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Operational Optimization of a Typical micro Gas Turbine

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Abstract

Micro Gas Turbines (mGTs) offer great potential for use in co-, tri or polygeneration applications. In these applications, where the heat from the exhaust gases is used in an efficient way, the mGTs achieve very high efficiencies. To be able to determine the number of units, the nominal parameters of the units and the specific operating strategy of the mGT, it is key to know precisely the performance of these units. Generally in co-, tri- or polygeneration applications with mGTs, this performance is considered to be known and fixed, and is therefore directly used to determine the operational strategy of the network, possibly linked with an economic analysis. In real world operating conditions, the parameters characterizing the operation of the mGT are measured with uncertainties. Depending on the model sensitivity to input parameters, these uncertainties may have a tremendous effect on the performance of the mGT. These uncertainties should be taken into consideration by the designers in an early stage of the design process to achieve a so-called robust design. In this paper, we present the operational optimization of a typical mGT, the Turbec T100 mGT, using a deterministic approach. In this approach, the parameter uncertainties are not taken into account, however, it is an important first step towards a full robust design, since it will set the reference. By varying Turbine Outlet Temperature (TOT) and compressor rotational speed, a Pareto front for maximal electrical power output and electrical efficiency is found. The two objectives are conflicting, making that the maximal electrical efficiency cannot be reached at maximal electrical power output. The results of this optimization will be used in our future study on the design optimization under uncertainties.

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Keywords: micro Gas Turbine (mGT); Combined Heat and Power (CHP), Operation Optimization; Deterministic Approach

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Nomenclature

CAF	Corrected Air Flow
mGT	micro Gas Turbine
NSPSO	Non-dominated Sorting Particle Swarm Optimizer
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
VUB	Vrije Universiteit Brussel

1. Introduction

Due to their rather low electrical efficiency (~30%), micro Gas Turbines (mGTs) are mostly used in co-, tri- or polygeneration applications. In these applications, where there is a specific need for heat and the remaining heat in the exhaust gases can be used efficiently, the mGTs achieve very high total efficiencies (>80%), making them profitable. Therefore, mGTs are considered as a valuable option as primary energy converter, by many researchers, in integrate energy networks with a clear power and heat demand. Several examples of the different usage of mGTs as common electricity and heat source in these networks are available in literature. Pilavachi [1], Kaikko et al. [2], Katsigiannis and Papadopoulos [3], Nikpey et al. [4] and Caresane et al. [5] studied the use of mGTs in typical cogeneration applications for heat production. Alternative integrations, like Bruno et al., using a mGT as power source in combination with a desalination plant, which absorbs the generated heat [6] and Ho et al., studying the performance of an mGT CHP system with absorption chiller, where the heat is used to provide cooling [7], are other typical examples of studies on mGTs integrated in polygeneration networks.

When designing these networks, typically, the number of Combined Heat and Power (CHP)-units (in this case: numbers of mGTs), the nominal power output and the operation strategy (heat or power load following) of the specific units need to be determined. Several examples of studies proposing different strategies can be found in literature. Carpaneto et al. presented a study on the planning of cogeneration under load uncertainties, using mGTs [8, 9]. Similar, Sanaye and Ardali also determined the optimal number of mGTs in a cogeneration system [10]. Campanari and Macchi performed simulations to optimize the operation of the mGT used for trigeneration applications [11, 12]. Depending on the study, the load profiles are considered with or without taking into account possible uncertainties on the future heat and power demand. On the other hand, all of the studies use a specific given full and part-load operation performance profile of the mGT, which is considered to be fully known and fixed.

In real world operating conditions, the thermodynamic parameters determining the mGT and its performance are also subject to uncertainties, which will have an effect on the operation. Depending on the sensitivity of the model to input parameters, these uncertainties may have a tremendous effect on the performance of the mGT, which, in turn, will affect the number of units, the nominal power output and especially the operational strategy. It is thus essential for the designers of these networks to consider, next to the uncertainties on the load profiles, also the uncertainties in model parameters from the early stage of the design process in order to achieve a so-called robust design, i.e. a design that is insensitive to natural variations of input variables. This is a quite challenging task, especially when the number of variable is high and/or when the computational model is costly-to-evaluate. However, before such a full robust design of the mGT operation can be performed, an essential initial step is the optimization of the mGT operation without considering these uncertainties. This optimized performance will then be used as reference case for the future optimization under uncertainty quantifications [13].

