

Simulations of fuels consumption in the CHP system based on modernised GTD-350 turbine engine

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Abstract: There were done simulations of fuels consumption in the system of electrical energy and heat production based on modernised GTD-350 turbine engine with the use of OGLST programme. In intention the system based on GTD-350 engine could be multifuel system which utilise post-frying vegetable oil, micronised biomass, sludge, RDF and fossil fuels as backup fuels. These fuels have broad spectrum of *LHV* fuel value from 6 (10^6 J·kg⁻¹) (e.g. for sludge) to 46 (10^6 J·kg⁻¹) (for a fuel equivalent with similar *LHV* as propane) and were simulations scope. Simulation results showed non linear dependence in the form of power function between unitary fuel mass consumption of simulated engine GTD-350 needed to production of 1 kWh electrical energy and *LHV* fuel value (10^6 J·kg⁻¹). In this dependence a constant 14.648 found in simulations was multiplied by *LHV* raised to power -0.875 . The R^2 determination coefficient between data and determined function was 0.9985. Unitary fuel mass consumption varied from 2.911 ($\text{kg}\cdot 10^{-3}\cdot \text{W}^{-1}\cdot \text{h}^{-1}$) for 6 (10^6 J·kg⁻¹) *LHV* to 0.502 ($\text{kg}\cdot 10^{-3}\cdot \text{W}^{-1}\cdot \text{h}^{-1}$) for 46 (10^6 J·kg⁻¹) *LHV*. There was assumed 7,000 (h) work time per year and calculated fuels consumption for this time. Results varied from 4,311.19 (10^3 kg) for a fuel with 6 (10^6 J·kg⁻¹) *LHV* to 743.46 (10^3 kg) for a fuel with 46 (10^6 J·kg⁻¹) *LHV*. The system could use fuels mix and could be placed in containers and moved between biomass wastes storages placed in many different places located on rural areas or local communities.

Keywords: biomass, cogeneration, electricity production from biomass, heat production from biomass, mathematical modelling, turbine engine

INTRODUCTION

Many inconvenient occurrences such as deserts areas growth [CORNEJO-DENMAN *et al.* 2018; WINCHESTER *et al.* 2018], inundation of low-lying coastal areas due to rising sea levels [GRIGGS, REGUERO 2021; RAHIMI *et al.* 2020], floods [KRUCZKIEWICZ *et al.* 2021; OSEI *et al.* 2021], droughts [GABRYSZUK *et al.* 2020; LI *et al.* 2020; RYBCZYK *et al.* 2020; ZUO *et al.* 2021], famine [LLOYD *et al.* 2021; SULSER *et al.* 2021], extreme weather events [ANDERSEN *et al.* 2020; TÓTH *et al.* 2021] and mass migrations [SCHWERDTLE *et al.* 2021; TSHIMANGA *et al.* 2021], of humans are results of climate changes. Climate change is the effect of global warming caused by emissions CO₂ and other greenhouse gases. In Poland electrical energy generation is mainly based on fossil fuel mix with predominantly share of solid fuels as hard coal or brown coal [GAWLIK, MOKRZYCKI 2019; PASKA *et al.* 2020; TOKARSKI *et al.* 2021].

Due to previously mentioned each solution which decreases or eliminates emissions CO₂ and other greenhouse gases is desired in Poland. There were created an idea of production electrical energy and heat in cogeneration mode for very small electrical power about 300 kW with the use broad spectrum of biomass fuels and alternative solid fuel RDF (Refuse Derived Fuel). In intention it should be a very small line which could be placed nearby biomass sources such as rural areas or local communities located far away from town, off-grid solutions, small processing plants of agri-food industry, or places where is not economically efficient to link them to national grid due to big investment costs of power lines. As a fuel the proposed line should use different available types of waste biomass (as straw, hay or wood), biogas, liquid biofuels or processed natural fats (eg. used oils after frying) and RDF (alternative solid fuel). According to local supplies possibility it could also use different types of mineral fuels as oil

or natural gas as backup fuel. However maximal use of local available biomass fuels or alternative fuels by the line was the main idea that was inspired by bioeconomy idea [EC 2018a, b], circular economy idea [EC 2020; OECD 2020] and A New Circular Economy Action Plan [EC 2020].

