Report of short term scientific mission.

1. Details of STSM

STSM title: Feasibility analysis of microturbine engine to fire innovative fuels

Reference: COST-ONLINE_STSM-CM1404-30846

Personal information:

Name: Tine Seljak

Date of Birth: 14th August 1984

Position: Researcher, PhD student

Institution: University of Ljubljana, Faculty of mechanical engineering, Department of power engineering, Laboratory for internal combustion engines and electromobility.

Area of expertise: Application of alternative fuels in internal combustion engines

Address of Home institution

University of Ljubljana

Faculty of mechanical engineering

Askerceva 6

Si-1000 Ljubljana

Slovenia

Address of Host Institution

Vrije Universiteit Brussel,

Faculty of Engineering,

Department of Mechanical Engineering,

Pleinlaan 2

B-1050 Brussels

Contact: prof. Francesco Contino

Type and length of stay

Length: 10.12.2015 – 18.12.2015 (8 days)

Type: PhD student

2. Objective

The goal of the visit was to estimate the feasibility of a microturbine engine (MGT) to be operated with innovative energy carriers with specific focus on liquefied lignocellulosic biomass. The data will be first used to obtain a reference for operating conditions on an experimental microturbine engine stationed in University of Ljubljana. Secondly, the possibility to perform further experiments with liquefied wood on a MGT, stationed in VUB will be evaluated and discussed based on construction, control system design and key operating parameters of MGT.

3. Timeline and activities:

Thursday 10/12/2015: Visual inspection of the MGT, discussion about operating principles and technical details, familiarizing with data acquisition system and technical manuals.

Friday 10/12/2015: Experimental activities

Monday 14/12/2015: Discussion and inspection of feasibility to adapt the MGT to liquid fuels.

Tuesday 15/12/2015: Analysis of data acquired through experimental activities.

Wednesday 16/12/2015: Comparison of analysed data to data from system on University of Ljubljana.

Thursday 17/12/2015: Definition of necessary steps to adapt the MGT to liquid fuels and risk assessment.

Friday 18/12/2015: Discussion of possible cooperation areas and topics with definition of timeline.

4. Major results

The STSM was focused on experimental work and analysis of key engine components and control system. The key information about the MGT is summarized in Table 1.

Table 1: Key information of MGT (T100), based on manufacturers data [1]:

Manufacturer/model	Turbec/T100
Compressor/Turbine type	Centrifugal / radial
Combustion chamber	Reverse flow, lean premix
Nominal pressure ratio	4,5
Nominal turbine inlet temperature	950 °C
Nominal speed	70000 rpm
Fuel type	Natural gas
Heat input	333 kW
Exhaust gas flow	0,79 kg/s
Electrical/heat efficiency	30% / 50%

General characteristics of the system are defining the suitability to fire different alternative fuels is presented below and is based on observations during the visit and data provided by host institution as well.

4.1 Gaseous fuels

The T100 is primarily designed to use natural gas (NG) as a fuel with consecutive gaseous fuel specific combustion chamber and fuel system. The fuel delivery system is provided as a separate unit (gas booster) for pressurization (screw compressor) and pulse width modulation (PWM) solenoid valves for delivery of main and pilot fuel injection. The fuel quantity control is done via a main control parameter – power output and turbine outlet temperature (TOT) which is internally recalculated also to turbine inlet temperature (TIT) and to lower heating value (LHV) of the fuel. The relatively complex fuel control system is thus managed in a closed loop manner. Minor variations in LHV of the gas are by fuel control system itself, as far as the Wobbe Index (WI) is within 43-55 MJ/m^3. In case of alternative gases with WI other than specified, a workaround through security protocols is required for higher end of WI, whereas for lower end of WI, remapping and resizing of PWM controlled valves is required up to the capacities of fuel delivery compressor. Very low values of WI might interfere also with screw compressor capacity, requiring the upgrade of compressor. In the case of upgraded fuel compressor, capable of supplying even fuels with very low WI, the lowest WI is limited with approximately 20% of nominal WI, where operation of main air compressor below the surge line is so far confirmed by experiments with water injection.