In this paper, we present thus the deterministic optimization of a typical mGT operation. This optimization, based on a classical multi-objective deterministic approach, where no uncertainties are taken into account, is, as mentioned before, an essential first step towards a robust design of the mGT and to a further extend the cogeneration network. A numerical model of the Turbec T100 mGT is constructed in Aspen Plus and its operation is optimized. The objectives of the optimization are maximizing electrical power output and efficiency by changing Turbine Outlet Temperature (TOT) and rotational speed within their boundaries. For the optimization, a multi-objective deterministic optimization method, the so-called Non-dominated Sorting Particle Swarm Optimizer (NSPSO) is used. In the following sections,

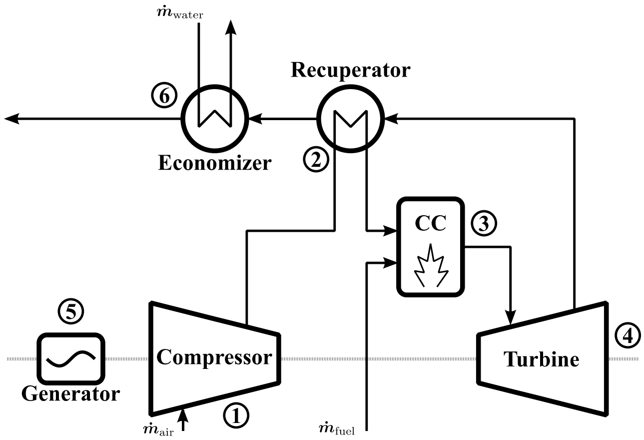

Figure 1: The used Turbec T100 mGT for the optimization is a typical recuperated Brayton Cycle.

first the numerical simulation model of the mGT is presented together with the used optimization algorithm, followed by the presentation of the optimization results. Finally, the conclusions and future work are formulated.

2. Simulation approach

For the results presented in this paper, first a simulation model of a mGT is constructed. As model mGT, the Turbec T100 is chosen, since the T100 is representative for the typical mGT and its performance. This mGT has been studied before in the group in different applications, both numerically [14, 15] and experimentally [16, 17]. This model is presented in the first subsection, followed by the introduction of the used optimization algorithm: a multi-objective deterministic approach.

2.1. Micro Gas Turbine (mGT) modelling

The Turbec T100 mGT works, like most mGTs, according the recuperated Brayton cycle principle (Figure 1). Fresh air enters the compressor (1), where it is compressed with a typical compression ratio of 4 to 5. To compensate the relative low pressure ratio and increase the efficiency of the machine, the compressed air is preheated before entering the combustion chamber in the recuperator by the exhaust gases (2). In this combustion chamber (3), the temperature of the air is increased further by burning fuel. The necessary power to drive the compressor is provided by the expansion of the gas over the turbine (4). The remaining power on the shaft is converted into electrical energy by the high-speed generator (5). After having preheated the exhaust gases, the remaining heat is recovered in an economizer (6) by generating hot water/steam, which can be used for heating purpose (CHP-mode).

For the parameters of the different components of the mGT, the actual values of the Turbec T100 mGT, measured or provided by the manufacturer, are used for both the design and off-design operation. In the simulations, the actual map of the radial compressor (similar to the map presented in [5]) is introduced to determine pressure ratio, air mass flow rate (based on the Corrected Air Flow (CAF)) and compressor efficiency based on the rotational speed. In addition, a mechanical efficiency of 99% is assumed. The recuperator is simulated as a counter-flow heat exchanger, with a contact surface of 120 m^2 and a phase-specific heat exchange coefficient. In reality, this recuperator is a mix between counter-flow (main part) and cross-flow (in- and outlet part) [18], however this is compensated in the contact area and the heat exchange coefficients. An area dependent pressure loss, based on experimental data, is used to determine the pressure loss in the recuperator on the high pressure site. A Gibbs free energy reactor with given pressure loss (5%) and heat loss (10 kW_{th}) simulates the combustion chamber. Inside the combustion chamber, the combustion is assumed to be complete. As fuel, a mixture of methane (90%) and nitrogen (10%) is taken, which corresponds to

Table 1: Operational parameters of the Turbec T100 mGT as used in simulation model.

