1] PhD.eng., Research & Development National Institute for Gas Turbines COMOTI, Romania
[2] Eng., Research & Development National Institute for Gas Turbines COMOTI, Romania
[3] Eng., Research & Development National Institute for Gas Turbines COMOTI, Romania
[4] Assist. PhD. student, Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail:corinamoga@yahoo.com
[5] Prof., Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania

idea is to utilize these gases in cogeneration systems in order to produce electrical and thermal energy.

Nowadays the European directives forbid the release into the atmosphere of landfill gases, for demands of the terrestrial atmosphere and ozone layer protection. In Romania, at present these gases are not capitalized. On the contrary, they are released into the atmosphere. In covered landfills, the fermentation of wastes evolves anaerobic, and the methane gas (that results inside the landfill), reaches the surface and can produce explosions, fires or noxious effects on population.

In this paper, the capitalization of landfill gases, by burning then in cogeneration power plants is analyzed. The utilization of a turbo–engine is proposed modified and adapted in such a way that the burning of landfill gas can be possible. The solution of cogeneration is very actual because it produces, at the same time, electrical and thermal energy.

In Europe, installations that use landfill gases have been set into operation since ’80 and in 2003 a capacity of 553 MW was already installed in cogeneration power plants. One estimates that up to 2010 a total of 1,366 MW will be installed. Is estimated that in the whole world, in 2010, a capacity of 4,500 MW will be installed in such cogeneration power plants, [1], [2].

The combustion in turbo-engines is an intensively studied international issue. Different techniques for calculating the thermodynamics of the combustion chamber have been proposed through the years. Some of them are based on experiments, others are based on thermochemical predictions. Since the costs for conducting experiments are very high, we try to reduce those costs through virtual experiments based on numerical simulations.

INCDT COMOTI has developed, up to now, turbo-engines of small and medium capacities, which are supplied with natural gases. The engines are integrated in industrial applications where mechanical, electrical and thermal energy is produced [3]. Turbo-engines that burn landfill gases is a further development of those technologies.

2. General solution of landfill gas capitalization, in cogeneration power plants

The measurements performed at an urban landfill provide the landfill gas mean composition, in volumes, of 50 % CH_4 and 50 % CO_2. In these conditions the landfill gas is considered „rich”, with a heat value around 5 [kWh/m^3]. This gas can be used as a primary energy source in installations for obtaining the electrical energy, [4].

Some stages must be followed for conceiving a cogeneration power plant that uses landfill gases as fuel. In Fig. 1, the principle for the biogas appearance and its utilization at an urban landfill is briefly presented.

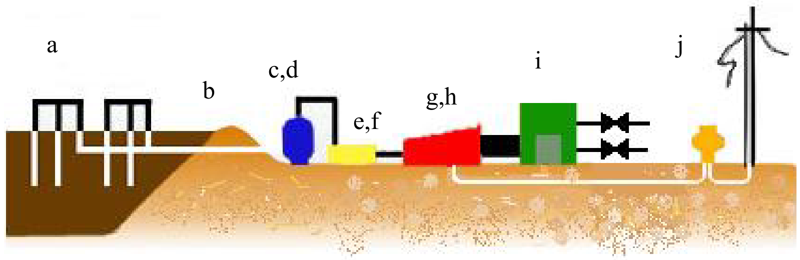


Fig. 1. The general scheme for capitalization of landfill gases

For the capitalizations of the landfill gas in cogeneration installations some others equipment must be installed such as:

a) *Wells, for landfill gas extraction* that are drilled inside the waste deposit. This first stage consists in the drilling of vertical wells through the wastes in order to permit the landfill gas to be collected. The realization of the wells requires a special attention taking into account the explosion hazard, caused by methane accumulation inside the landfill.

b) *The pipe system* used for the transportation of the landfill gas up to the mixing chamber.

c) *The mixing chamber* is necessary because the components of the landfill gas (obtained from different wells) vary in concentration, compositions of the gas and concentrations of methane.

d) *Treatment/purifying installation* for the landfill gas. Within those installations the carbon dioxide, hydrogen sulfide, particles and other components that damage the cogeneration equipments are eliminated. These installations can rich 99% efficiency.

e) *The tanks* used for the landfill gas storage, which can accommodate a volume of landfill gas up to 1.000 m^3.

f) *The screw compressor* used to increase the gas pressure at the turbo-engine entrance.

g) The turbo-engine, which transforms the chemical energy incorporated in the landfill gas into mechanical energy; the engine permits the utilization of the landfill gas (with a methane concentration down to 50 %). The turbo-engine is directly coupled to a power generator. The heat of the burned gases will be recovered and utilized, to supply heat or hot water.

h) *The power generator*, which transforms the mechanical energy into electrical energy.

i) *The boiler*, inside which the hot, burned gases pass. This equipment assures the second form of energy obtained from the cogeneration process - the thermal energy.

j) Equipment and installation used to connect the cogeneration power plant to the energetic grid system.