The design of combustion chamber assumes the lean-premix type of combustion. The positions of main and pilot fuel injection are presented in Figure 1 and could be implemented also with other gaseous fuels, however the stoichiometric ratio of fuel might influence the ratio between pilot and main injection according to geometry-defined air quantity in the premixing zone. Also, the flammability limits of the fuel can play an important role when determining the main line injection quantity, particularly with fuels, exhibiting wider flammability limits which could result in increased probability of flashback occurrence.

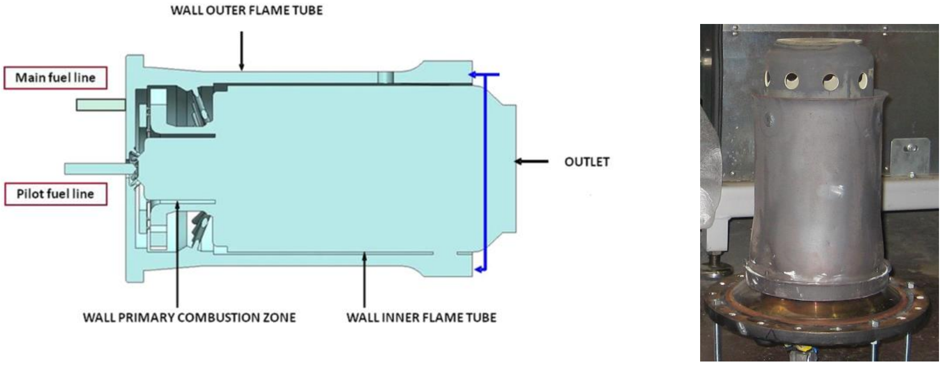

Figure 1: Main and pilot fuel injection in T100 gaseous combustion chamber [2].

Thus, considering gaseous fuels, the T100 provides a sufficiently equipped platform for testing wide spectra of different fuels. With modifications of the fuel system capacity the list could be further expanded also to low heating value gasses. To protect the gas system components, sufficient filtration and reduction of tar content is important, however this can be done individually for tested fuels according to the composition of impurities.

4.2 Liquid fuels

The applicability of liquid fuels to T100 designed for NG is generally very limited. The main obstacles to directly apply liquid fuel is:

- the absence of liquid fuel delivery system with accompanying control system,
- the design of combustion chamber, which is able to support only highly volatile fuels with very low evaporation and/or carbon residue.

The original fuel system could be adapted to a certain degree by replacing key components to suit liquid fuels (i.e. compressor for pump, gas buffer for hydraulic accumulator, gaseous ports for liquid injection nozzles). By simultaneously remapping the fuel control valves (originally performed by PWM driven solenoids), the existing T100 control system could be used, however it would be, to a certain extent fuel specific due to different pressure requirements for different types of fuels – either due to different volumetric heating value or different viscosities requiring different atomization parameters. The main advantage of this approach lies in the fact that original start-up and shut-down procedure could be preserved and no serious interference with control system would be necessary. However, the drawback in this case is an inability to use heavy fuels with low volatility and high autoignition temperature as an initial ignition sequence could likely be seriously compromised. In such cases, complementary, autonomous fuel system is required to pressurize/preheat and condition liquid fuels which can then be introduced in the combustion process after operational parameters of MGT are stabilized with the use of original design fuel. Essentially, a dual-fuel operation with on-line fuel switch is necessary to provide sufficiently flexible machine.

For such purposes, already developed stand-alone fuel system is available at University of Ljubljana. Currently, the capacities are sufficient to support required heat input for T100, taking into account that heating value of the fuel does not drop below 15 MJ/kg at density 1,3 kg/L. Control of the fuel system is via coriollis mass flow meter and volumetric pump providing constant fuel supply also in case of pressure fluctuations in combustion chamber.