The success of BioCHP project [BioCHP 2021] proved that modified turbine engine can be supplied by different fuel types [GOLEC, NEHRING 2021]. It is expected that other turbine engines with different power could be accommodated to different fuel types. Biomass solid wastes are available at local level in Poland [BĘLDYCKA-BÓRAWSKA *et al.* 2021]. Also RDF are collected at local level in Poland [SMOL *et al.* 2020]. In future they can be fuel sources for a potential local installation for production of heat and electrical energy. Local installation would be preferred over a big one due to preventing emissions from fuel transport and cost saving on transport. It is predicted that it should have small power output because installations with small power output consume smaller amount of fuel in compare to installation with relatively big power output. Also the advantage of smaller installation above a big one is possibility to install them in much more places according to preferred by EU distributed energy production rule for local energy communities [MORONI *et al.* 2019]. Searching on potential candidates among available turbine engines drew attention to GTD-350 engine produced to Mi-2 helicopter in Poland [PWRZE 2020]. Mi-2 helicopters were and are in service in Polish Army. However they are going to be exchanged on other helicopter types [SABAK 2020]. In the Army magazines are also additional spare GTD-350 engines for exchange of engines mounted on-service helicopters. Engines both from dismissed from duties helicopters and spare engines could be a base for redesign, reconstruction, rebuilding and accommodation to different fuel locally available types. RYS [2011] proved that even engines dismissed from duties in aviation can be accommodated to stationary work and electrical energy generation on different fuel types. Stationary use of these engines gives some freedom in implementation of quite new design and materials solutions. Purpose of this work will be simulations of fuel mass consumption needed to production of $1 \cdot 10^3$ W·h electrical energy according to calorific different fuel values. The scope of calorific fuel values will in the range from $6 \cdot 10^6$ J·kg⁻¹ (such value owns sludge with moisture content about 80%) to $46 \cdot 10^6$ J·kg⁻¹ (such value owns purified biogas to the natural gas quality). GTD-350 engine will be redesigned and accommodated to use different fuels types (gaseous, liquid or solid). Normally the engine accepts liquid or gaseous fuels without any makeover. However intended use of solid waste biomass, sludge or even RDF will need some changes in the construction of the engine burning chamber. Also it will be equipped with devices which allow pre-processing of different fuels types to the shape acceptable by modified GTD-350. For example in BioCHP project a bigger one turbo engine from aircraft was equipped with powder burners which enabled to use micronised biomass as a fuel. There was tested in real conditions a line for electricity and heat production from different micronised types of biomass. For GTD-350 will be used similar technical solutions as in BioCHP project for use of micronised solid type fuels. Such solutions will give very big flexibility to use wastes as fuels to power generation by GTD-350. GTD-350 has nominal mechanical power of $0.235 \cdot 10^6$ W which is relatively very small in compare to turbines implemented in electro-power stations or

big factories which powers are in the range of $20 \cdot 10^6$ W to $500 \cdot 10^6$ W. Small power means smaller demand for fuels. Thus a small energy production system based on modernised GTD-350 engine should be suitable for wastes development as fuels in small municipalities, local communities, small factories placed on rural areas. Usually there occurs biomass wastes and other wastes appropriate to use for energy purposes but in small amount. For example logistic costs drastically limits biomass wastes supplies to big scale electro-power stations in Poland. In our opinion land development of rural areas needs small and very small scale technical solutions for wastes utilisation and energy production. In such case will occur reduction of Greenhouse Gases (GHG) emissions, deceleration of climate warming process, rural areas development, stopping spending money for wastes utilisation by present methods, saving money for energy purchase what should lead to the increase of welfare of rural areas (saved money could be used for other purposes or needs). However for planning purposes and choice of optimal localisation of the system it should be known some technical parameters as fuel mass consumption needed to the production of $1 \cdot 10^3$ W·h of electrical energy according to calorific fuel value. Different types of wastes could be characterised by calorific value. The knowledge of fuel mass consumption by individual wastes types is important to planning of these wastes development in real cases.

MATERIALS AND METHODS

Calculations were done with the help of OGLST programme (Gas dynamic calculations of aviation turbine engines) elaborated by [GIERAS 2013]. The programme interface has been done in Polish language. The programme can make calculations for 10 different types of turbine engines implemented in aviation. GTD-350 is aircraft turbine from helicopter with two shafts. In the program such type engine was chosen.

