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Steam injection experiments in a microturbine – A thermodynamic performance analysis

Ward De Paepe [a,*], Frank Delattin [a], Svend Bram [a,b], Jacques De Ruyck [a]

[a] Vrije Universiteit Brussel, Dept. of Mechanical Engineering (MECH), Pleinlaan 2, 1050 Brussel, Belgium
[b] Erasmushogeschool Brussel, Dept. of Industrial Sciences and Technology, Nijverheidskaai 170, 1070 Brussel, Belgium

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ABSTRACT

This paper reports on a series of steam injection experiments on a Turbec T100 microturbine. Combined Heat and Power (CHP) systems, such as the considered T100 microturbine, use one single primary fuel to simultaneously produce electric and thermal power. In doing so, they realize significant energy savings compared to conventional schemes of separated production. However, a reduction in the demand for heat (e.g. in summertime) will force this type of units to shutdown. This significantly reduces the amount of operating hours and has a severe negative impact on the net present value of such CHP investment projects.

The aim of this paper is to investigate and demonstrate the effects of steam injection in the compressor outlet of a microturbine operating under reduced heat demand conditions, in order to keep the unit running. The necessary steam can be auto-raised with heat available in the turbine exhaust downstream of the recuperator. Such an injection will keep the unit running and thus avoid a forced shutdown. Furthermore, it is expected that the electric efficiency will rise and that the power production will become more economically viable as a result of the increasing operating hours.

This paper reports on the influence of steam injection on the electrical efficiency and shaft speed of a T100 unit. ASPEN® simulations of the behavior of the CHP unit are also presented. These simulations predicted a 2.2% rise in electric efficiency at nominal electrical output when 5% of the mass flow rate of air is replaced by steam.

The steam injection experiments resulted in stable runs of the unit, a predicted reduction in shaft speed and increasing electrical efficiency. Validation of the ASPEN® simulations against the experimental data revealed the necessity for a more accurate determination of the air mass flow rate and more precise compressor characteristics.

1. Introduction

Microturbines are in general cost effective [1,2], but in our specific (residential) case, the attractiveness of the investment depends strongly on the yearly amount of running hours of the unit. A non-continuous heat demand reduces the amount of yearly running hours and negatively affects the profitability. Current research on improving microturbine efficiency focuses mainly on improving the thermal resistance of the inner microturbine parts and on recuperator designs with increased heat exchanger efficiency [3–5]. This paper presents an alternative route to increase the yearly amount of running hours. By injection of steam, auto-raised with the available heat in the turbine exhaust, the fuel consumption can be reduced during hotter periods with reduced heat demand. The injection of steam increases electric efficiency of the unit and more importantly avoids the shutdown of the unit. This increases the engine running hours, which has a positive impact on the net present value, resulting in a more interesting Combined Heat and Power (CHP) investment project [6].

2. Approach

In previous work [6], the dry and wet operation of the T100 microturbine were simulated with the ASPEN® plus process simulation tool (Version 2006.5). Dry simulations were compared with experiments for validation. In this work, experiments on the T100 microturbine were performed to validate the wet simulations. Wet simulations predicted a 2.2% rise in electric efficiency at nominal electrical output if 5% of the mass flow rate of air is replaced by steam.

In a first step, an analytic perturbation model was set up to accurately calculate changes in microturbine parameters and overall efficiency. Based on the variation of the shaft speed and the injected steam flow, the perturbation of all parameters can be calculated accurately. Verification of the model was performed by comparing it to the ASPEN® simulations [6].

* Corresponding author. Tel.: +32 2 6293182; fax: +32 2 6292865.
E-mail address: wdepaepe@vub.ac.be (W. De Paepe).

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Nomenclature

CAF	corrected air flow, defined as $\dot{m}_{air}\sqrt{T_1}/p_1$ (kg$\sqrt{K}$/s/bar)
CHP	Combined Heat and Power
C_p	heat capacity (J/kg K)
HRSG	Heat Recovery Steam Generator
LHV	lower heating value (MJ/kg)
k	specific heat ratio, C_p/C_v
$\dot{m}_{air}$	air mass flow (kg/s)
$\dot{m}_{comp}$	mass flow through compressor (kg/s)
$\dot{m}_{fluegas}$	flue gas mass flow (kg/s)
$\dot{m}_{fuel}$	fuel mass flow (kg/s)
$\dot{m}_{steam}$	injected steam mass flow (kg/s)
$\dot{m}_{turb}$	mass flow through turbine (kg/s)
N	compressor shaft speed (%) of nominal speed
p	pressure (bar)
PIT	turbine inlet pressure (bar)
POT	turbine outlet pressure (bar)
T	temperature (°C)
TIT	turbine inlet temperature (°C)
TOT	turbine outlet temperature (°C)
$\dot{W}_{comp}$	power consumed by compressor (kW)
$\dot{W}_{el}$	delivered net electrical power (kW)
$\dot{W}_{turb}$	delivered turbine power (kW)