Operational Parameter	Value
Inlet air temperature of the compressor (T_{in})	15°C
Inlet air pressure of the compressor (P_{in})	1.013 bar
Pressure ratio (π)	variable[1]
Corrected Air Flow rate of the compressor (CAF)	variable[1]
Isentropic efficiency of the compressor ($\eta_{is,comp}$)	variable[1]
Recuperator surface (A)	120 m²
N_2 content of the natural gas	0.1
Heat loss in the combustion chamber (Q_{loss})	10 kW_{th}
Isentropic efficiency of the turbine ($\eta_{is,turb}$)	85%
Outlet pressure of the turbine (p_{out})	1.050 bar
Choking constant of the turbine	6.5

[1]For the operational parameters of the mGT compressor, the actual map of the radial compressor (similar to the map presented in [5]) was used in the simulations.

the typical natural gas that is provided to the experimental test rig in the labs of the Vrije Universiteit Brussel (VUB) [19]. The turbine is assumed to be chocked, with a back-pressure of 1.050 bar and having an isentropic and mechanical efficiency of respectively 85% and 99%. For the high-speed generator and attached power electronics, to convert the power to the grid voltage and frequency, a total efficiency of 94% is taken. Finally, the economizer is considered a cross-flow heat exchanger with given heat exchange coefficient and area.

The control system of the mGT allows the operator to set the power output constant. In addition, the TOT is kept constant at a value depending on the inlet air temperature (645°C at nominal inlet conditions). The TOT is controlled by changing the fuel mass flow rate, injected in the combustion chamber, while the power output is controlled by adjusting the rotational speed of the compressor and turbine shaft. For the simulations, the TOT control is kept, but the constant power output is not implemented and changed into a rotational speed control. This gives more flexibility to the optimization algorithm that is used to find the optimal operating points. This approach does not differ much from the actual control system, where the rotational speed is first set based on fixed tables linking inlet air temperature and power output with rotational speed and afterwards corrected based on the measured power output.

The simulation model of the Turbec T100 mGT is built in Aspen Plus and this model was previously validated experimentally [14]. The used operational parameters, as inserted in the simulation model, are presented in Table 1.

2.2. Multi-Objective Deterministic Optimization

Particle swarm optimization is a metaheuristic optimizer based on the principles of swarm intelligence [20]. In the present study, the Non-dominated Sorting Particle Swarm Optimizer or NSPSO [21] is used to handle the multiple objectives of the described test case. The population in NSPSO consists of particles which are able to memorize their best solution found so far and communicate with other particles, in terms of the global best. The search strategy is based on these two cognitive abilities, while the search step is limited by a maximum velocity of the particle. Furthermore, the selection mechanism of the NSPSO is similar to the one developed by Deb et al. [22]. The method collects in each generation the updated particles and the particle's best location, in order to obtain the non-dominated ones. Thus, useful non-domination relationships can be used for a better selection of the new swarm. The non-dominated particles then, are stored in an archive and sorted according to a crowding metric, measured in the objective space. This allows the better clustering of the particles in the objective space, leading finally to an optimal Pareto front with improved diversity.

Table 2: Design parameter space used for the optimization.