Focusing on combustion chamber design, the main obstacles are generally linked to the fact that premixing, gaseous fuel combustion is predicted during operation of the T100:

- Complex geometry for delivery of main fuel stream to the secondary zone would require prevaporization of liquid fuel and delivery of only gaseous fraction, as the discharge surfaces of main fuel stream compartment (Figure 2-a) are not suitable for additional fuel injection nozzle installation. The dimensions of discharge surface would require several nozzles to assure uniform circular distribution of the fuel.
- Location of pilot fuel injection and rough dimensions of surrounding flame tube sections (Figure 2-b) suggests that in order to avoid the surface impingement of liquid fuel, a very narrow spray patter would be required (< 30°). High axial velocities obtained with narrow angles of spray pose a significant risk of excessive droplet penetration rates resulting in either repositioning of the flame closer to a turbine inlet duct or significant chemical losses in form of unburnt hydrocarbons.

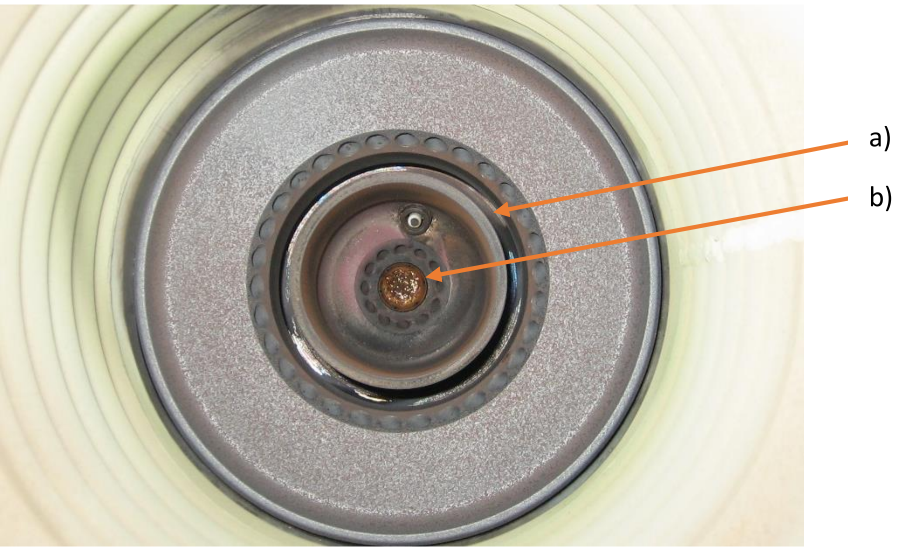

Figure 2: Combustion chamber main fuel outlet (a) and pilot fuel outlet (b)

From this point of view, the liquid fuel would require adaptation or development of liquid fuel specific combustion chamber which would also incorporate the geometrical properties required for evaporation of fuels. Ideally, to increase the fuel flexibility, vaporization tube and premixing should be omitted in the first stage of activities. To ease the adaptation procedure, centreline fuel injection would be beneficial. At the same time, the combustion chamber should also be able to support NG combustion which would allow start-up and stabilization of operational parameters with NG to avoid transient operation before switching to liquid fuel. Generally, the combustion chamber should therefore be able to support dual-fuel operation, meaning that two concentric or twin-fluid injection nozzle would be required.

4.2 Proposed solutions for liquid fuel adaptation

4.2.1 Combustion chamber

Two options exist for adaptation of combustion chamber, both rely on an existing can that is currently installed in the experimental setup of University of Ljubljana. The first option is to adapt the can type from co-flow combustion chamber (Figure 3) to counterflow. This can be done by adding an outer combustion chamber wall. This procedure involves careful dimensioning and notable adaptations of co-flow combustion chamber, however it assures compact solution and installation in an existent T100 combustion chamber casing. The adaptation procedure would start with flow field analysis, followed by optimization and development of prototype solution.