Greek symbols

π	pressure ratio, defined as p_2/p_1

Subscripts

1	conditions at compressor inlet
2	conditions at compressor output
4	conditions at recuperator outlet
comp	conditions inside compressor
fluegas	conditions of flue gases
is	isentropic conditions
ref	dry reference case
steam	condition of injected steam
turb	conditions inside turbine
Surge	conditions at surge limit
Working	conditions at operating point

In a second step, experiments with externally produced steam were performed on the T100 microturbine at nominal and partial load. Measurements were used to validate the ASPEN® model simulations.

3. Microturbine layout

Fig. 1 shows the standard microturbine layout. After entering the compressor (1), the compressed air enters the recuperator (2) for partially recuperating residual heat from the flue gases. Fuel is injected in the combusting chamber in order to raise temperature till the maximum turbine inlet temperature (3). Behind the air recuperator, a secondary heat exchanger provides hot water for residential heating purposes (4). Through a single shaft, the microturbine is connected to a high-speed electric generator. The power output of the generator is adapted by power electronics to deliver 50 Hz electricity.

4. Experimental setup

The experiments were performed using a Turbec T100 microturbine, with a nominal power output of 100 kW. The microturbine produces a fixed electrical power output by adjusting its rotation speed. Table 1 reports the thermodynamic conditions of the T100 at each stage of its cycle in Fig. 1, in nominal 'dry' mode and in nominal 'wet' mode.

Microturbine electric efficiency is calculated using Formula (1)

$$\eta_{el} = \frac{\dot{W}_{el}}{\dot{m}_{fuel} LHV} \tag{1}$$

Although externally produced steam is injected in the microturbine during the described tests in this paper, the energy from the injected steam is not considered in efficiency calculations (see Eq. (1)). In the final lay-out of the microturbine, the goal is to use steam, auto-raised in a low pressure steam generator with the available heat in the turbine exhaust (see Fig. 1). The amount of injected steam, externally produced with a steam generator, as described in paragraph 4.2, matches the maximum possible amount of steam that can be auto-raised, using a Heat Recovery Steam Generator (HRSG). For the lab setup however, no HRSG was installed for steam production. Instead, an electric steam generator was used to produce the necessary steam in order to obtain a higher flexibility in the injected steam mass flow during the test. The steam generator also allows a better insight in the experiments.

A Diris multimeter (Socomec) is used to measure the generated electric power with an accuracy of 1%. The LHV of the fuel was provided by the fuel supplier on a daily basis, together with the composition. Based upon this composition, the LHV has been recalculated in ASPEN®, resulting in a difference of 0.17% with the LHV provided by the supplier. An Actaris diaphragm meter (accuracy 0.5%) measures the fuel flow, resulting in an absolute error on the electric efficiency of 0.5%. The injected amount of steam is very small (maximum 5% of the total mass flow of air) and the predicted rise in efficiency is 0.44% per injected steam fraction[1] at nominal load, resulting in a very small change in fuel flow (2% less fuel consumption). The fuel flow meter is however incapable of accurately measuring this small variation in fuel flow. This problem can be solved using an analytical perturbation analysis.

In this perturbation model, an analytical model of the microturbine is built, in order to accurately calculate the efficiency rise. Starting from a *reference case* (dry case, ψ_{ref}), which is perturbed by steam injection, the new condition (called the *adapted case*, $\psi_{adapted}$) is calculated using only perturbation ($\delta\psi$) of accurate measurable parameters. (Rotation speed N and injected steam flow $\dot{m}_{steam}$) (see Formula (2))

$$\psi_{adapted} = \psi_{ref} + \delta\psi \tag{2}$$

4.1. Perturbation analysis

The electric efficiency of the microturbine can be calculated using Formula (1). When water is injected in the microturbine, electric power will rise, but the T100 delivers constant output power, so the controller will interfere and adjust the injected fuel in the combustion chamber. Thus, the rise in efficiency caused by steam injection can be calculated using Eq. (3) (produced electric power remains constant).

$$\frac{\delta\eta_{el}}{\eta_{el,ref}} = -\frac{\delta\dot{m}_{fuel}}{\dot{m}_{fuel,ref}} \tag{3}$$

[1] Steam fraction is equal to $\frac{\dot{m}_{steam}}{\dot{m}_{total}}$ with $\dot{m}_{total} = \dot{m}_{comp} + \dot{m}_{steam}$, taking into account the decreasing airflow because of the decreasing shaft speed.