Design parameter	Lower limit	Upper Limit
Rotational Speed (*n*)	950 Hz	1250 Hz
Turbine Outlet Temperature (TOT)	560°C	645°C

For the optimization of the mGT operation, the TOT and the rotational speed are varied over their boundaries (Table 2), as would be done by the actual control system. The limits for the TOT control are set to 560°C (lower limit, similar to the limit used in the current T100 mGT control system) and 645°C (upper limit, which corresponds to a Turbine Inlet Temperature (TIT) of 950°C, which is the limit of the turbo-machinery material). Controlling TIT instead of TOT would have been another possibility. However, since in the actual machine, for technical reason, TOT is used to control the fuel flow rate, this control was adopted in the simulation model. This will allow to transfer the simulation model into an actual control strategy for the mGT. For the rotational speed, the lower limit is set to 950 Hz, while the upper limit was taken at 1250 Hz. The nominal rotational speed limit of the actual T100 is 1166 Hz (or 70000 rpm). For the optimization presented in this paper, this limit is extended, however, it should be kept in mind that the higher frequencies can correspond to the critical frequencies of the shaft. Next to the design parameters, two constraints are also introduced: surge and stone limit. The optimal solution should respect a minimal surge limit of 10% and should not cross the stone-wall.

As objectives for the optimization, maximal electrical efficiency and power output were selected. In some typical stand-alone applications, the power output of the mGT is determined by the demand of the user and in these cases efficiency is the only parameter to be optimizing. We are focusing more on complete energy systems, where several mGTs can operate in combination with back-up batteries, boilers and a possible grid connection. For this type of applications, where the electrical power can be provided by several other source, it can be interesting to optimize efficiency together with power output, since it will allow the user to decide more flexible on the operation of the mGT. To optimize this decision process, it is key to have accurate performance data of the mGT, which is provided by this optimization. Finally, cost optimization would be an additional objective, however in this paper, we only focus on the technological part and the economic optimization is thus not within the scope of the paper.

3. Results

The complete objective space, obtained by varying the design variables TOT and rotational speed over their domain is presented in Figure 2. The solutions violating the surge and stone-wall conditions are removed from the solution space, however very limited combinations of the design parameters actually led to a surge or stone-wall limitation violation. The genetic optimization algorithm results in a clear Pareto front of non-dominated solutions (red line on Figure 2) for maximal power output and electrical efficiency. Two other Pareto front can be identified from this solution space: a Pareto front for maximal efficiency, but minimal power output (lower right limit of the objective space) and a Pareto front for maximal power output, but minimal electrical efficiency (upper left limit of the objective space). These options are however less desirable from an operator point of view and are therefore not further discussed.

The genetic optimization algorithm results in a very clear Pareto front for maximal power output and electrical efficiency (Figure 3). It is clear to see that the two objectives: maximized power output and maximized efficiency, are conflicting: the set of design parameters leading to the highest power output does not necessary leads to the optimal electrical efficiency and vice-versa. The electrical efficiency strongly depends on the TOT, since a higher TOT results in a higher TIT, which increases the efficiency significantly. This is reflected in the corresponding TOT design values with the solutions of the Pareto front: with increasing electrical efficiency, the TOT has to increase. The maximal electrical efficiency (31.5%) is thus reached at maximal TOT of 645°C, but at a rotational speed below the upper limit (1185 Hz). The power output is mainly function of the rotational speed of the compressor, since it will set the air mass flow rate going through the engine. Higher air mass flow rate results in higher electrical power output. However, when going to higher rotational speed, the compressor operation point shifts into the compressor map towards the zone with lower efficiency. Due to this efficiency reduction, more turbine power and thus more fuel energy is necessary for air

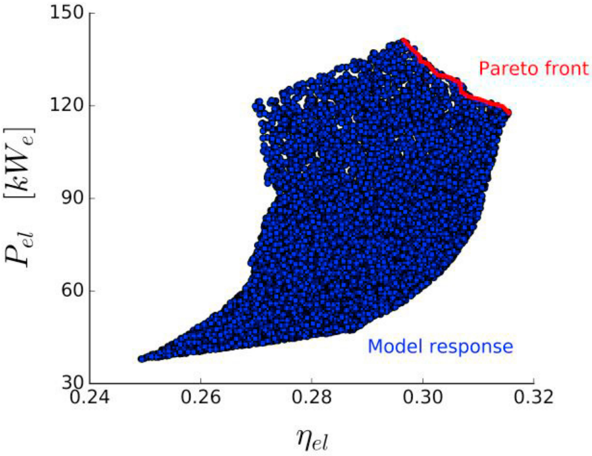

Figure 2: The full solution space with Pareto front.

