Ultra-High-Energy-Density Converter for Portable Power

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Abstract

Mesoscale gas turbine generator systems are a promising solution for high energy and power density portable devices. This paper presents an overview of a two-stage system with a power output of 100 W. There is a need for catalytic combustion and new ceramic materials. An existing turbine expander and a compression system are downscaled and a high-speed test-bench setup for the electrical system has been built. A simulation toolbox for small thermal machines and model-based control and diagnostics are developed.

1. Introduction

The increasing need for high energy density portable power devices has led to intense research and development efforts on mesoscale systems with power outputs up to a hundred Watts [1]. Gas turbine generator sets offer advantages over battery based portable power systems due to the higher chemical energy density of fuel. In contrary to other international mesoscale gas turbine projects the basic setup of the envisaged system has two compressor/turbine stages. A configuration with two shafts has the advantages of a higher possible pressure ratio than with a single shaft system, which improves the overall efficiency of the system. With an increased efficiency and a fixed total system mass (including fuel) the allowed mass of the machine increases and compensates for the drawback of a more complex system. Assuming a total system mass of one kilogram the relationship between overall system efficiency and the maximum possible machine mass (system mass without fuel) for butane fuel is shown in Figure 1. If the system has a total efficiency of 8% then the required fuel for the 10 hour operation of the machine already takes up the whole weight – therefore nothing is left for the machine itself. The gradient of the available machine mass is very high in the 10% to 20% efficiency region – even very small gains in the system efficiency give room for a much heavier machine design.

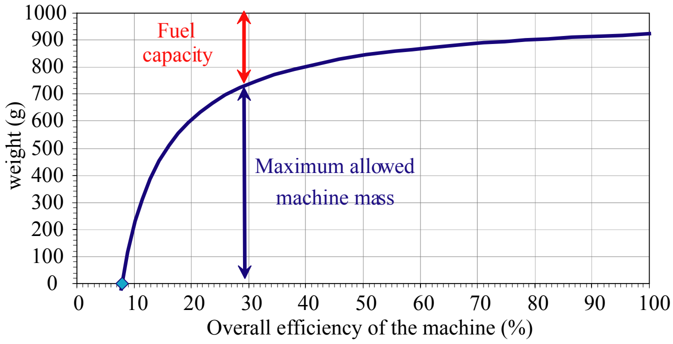

Figure 1. Trade-off between overall efficiency and available mass for the machine for a fixed total system mass of 1 kg and butane fuel.

This paper presents the considerations for a two stage gas turbine system according to Figure 2. The goal is an integrated system with an electrical power output of a hundred Watts over ten hours in a volume of one litre and a mass less than one kilogram, including fuel. The paper identifies challenges in the five areas combustion, compressor and turbine design, materials, control and modelling and electrical system design. Furthermore, a model library for predicting pressures, efficiency and temperatures is presented.

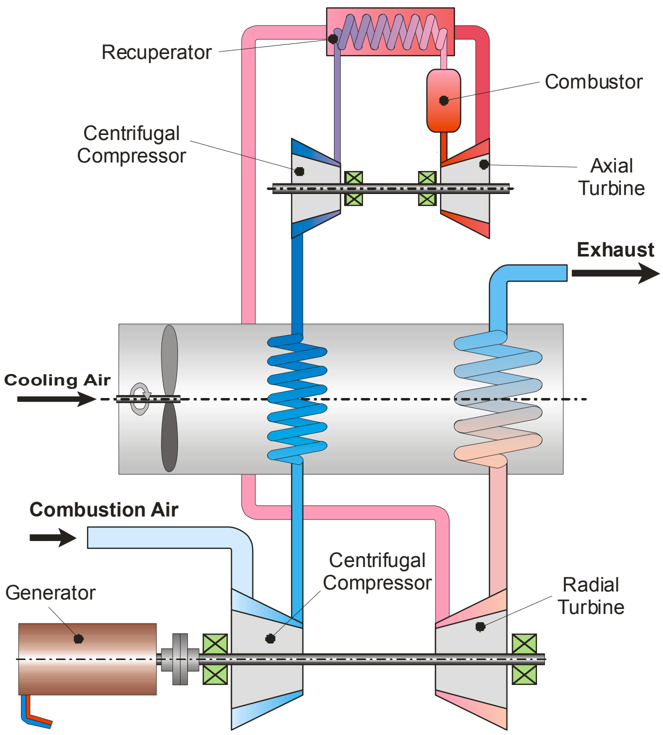

Figure 2. Setup of a two-stage gas turbine system.