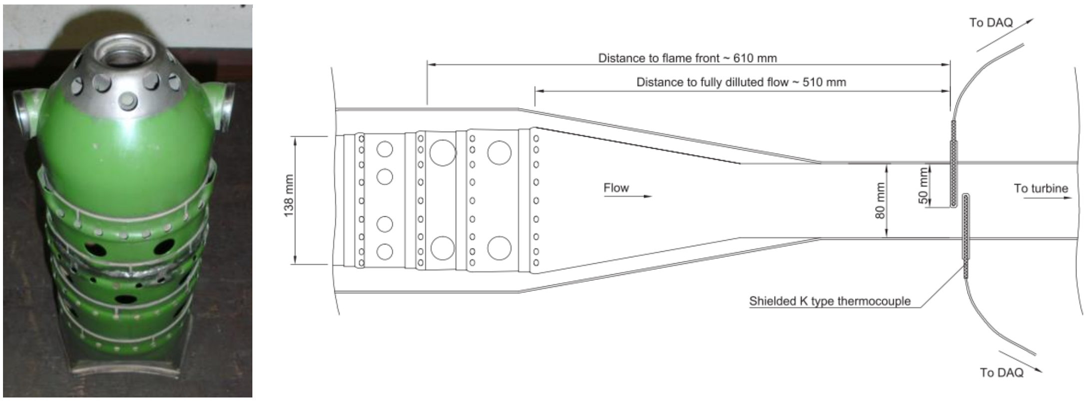

Figure 3: Can type, co-flow combustion chamber with centreline fuel injection that can adapted to fit into existent combustion chamber casing of T100.

Alternative option is to base on an existing experimental setup at University of Ljubljana with aforementioned can type co-flow combustion chamber without any modifications. In this case, the complete air-path together with combustion chamber casing and intake/outflow tubes would be used in T100. The complete air-path (shown in Figure 4) would be connected to recuperator discharge and turbine intake duct of T100, thus completely bypassing the current section between recuperator and turbine. This would provide a much more robust layout with easily interchangeable components and already installed injection nozzle. However, a technically more demanding coupling to the T100 is predicted due to flangeless recuperator and turbine connections.

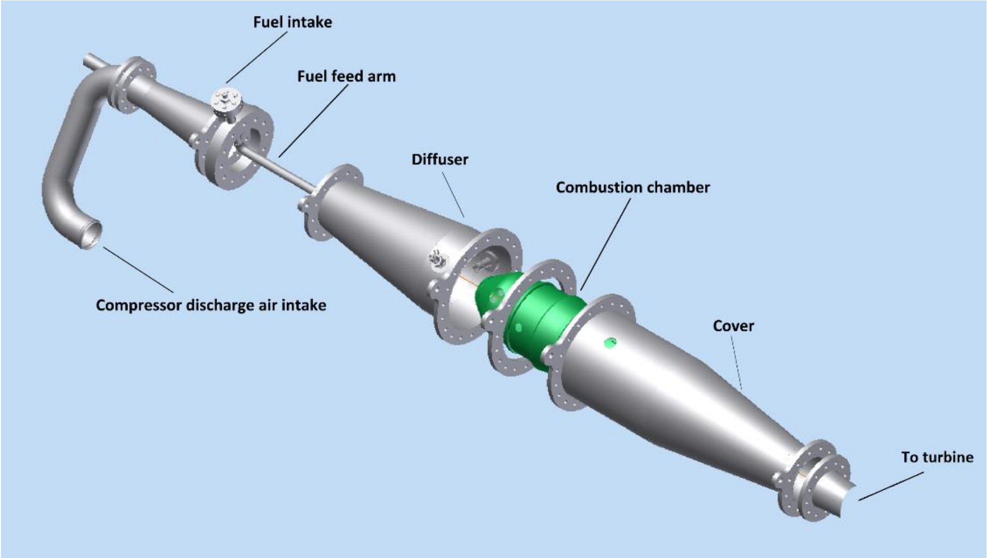

Figure 4: Complete air-path which can be used to bypass the existing T100 combustion chamber, requiring no adaptations of co-flow combustion chamber.