compression, leading to lower electrical efficiency. Additionally, higher air mass flow rates result in a higher air velocity in the recuperator, which will result in proportional higher pressure losses. The pressure losses in the recuperator also have a significant effect on the mGT performance [18]. Both these effects explain the decreasing trend in the corresponding rotational speed to the solutions of the Pareto front. The maximal achievable power output is 141.3 kW_e at an electrical efficiency of 29.7% with corresponding design variable values of 1249.6 Hz for the rotational speed (upper limit) and a TOT of 614.3°C.

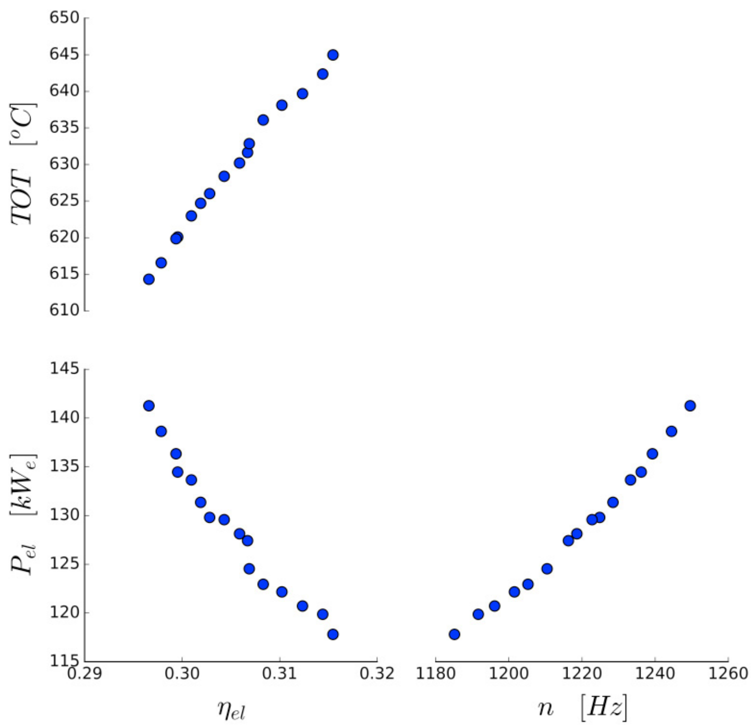

Figure 3: The Pareto front with corresponding values of the design variables, the rotational speed (n) and the Turbine Outlet Temperature (TOT), indicates that both objectives, maximal electrical power output (P_{el}) and electrical efficiency (η_{el}), are conflicting.

4. Conclusion and perspective

In a first step towards the robust design of a mGT system, in this paper, the results of a deterministic optimization of the operation of this mGT have been presented. In the deterministic optimization, it was aimed to maximize both electrical power output and efficiency by varying the design parameter: TOT and the rotational speed. The optimization led to a clear Pareto front, showing that both objectives were conflicting. The maximal achievable electrical power output and efficiency are 141.3 kW_e and 31.5%, but both values cannot be reached simultaneously.

In the future work, the design optimization of the mGT system will be repeated, however, uncertainties will be taken into account, leading to a robust design. In the robust optimization, used to find this robust design, the uncertainties on both design and operational parameters are taken into account. In this robust design optimization, typically, a trade-off needs to be made between optimal solution and the uncertainty on this solution. In the specific case of the mGT, we are interested in the effect of the uncertainties of the compressor operation (pressure ratio, mass flow rate and efficiency) on the final optimal operating point.