3. A helicopter turbo-engine adapted to function with landfill gas

Taking into account the turbo-engines portfolio that is available at INCDT COMOTI for the research activities, the *TV 2 – 117 A* engine was chosen for these research activities (Figure no. 2). The engine was taken from a Mi - 8 helicopter that was produced by KLIMOV CORPORATION from Russia. This engine has a free turbine, [5].

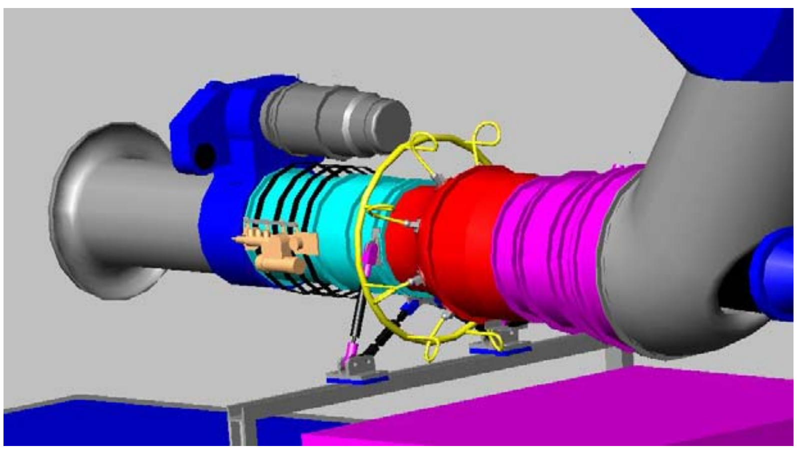


Fig. 2. *TV2 – 117 A* gas turbine engine

At the nominal regime, the *TV2 – 117 A* turbo-engine has the following characteristics:

- The breathed-in air flow, Da: 8.4 [kg/s];
- The rotation speed of compressor turbine, Ngg: 20,352 [rotation/minute];
- The rotation speed of free turbine, Ntl: 12,000 [rotation/minute];
- The power at the free turbine axis, Ptl: 882 [kW];
- The specific consumption of fuel (kerosene), Ch: 422 [g/kWh].

For the utilization of landfill gas inside a turbo-engine from a helicopter several changes must be made to the injection system (the system passes from the liquid fuel, kerosene, to the gaseous fuel). In the laboratory different compositions of methane and carbon dioxide up to 50 % were tested.

4. The turbo-engine adapted to function with landfill gas – numerical simulation CAD - CFD

During this phase of research it was considered that the landfill gas is burnt in the combustion chamber and the composition of gas was maintained constant during the measurements.

For the realization of simulation in CFD the combustion chamber was designed in 3D. Thus, the ignition system and the injectors were modified to permit the function with landfill gas (Fig.3). In the calculations a burning model with seven chemical species in resulted burned gases (N_2, O_2, CH_4, CO_2, H_2O, CO and NO) was used, the viscous- turbulent model being k-ε, [6].

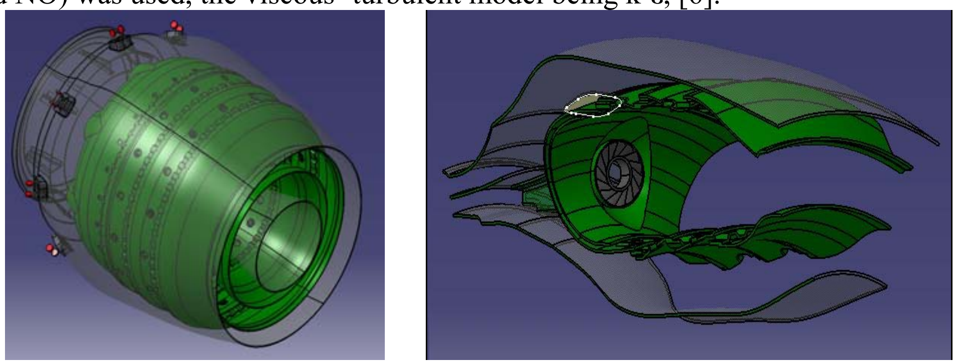


Fig. 3. Combustion chamber of the TV2 turbo/ engine designed in 3D and adapted for landfill gas

The tests were successfully made and they validated the new combustion chamber solution. In Fig. 4 certain experimental data registered during the tests are presented.