The decision between upper two options will rely on actual dimensions of original T100 gaseous combustion chamber, which will reveal the extent of required adaptations on proposed combustion chamber.

4.2.2 Fuel / injection system

Considering fuel injection system, the liquid fuel injection nozzle is fuel-specific and should be chosen according to target fuel properties. In case of testing liquefied wood (previously analysed in [3-5]), a twin-fluid swirl-air nozzle is required (Figure 5). For natural gas, which is required to start up and shut down the T100, either a multi-point annular nozzle for NG, surrounding the liquid fuel nozzle or several separate single-point injection nozzles would be required. There is also a possibility to use NG as an atomizing agent instead of air in a twin-fluid nozzle. This would allow to use the same nozzle for both fuels, however a fuel flow control would be demanding as quantities of liquid and gaseous fuel would in this case be interrelated.

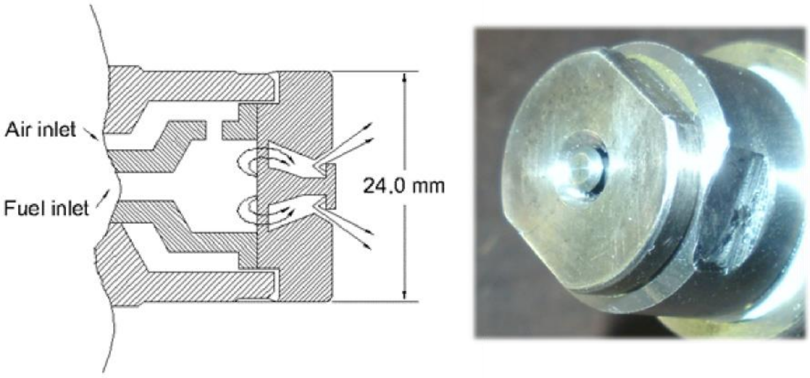

Figure 5: Twin-fluid nozzle

The existing fuel system on University of Ljubjlana can be used on T100 as is, as it was developed according to parameters required by T100. The layout of the fuel system is presented on Figure 6. Coupling of the liquid fuel system to T100 at a first stage could be done by a separate manual control of liquid fuel flow which would only be performed at stabilized operation with NG. The predicted procedure would be to first slowly increase the liquid fuel flow from 0 kg/s upwards. With additional energy delivered with liquid fuel, the original T100 fuel control system would initiate a reduction in NG flow as it would assume that either the heating value of the gas has changed or the air-flow is reduced.

Bypassing the safety procedures, the quantity of the NG could be reduced to the point where main fuel line is shut off and only pilot injection quantity is delivered (15% of heat input). The pilot NG injection quantity would still be linked to original T100 fuel system, therefore it would be able to even out fluctuations in operational parameters in terms of load, TOT and rotational speed. In this case the delivery of the liquid fuel could be constant with no required input from T100 apart from emergency switch-off which would be best linked to T100 emergency shut-off command.