In the program Lower Heating Value (LHV) input data was changed in range from $6 \cdot 10^6$ J·kg⁻¹ to $46 \cdot 10^6$ J·kg⁻¹. The engine has some geometric constraints which are derived from the design like dimensions of air inlet tubes, exhaust gases tubes, internal ducts, compressor elements, turbine elements which are inside the case. All geometrical constraints limits possible air intake by the engine. It is assumed for simulations that fuel volume is negligible in compare with air volume which is needed to fuel oxide. There was established air demand by the engine as $14.9 \cdot 10^3$ air m³·(fuel kg)⁻¹ found in the literature [GIERAS 2013]. All input parameters are presented in Table 1. Most of them are related to internal engine construction and taken from [GIERAS 2013].

Exact mathematical calculation model which are lying behind of the OGLST programme are described by GIERAS [2013]. They were done with following simplification recommendations (a) no heat exchange with environment, (b) working gas inside engine satisfies the Clapeyron equation, (c) fields of temperatures, speeds and pressures are homogenous in specific characteristical crosssections, (d) no thermal dissociation of exhaust gases, (e) temperature drop of exhaust gases by mixing them with chilling air is not included. The calculation procedure can be presented as follows. At the beginning temperature at the engine inlet T_1 (in K) is calculated according to Equation (1):

Table 1. Input parameters

Symbol	Name	Unit	Value
H	flight altitude	m	0
M	Mach speed of flight	Ma	0
W_d	fuel lower heating value (range)	$10^6 \text{ J}\cdot\text{kg}^{-1}$	6–46
L_t	theoretical air demand	(air kg) \cdot (fuel kg) $^{-1}$	14.9
π_{WL}	air compression ratio on inlet	–	0.986
π_S	compression ratio of compressor	–	5.4
η_S	efficiency of compressor	–	0.79
ξ_{KS}	degree of heat transfer in burning chamber	–	0.98
π_{KS}	compression ratio in burning chamber	–	0.93
T_3	temperature in burning chamber	K	1193
η_{TS}	mechanical efficiency of compressor	–	0.99
π_{TW}	mechanical efficiency of free drive turbine	–	0.995
φ_D	speed loss degree at the engine outlet	–	0.75
N_{zr}	mechanical power reduced to the propeller shaft	10^3 W	235.4
v_{Chl}	relative mass flow of the cooling air	–	0.029
v_{Up}	relative bleed air mass flow for in-flight use	–	0
v_w	relative mass flow of the cooling air returning to the turbine flow channels	–	0
M_4	the turbine exhaust gases speed	Ma	0.4
η_r	mechanical efficiency of reducer	–	0.985
η_{sm}	mechanical efficiency of propeller shaft	–	0.99

Source: own elaboration.

$$T_1 = T_H \left(1 + \frac{k-1}{2} M_H^2 \right) \quad (1)$$

where: T_H is air temperature (in K) at the flight altitude, k = dimensionless adiabatic exponent for air ($k = 1.4$), M_H = Mach speed of flight.

Pressure p_1 (in Pa) at the inlet to the engine can be calculated according to Equation (2).

$$p_1 = \pi_{WL} \cdot p_H \left(1 + \frac{k-1}{2} M_H^2 \right)^{\frac{k}{k-1}} \quad (2)$$

where: π_{WL} = dimensionless air compression ratio on inlet to the engine, p_H = air pressure at the flight altitude (Pa), k (see Eq. 1), le_s = effective work of compressor ($\text{J}\cdot\text{kg}^{-1}$), dependent on temperature T_1 , it can be expressed by Equation (3):

$$le_s = \frac{kR}{k-1} T_1 \frac{\pi_S^{\frac{k-1}{k}} - 1}{\eta_S} \quad (3)$$

where: R = gas constant for air ($R = 287 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$), π_S = dimensionless compressor ratio, η_S = dimensionless efficiency coefficient of compressor investigated under normal conditions in ambient temperature 293.15 K (20°C).

Compressed air owns other temperature at the compressor output in compare to input and can be calculated from Equation (4):

$$T_2 = T_1 + le_s \frac{k-1}{Rk} \quad (4)$$

where: T_2 = air temperature at the compressor output (K).