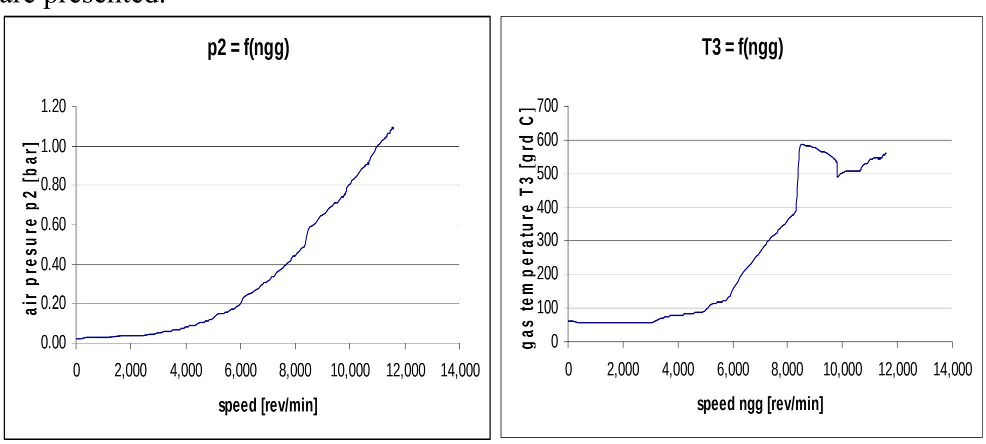


Fig . 4. Experimental data

Both diagrams presented in Fig. 4 show the evolution of the air pressure in the compressor outlet, p_2, and temperature level in the combustor chamber, T_3, in relation with the speed of the gas turbine engine, for reduced levels of function regimes, [7].

The combustion chamber of the gas turbine engine is equipped with 17 twin temperature transducers for gas temperature measurement. In Fig. 5 a cross thermal plane of combustion chamber, in degree Celsius is represented. A good distribution for temperature level can be observed. The differences can be explained through the fact that the 17 thermal transducers and 8 burners have a different distribution pitch.

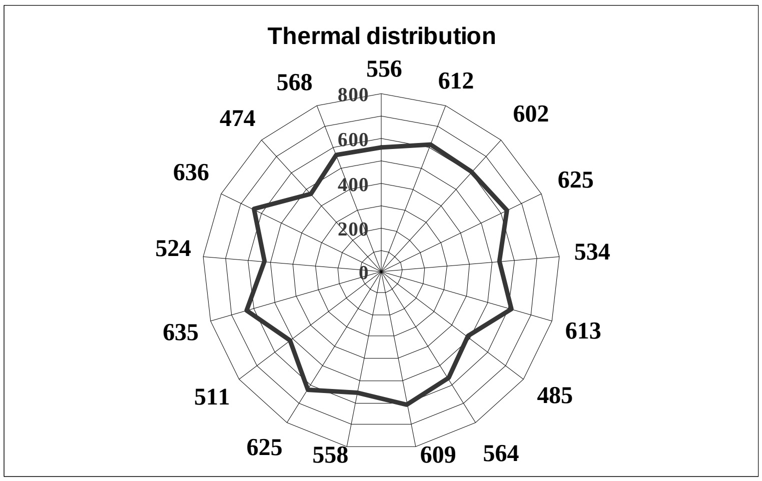


Fig. 5. A cross thermal plane of combustion chamber

The research activity will continue with new tests to determine the whole envelope of gas turbine engine function and to improve the combustion chamber design/solution.

The air pumped into the combustion chamber contains oxygen O_2 and nitrogen N_2 in 1:3.76 molar ratio. The mass flow is 6.75 kg/s = 8 x 0.84375 kg/s and the working pressure is 6.4 bar. Due to the fact that the compressor of the engine has moving stators the two parameters were considered as constant.

Three fuels were considered during the tests, to see the differences caused by their composition. The first was landfill gas, formed by carbon-dioxide CO_2 and methane CH_4 in 1:1 molar ratio. The second fuel was natural gas, considered to be formed of methane CH_4, carbon-dioxide CO_2, ethane C_2H_6, nitrogen N_2 and propane C_3H_8 in 85:7.06:5:2.34:0.6 molar ratio. The third fuel was pure methane CH_4. The three compositions are either statistical or theoretical composition of the well known fuels. The mass flows of the three fuels were determined from thermodynamics after choosing three working regimes, as shown below.