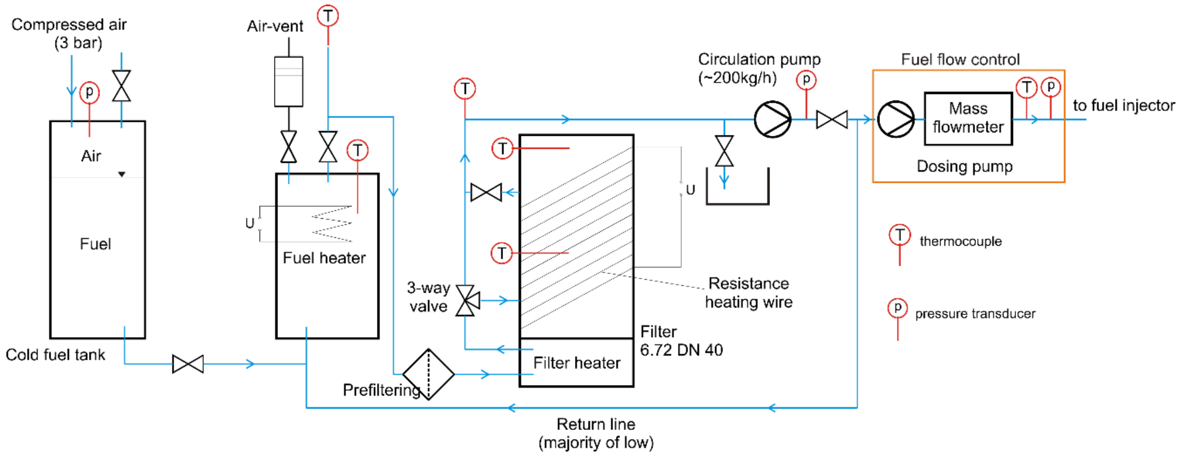

Figure 6. Fuel preheating/delivery system for liquid fuels

4.3 Comparison of T100 and experimental system on University of Ljubljana

The data, obtained through measurements on T100 provides the benchmark for operation of fuel system as well as an insight into general parameters of T100 operation, which serve as an input for estimation of feasibility to fire liquefied wood in T100. The baseline conditions required for obtaining stable combustion of liquefeid wood were previously determined on experimental system on University of Ljubljana and are roughly as follows:

- Turbine inlet temperature >800°C
- Primary air temperature >400°C
- Fuel temperature >90°C

The parameters of T100 operation in most cases preceed the upper conditions, with exception of fuel temperature which could be controlled by fuel system proposed above.

Time-resolved key operational parameters during 200s time interval are shown on Figure 7. These give an insight into stability of fuel supply system.