The air pressure p_2 (in Pa) at the compressor output can be expressed by Equation (5):

$$p_2 = p_1 \pi_S \quad (5)$$

Unitary fuel consumption τ (in $\text{kg}\cdot\text{s}^{-1}$) can be calculated from Equation (6):

$$\tau = c_{umKS} \frac{T_3 - T_2}{\xi_{KS} W_d} \quad (6)$$

where: T_3 = temperature in burning chamber (in K, $T_3 = 1193 \text{ K}$), ξ_{KS} = dimensionless degree of heat transfer in burning chamber ($\xi_{KS} = 0.98$), W_d = Lower Heating Value ($10^6 \text{ J}\cdot\text{kg}^{-1}$). For processes taking place in the combustion chamber is assumed as $c_{umKS} \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}$ conventional specific heat (from Eq. 6) which could be expressed by temperatures before and after burning chamber (see Eq. 7).

$$c_{umKS} = 1000[0.9089 + 0.0002095(T_3 + 0.48T_2)] \quad (7)$$

N_{zrj} = unitary power received on the propeller shaft (10^3 W) (see Eq. 8).

$$N_{zrj} = \eta_r \left[(1 - v_{Chl} - v_{Up} + v_w)(1 + \tau) le_{TS} - \frac{le_S}{\eta_{mTS}} \right] \quad (8)$$

where: η_t = dimensionless shaft efficiency ($\eta_t = 0.985$), v_{Chl} = dimensionless relative flow of cooling air ($v_{Chl} = 0.0299$), v_{Up} = dimensionless relative flow of discharge air from compressor ($v_{Up} = 0$), v_w = dimensionless flow of air returning to the engine flow channel ($v_w = 0$), η_{mTS} = 0.99 dimensionless mechanical efficiency of compressor ($\eta_{mTS} = 0.99$), le_{TS} = effective work of turbine ($\text{J}\cdot\text{kg}^{-1}$) expressed by Equation (9):

$$le_{TS} = \frac{k'R'}{k'-1} T_3 \left(1 - \pi_{TS}^{\frac{k'-1}{k'}} \right) \eta_{TS} \quad (9)$$

where: k' = dimensionless adiabatic exponent for exhaust gases ($k' = 1.33$), R' = gas constant for exhaust gases ($R' = 289.3 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$), $T_3 = 1193 \text{ K}$ temperature after burning chamber suggested by GIERAS [2013], π_{TS} = dimensionless turbine compressing ratio ($\pi_{TS} = 0.92$) from GIERAS [2013], 0.995 = dimensionless mechanical efficiency of turbine from GIERAS [2013].

Equation (10) presents $b_{zr} \text{ kg}\cdot 10^{-3}\cdot\text{W}^{-1}\cdot\text{h}^{-1}$ unitary fuel consumption related to the unitary power received on the propeller shaft.

$$b_{ezr} = \frac{\tau}{N_{zrj}} \quad (10)$$

The simulations were done with assumption of the system work $t = 7,000 \text{ h}\cdot\text{y}^{-1}$ (about 80% time of year) with maximal nominal mechanical power of $N = 0.235 \cdot 10^6 \text{ W}$. The rest of the time is predicted for necessary renovations and stops for changing fuel type. $F_{\text{consumption}} \text{ kg}\cdot\text{y}^{-1}$ total fuel consumption per year can be calculated from Equation (11):

$$F_{\text{consumption}} = b_{ezr} \frac{N}{\eta_{el}} \quad (11)$$

where: η_{el} = dimensionless efficiency of electrical energy production from the engine mechanical energy ($\eta_{el} = 0.9$).

The set of simulation results was analysed by fitting to them the regression exponential function and R^2 determination coefficient with Excel functions implementation.

RESULTS AND DISCUSSION

Table 2 presents results of simulations for unitary fuel mass consumption calculated from Equation (10) and fuel consumption per year in relation to LHV calculated from Equation (11).