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6. References

[1] Pilavachi PA. Mini- and micro-gas turbines for combined heat and power. Applied Thermal Engineering. 2002;**22**:2003-14.
[2] Kaikko J, Backman J. Technical and economic performance analysis for a microturbine in combined heat and power generation. Energy. 2007;**32**:378 - 87.
[3] Katsigiannis PA, Papadopoulos DP. A general technoeconomic and environmental procedure for assessment of small-scale cogeneration scheme installations: Application to a local industry operating in Thrace, Greece, using microturbines. Energy Conversion and Management. 2005;**46**:3150-74.
[4] Nikpey H, Assadi M, Breuhaus P. Development of an optimized artificial neural network model for combined heat and power micro gas turbines. Applied Energy. 2013;**108**:137-48.
[5] Caresana F, Pelagalli L, Comodi G, Renzi M. Microturbogas cogeneration systems for distributed generation: Effects of ambient temperature on global performance and components' behavior. Applied Energy. 2014;**124**:17-27.
[6] Bruno JC, Ortega-López V, Coronas A. Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: Case study of a sewage treatment plant. Applied Energy. 2009;**86**:837-47.
[7] Ho JC, Chua KJ, Chou SK. Performance study of a microturbine system for cogeneration application. Renewable Energy. 2004;**29**:1121-33.
[8] Carpaneto E, Chicco G, Mancarella P, Russo A. Cogeneration planning under uncertainty: Part I: Multiple time frame approach. Applied Energy. 2011;**88**:1059-67.
[9] Carpaneto E, Chicco G, Mancarella P, Russo A. Cogeneration planning under uncertainty. Part II: Decision theory-based assessment of planning alternatives. Applied Energy. 2011;**88**:1075-83.
[10] Sanaye S, Ardali MR. Estimating the power and number of microturbines in small-scale combined heat and power systems. Applied Energy. 2009;**86**:895-903.
[11] Campanari S, Boncompagni L, Macchi E. Microturbines and Trigeneration: Optimization Strategies and Multiple Engine Configuration Effects. Journal of Engineering for Gas Turbines and Power. 2004;**126**:92-101.
[12] Campanari S, Macchi E. Technical and Tariff Scenarios Effect on Microturbine Trigenerative Applications. Journal of Engineering for Gas Turbines and Power. 2004;**126**:581-9.
[13] Abraham S, Raisee M, Ghorbaniasl G, Contino F, Lacor C. A robust and efficient stepwise regression method for building sparse polynomial chaos expansions. Journal of Computational Physics. 2017;**332**:461-74.
[14] Delattin F, Bram S, Knoops S, De Ruyck J. Effects of steam injection on microturbine efficiency and performance. Energy. 2008;**33**:241-7.
[15] De Paepe W, Delattin F, Bram S, De Ruyck J. Water injection in a micro gas turbine – Assessment of the performance using a black box method. Applied Energy. 2013;**113**:1291-302.
[16] De Paepe W, Delattin F, Bram S, De Ruyck J. Steam injection experiments in a microturbine – A thermodynamic performance analysis. Applied Energy. 2012;**97**:569-76.
[17] Montero Carrero M, De Paepe W, Magnusson J, Parente A, Bram S, Contino F. Experimental characterisation of a micro Humid Air Turbine: assessment of the thermodynamic performance. Applied Thermal Engineering. 2017;**118**:796-806.
[18] Lagerstrom G, Xie M. High Performance and Cost Effective Recuperator for Micro-Gas Turbines. ASME Conference Proceedings (ASME paper GT2002-30402). 2002:1003-7.
[19] De Paepe W, Montero Carrero M, Bram S, Contino F. T100 micro Gas Turbine converted to full Humid Air Operation: Test rig evaluation. Conference Proceedings (ASME paper GT2014-26123). 2014:V03AT7A020 , 11 pages.

[20] Kennedy J, Eberhart R. Particle swarm optimization. Proceedings of the IEEE International Conference on Neural Networks. 1995;**4**:1942–8.
[21] Li X. A non-dominated sorting particle swarm optimizer for multiobjective optimization. Genetic and Evolutionary Computation—GECCO 2003: Springer; 2003. p. 198-.
[22] Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation. 2002;**6**:182-97.