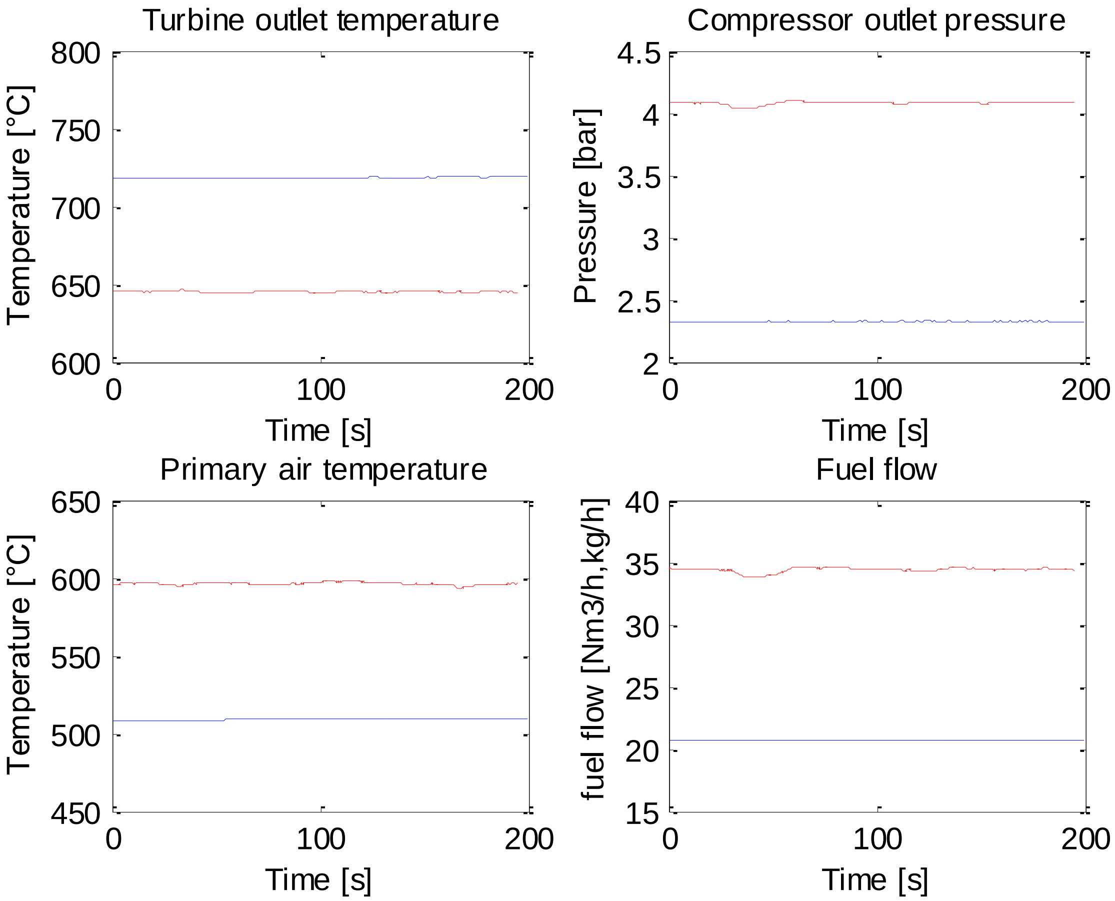

Figure 7: Time-resolved parameters of Turbec T100 (red) and experimental turbine on University of Ljubljana (blue).

The relatively low deviation of values reveal sufficiently good control of fuel flow to safely support the operation of T100 under the assumption that required fluctuations in fuel flow would be covered by T100 original fuel system.

5. Future colaboration and forseen publications

The timeline of further cooperation on specific topic of STSM is planned to be the following:

- Ash analysis of the latest fuel formulation will be performed by University of Ljubljana (by January 2016).
- Dimensional data of current T100 combustion chamber will be provided by VUB (By February 2016).
- After above two points, a joint risk assesment of the T100 adaptation to liquid fuel will be done (by February 2016).

During the STSM, other potential cooperation areas between VUB, department of mechanical engineeering were identified:

- Common experimental campaings on MGT, resulting in publications on alternative fuels using jointly-developed MGT with liquid/gaseous fuels.
- Common project applications on these topics on either EU-funded projects or projects with national funding.
- Marie-Skodlowska Curie actions
- Bilateral cooperation financing (provided by Slovenian research agency), when conditions are met.

Forseen publications are strongly related to presented timeline of further cooperation and only after thorough risk assesment, a more defined timeline of publication could be determined. The area of forseen publication is strongly pointed towards MGT and the use of alternative fuels in MGT systems.

6. References

[1] T100 microturbine system CHP system - *Technical description* Ver 4.0. Turbec AB, Malmö, Sweden, 2001.

[2] Cadorin M., Pinelli M., Vaccari A., Calabria R., Chiariello F., Massoli P., Bianchi E. Anaylsis of a MGT fed by natural gas and synthesis gas: MGT test bench and combustor CFD analysis. Journal of engineering for gas turbines and power, 2012, Vol. 134, p. no. 071401.

[3] Seljak T., Rodman O.S., Kunaver M., Katrašnik T. (2012). Wood, liquefied in polyhydroxy alcohols as a fuel for gas turbines. Appl Energ, vol. 99, 40-49.

[4] Seljak T., Rodman O.S., Katrašnik T. (2014a). Microturbine combustion and emission characterisation of waste polymer-derived fuels. Energy, vol. 77, 226-234.

[5] Seljak T., Rodman O.S., Kunaver M., Katrašnik T. (2014c). Effect of primary air temperature on emissions of a gas turbine, fired by liquefied spruce wood. Biomass Bioenerg, vol. 71, 394-407.