Considering the thermodynamics of a turbo-engine, it can be said that the working regime of a combustion chamber is given by the heat of reaction (combustion), Q_p, which determines the temperature at the exit of the combustion chamber and the available power for the turbine [8]. Corresponding to some power necessities at the shaft, three levels have been selected: 470 kJ/kg, 550 kJ/kg and 600 kJ/kg. The next step was to calculate the necessary amount of fuel to obtain a given Q_p. During the chemical reaction of combustion appear, in addition to the mentioned species, the water H_2O, the nitric-oxide NO and the carbon-monoxide CO, so the combustion reaction can be written:

$$\frac{1}{\lambda} fuel + air \rightarrow uCO2 + vH2O + wN2 + xO2 + yNO + zCO \tag{1}$$

where: λ represents the excess of air and is equal to unity when the amount of air is minL which represents the minimum quantity of air to burn 1 kg of fuel; *u, v, w, x, y, z* are determined using Gibbs free energy minimization [9]. It results from the definition of minL that this value is different from one fuel to another; because of the different fuel chemical composition minL can be easily calculated by writing the stoechiometric combustion equation for each fuel. This means that although λ is the same, the mass fuel flow will be different for the same working regime and different fuels. The formula giving the mass fuel flow is:

$$m_{fuel} = \frac{m_{air}}{\lambda \quad \min L} \tag{2}$$

For the three working regimes and the three types of fuel the following mass fuel flows were considered:

Table 1

Mass fuel flows for the three regimes and the three fuels

Q_p [kJ/kg]	λ	minL	m_{air} [kg/s]	$m_{landfill\ gas}$ [kg/s]	$m_{natural\ gas}$ [kg/s]	$m_{methane}$ [kg/s]
470	6	4.576	0.84375	0.030731	0.010287	0.008195
550	5	13.67	0.84375	0.036877	0.012345	0.009834
600	4.75	17.16	0.84375	0.038818	0.012994	0.010351

Solid Works was used to build the geometry that was pre-processed with Gambit and the CFD solver is Fluent.

For the air inlet condition Mass Flow Inlet with the given mass air flow was used as boundary and a gauge pressure of 6.4 bar; for the fuel inlet Mass Flow Inlet with the calculated mass flow depending on the fuel and the desired working regimes, and a gauge pressure of 7.5 bar were also used. In order to obtain an injection pressure around 7.5 bar for all fuels, some small changes were done to the injector, meaning that the diameters of the inlet nozzle were modified. Periodic boundary conditions of rotation were provided because only one pie from the eight identical ones was used. The exit of the combustion chamber was simulated as the Pressure Outlet boundary condition, with 6.25 bar gauge pressure.

5. Results and interpretation

The main results are shown below to see the differences in using one of the three fuels at the chosen working regimes.

Species distributions in the middle plane of a pie and on the sides of a plane are shown to see how the different necessary mass fuel flows affects the mixing and the flame into the combustion chamber. CH_4 distribution shows best the shape of the injected jet of fuel; H_2O and/or CO distributions show the shape of the flame inside the combustion chamber. Another important result shown below is temperature distribution and average temperature in the exit section of the combustion chamber. This print of temperature will affect the durability of the turbine and it is good to know which fuel provides a better distribution.

Table 2

CH_4 distribution on the middle plane of a pie

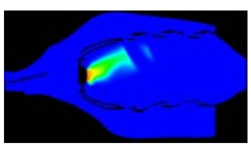
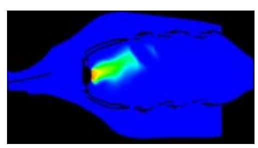
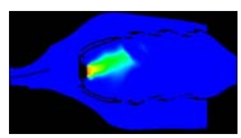
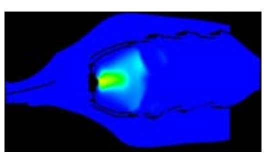
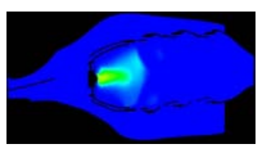
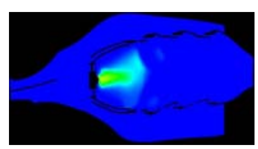
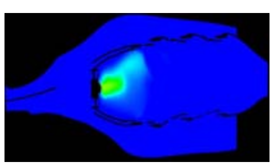
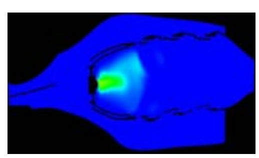
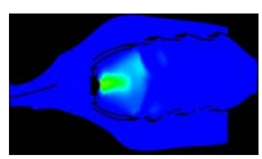
Working regime/ Fuel	Q_p=470 kJ/kg	Q_p=550 kJ/kg	Q_p=600 kJ/kg
Landfill gas			
Natural gas			
Methane			