2. COMBUSTION

A volumetric combustor would be inappropriate to deliver high temperature gases to drive the micro-turbine, thus the path of catalytic conversion of the fuel is chosen. A catalytic combustor guarantees almost complete conversion of the fuel at high-enough temperatures, since it provides enough surface-to-volume ratio and also assists an optimal thermal management. A functioning catalytic combustor design should address issues such as identifying favourable operating conditions for catalytically-sustained combustion, maximum allowable temperatures and temperature gradients, full fuel conversion for extremely low residence times and possible presence of combustion in the gaseous phase (Figure 3). The experimental/numerical methodology followed for this case includes in situ measurements of major and minor gas-phase species concentrations over the catalyst boundary layer in an experimental catalytic channel-flow combustor along with detailed numerical predictions treating full hetero/homogeneous chemistry and accounting for all relevant heat transfer mechanisms [2]. Current research is aiming towards the construction of quantitatively correct stability maps for the catalytic combustion of methane in the confinement of micro-combustor channels with dimensions $O(10^0)$ mm in length and diameter, research which will be extended to hydrocarbons of higher order.

3. COMPRESSOR AND TURBINE DESIGN

The core part of the micro-turbine would be the compressor and the turbine. The flow can be expected to be highly three-dimensional. Nonetheless the compressor and the turbine are designed classically. The efficiency of the micro-turbine is much smaller in comparison to normal size gas turbines because of several reasons. One big issue is the manufacturing tolerances so the tip gap becomes relatively big when downscaling a compressor or a turbine. The heat flux through the shaft transferring heat from the hot turbine side to the cold compressor side has also a negative influence on the efficiency. Because efficiency is an issue the turbine consists of two spools. This leads to a two-stage compressor so the pressure raise over the compressor increases which results in higher efficiency.

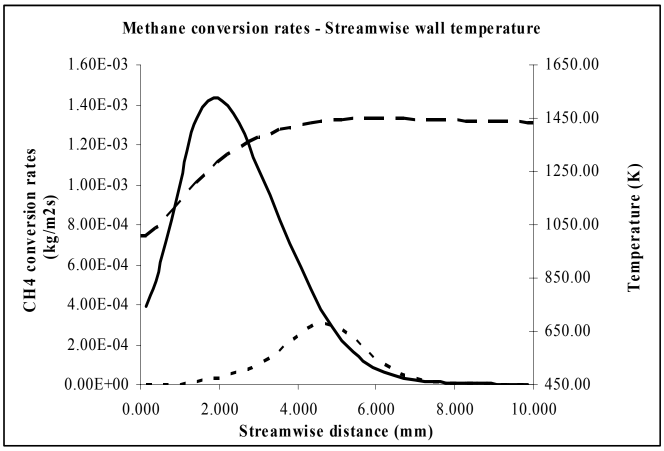

Figure 3. Prediction of basic flame and combustor properties for a combustor of 10mm in length and 2 mm hydraulic diameter. Continuous line: catalytic conversion rate, dotted line: gaseous conversion rate, dashed line: wall temperature. Other parameters are: atmospheric pressure conditions, inlet temperature T=743 K, φ=0.4, wall thickness Lw=100 μ, wall thermal conductivity kw=2.0 W/mK, heat losses coefficient h=3.0 W/m^{2}K, mixture inlet velocity Vin=1.0 m/s.

3.1. Compressor

The compressors in the gas turbine have both the same shape. They are centrifugal compressors and geometrically similar to each other. The compressor behaviour at large scale is well known since two larger versions at different sizes have already been manufactured and tested at ETH Zurich [3]. The compressor has seven blades and seven splitter blades. The outer diameter for the low-pressure stage is 18 mm and for the high-pressure stage 12 mm. The Mach number is 0.23.

3.2. Turbine

A two stage axial turbine drives the low-pressure spool and a single stage turbine drives the high-pressure spool. The turbines are also geometrically similar and scaled to match the compressors of each spool. The turbine has sixteen stator blades and sixteen shrouded rotating blades [4].