The equation of regression function (12) owns $R^2 = 0.9985$ dimensionless determination coefficient.

$$b_{ezr} = 14.648LHV^{-0.875} \quad (12)$$

The regression function is power function and indicates on strong nonlinear dependence between unitary fuel mass con-

Table 2. Fuel mass consumption and related to it fuel consumption per year by GTD-350 according to LHV for 7,000 $\text{h}\cdot\text{y}^{-1}$ of the engine work

LHV ($10^6 \text{ J}\cdot\text{kg}^{-1}$)	Unitary fuel mass consumption ($\text{kg}\cdot 10^{-3}\cdot\text{W}^{-1}\cdot\text{h}^{-1}$)	Fuel consumption ($10^3 \text{ kg}\cdot\text{y}^{-1}$)
6	2.911	4,311.19
10	1.967	2,913.13
12	1.690	2,502.89
15	1.400	2,073.40
18	1.193	1,766.83
21	1.040	1,540.24
24	0.921	1,364.00
26	0.856	1,267.74
30	0.750	1,110.75
35	0.650	962.65
40	0.573	848.61
42	0.547	810.11
46	0.502	743.46

Explanation: LHV = Low Heating Value.
Source: own study.

sumption and LHV . It is reflected on fuel consumption per year by GTD-350 according to LHV for assumed 7,000 $\text{h}\cdot\text{y}^{-1}$ of the engine work.

Results of investigation are unique and very important for the future planning fuels supply. Exhaust gases have 602°C according to simulations results. They can be directed to heat exchanger where the heat from exhaust gases could be used for heating processes. With the assumption of 80% efficiency of total cogeneration process and about 46% efficiency of heat energy production in the cogeneration process for small units [PAJAK 2014] it could be concluded that nominal heat power which could be directed from the GTD-350 engine to heat exchanger is about $0.318 \cdot 10^6 \text{ W}$.

Results of simulations are similar to values obtained in Japan during electricity production from wood chips related to $0.235 \cdot 10^6 \text{ W}$ as $2,298 \cdot 10^3 \text{ kg}\cdot\text{y}^{-1}$ [IRENA 2019] with LHV $12 \cdot 10^6 \text{ J}\cdot\text{kg}^{-1}$. Similar values for electricity production from biomass were given by [MIROWSKI *et al.* 2019] as $2,380 \cdot 10^3 \text{ kg}\cdot\text{y}^{-1}$ with LHV $12 \cdot 10^6 \text{ J}\cdot\text{kg}^{-1}$ related to power $0.235 \cdot 10^6 \text{ W}$.

In our simulations was achieved value $2,502 \cdot 10^3 \text{ kg}\cdot\text{y}^{-1}$ for similar LHV . It proves that program works well and gives proper values.

CONCLUSIONS

The proposed system core will be GTD-350 turbine engine. It will consume fuel and drive electricity generator. Unique feature of this engine is inherited possibility of use liquid or gaseous fuels due to internal design and construction of the engine. Its output power depends mainly on LHV of used fuel. The engine can be modernised to use also solid type fuel as for example micronised biomass in similar way as it was done with AI-20 turbine engine modernised in BioCHP project. AI-20 turbine engine had nominal power of 2.5 MW which is seven times more in compare with GTD-350 engine. Proved technical concepts and solutions from BioCHP project can be implemented for modernisation of GTD-350. There could be a mix of different fuels accessible in the nearest area of GTD-350. Defined during simulations the regression exponential function is very important for determination of local fuel resources needed to GTD-350 engine running. A calculator of fuel mix based on the determined regression power function could be done for optimal use of available local resources including in it for example biomass wastes or RDF. The calculator should have possibility to introduce fuel type, LHV and amount. After calculations it could give information about possible energy production based on introduced data. It should support the system localisation in the area where will be enough fuel resources. There should be remarked that for smaller energy systems it can be easier to find a localisation than for a bigger one due to dissipation of fuel local resources. Due to this reason systems based on GTD-350 turbine engine can be placed in bigger amount of localisations than systems based on AI-20 turbine engine. Heat from the exhaust gases can be used for biomass drying because of LHV increase. If biomass is more dried (have less moisture content) the higher LHV owns. This is the task for further improvement of the system, for effective sludge implementation as a fuel near small, local treatment stations.

The system could be work in moments when there is a peak demand for electricity. Then electricity prices are much much

higher than electricity prices distributed in other hours. It is the most economically efficient solution. At these moments system could produce both electricity and heat. Heat could be stored in water accumulation tanks which supply heat to local heating system or to local hot water production systems. The system could be supplied by different types biomass wastes which usually occurs in relatively small amounts in local communities or rural areas. The system could be also assembled in containers. It enabled to move the system, to places where small resources of waste biomass are available and their logistic to processing places would be too costly. In this case most of currently unused or unprocessed wastes could be recycled for energy production, according to A New Circular Economy Action Plan, Bioeconomy Strategy and The European Way to Use Our Natural.

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