Table 3

H_2O distribution on the middle plane

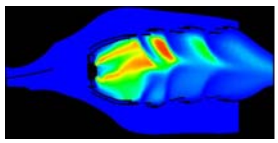
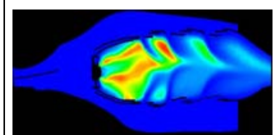
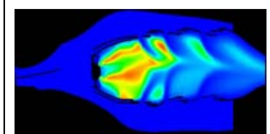
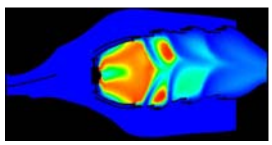
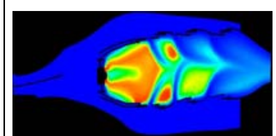
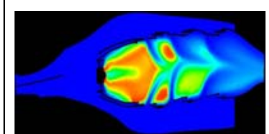
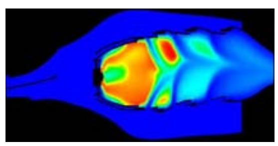
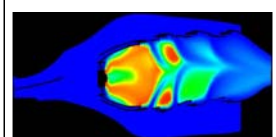
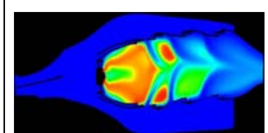
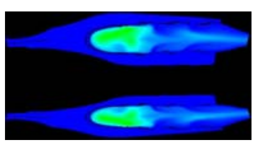
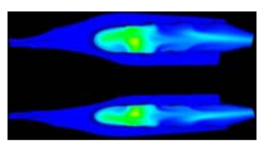
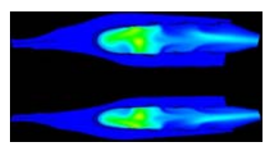
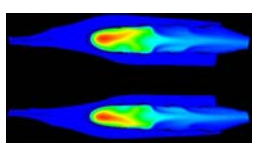
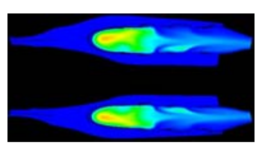
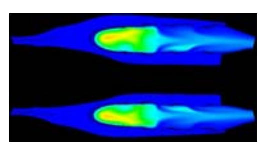
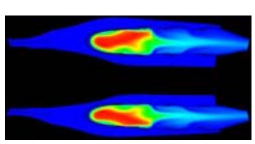
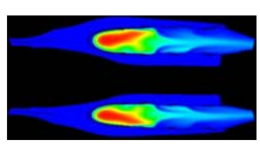
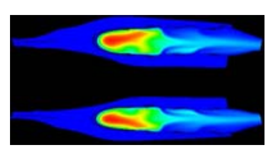
Working regime/ Fuel	Q_p=470 kJ/kg	Q_p=550 kJ/kg	Q_p=600 kJ/kg
Landfill gas			
Natural gas			
Methane			

Table 4

H_2O distribution on the sides

Working regime/ Fuel	Q_p=470 kJ/kg	Q_p=550 kJ/kg	Q_p=600 kJ/kg
Landfill gas			
Natural gas			
Methane			

6. Conclusions

1. The cogeneration power plants equipped with turbo-engines provides a good solution for landfill gases utilization as a elementary energy source.

2. By using the turbo-engines taken from aviation the economical efficiency of these engines is increased.

3. Mathematical modeling in CFD and numerical simulations of the combustion chamber with different composition of landfill gas shows the same results as the one obtained from experimental researches, the error does not exceed 5%.

4. By mathematical modeling the extension of functioning range with mixtures of carbon dioxide and methane up to 50% was possible and the thermal regimes be determined.

5. Based on these theoretical and experimental researches new constructive solutions of turbo-engines, taken from helicopters and airplanes, are materialized, which will be used in cogeneration power plants that uses landfill gases.

The researches will continue and a prototype installation will be mounted at an urban landfill.

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