3.3. Compressor and turbine matching

The turbine did not match the compressor at the beginning because each component was built for a different application. For matching the compressor the axial Mach Number has been kept constant and the mass flow that defines the size of the turbine has been adjusted to the mass flow of the compressor (1).

$$M_{ax} = \frac{\dot{m}\sqrt{RT}}{pA\sqrt{\gamma}}\left(1+\frac{\gamma-1}{2}M_{ax}{}^2\right)^{-\frac{1}{2}} \quad (1)$$

The through flow area can be derived from the Mach Number and the mass flow (2).

$$A = \frac{\dot{m}\sqrt{RT}}{p\sqrt{\gamma}M_{ax}}\left(1+\frac{\gamma-1}{2}M_{ax}{}^2\right)^{-\frac{1}{2}} \quad (2)$$

The turbine and matching compressor can be seen in Figure 4.

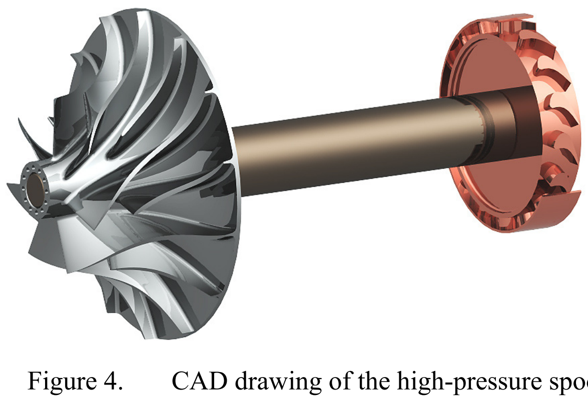

Figure 4. CAD drawing of the high-pressure spool with the centrifugal impeller and the turbine.

4. Materials

For an ultra-high-efficiency microturbine there is a need to evaluate and produce materials that will be able to withstand the operating conditions, especially the high temperatures. The materials properties (such as corrosion, oxidation, creep and strength) limit these temperatures (Figure 5). In the long term, the full performance of microturbines can probably only be achieved with ceramic materials.

A candidate list of potential advanced materials up to now exists and future work will show the applicability and reliability of these materials. In order to fabricate components critical decisions have to be made. First the selection of the material that is best suitable and second the type of manufacture. A successful material candidate must include the following specifications:

- low thermal expansion,
- high thermal-shock resistance,
- good corrosion and oxidation resistance,
- high thermal strength,
- good creep resistance,
- ease to fabricate, and
- low cost.

5. Modelling, Control and Fault Diagnosis

For the purpose of model-based control and fault detection a control oriented model (COM) is necessary [5]. A COM models the input-output behaviour of the micro gas turbine system with reasonable precision at low computational complexity. It is designed to include explicitly all relevant transient effects and is represented by a set of nonlinear ordinary differential equations, which are derived from physical first principles.

Faults in a control loop of a micro gas turbine are particularly important since feedback from a faulty sensor or actor very quickly result in instability causing a complete failure of the device. Such faults might need to be detected within just a few samples. Therefore it is important that faults are detected during normal operation of the gas turbine, without the need to perform any additional tests to perform the diagnosis.

The gas turbine process is regulated by a controller and the known variables consist of controller outputs and sensor data. Such a situation is depicted in Figure 6, which also illustrates a fundamental complication faced by the diagnosis system designer. Disturbances, also called unknown inputs, and considered faults also influence the process. The diagnosis system must be capable of separating the influences caused by these unknown inputs and the faults. A certain redundancy is thus needed to detect and isolate faulty components. The detection and isolation of actuator as well as sensor failures will be done with the multiple model adaptive estimation method (MMAE). This algorithm is composed of a bank of parallel Kalman filters, each matched to a specific hypothesis about the failure status of the system. Where necessary, certain Kalman filters in the filter bank will be replaced by an extended Kalman filter [6].

6. Electrical System

All gas turbine power supply systems require an electrical system consisting of a high-speed generator/starter, power electronics, a control platform and a form of energy storage to power the starting of the turbine.

6.1. Generator

High-speed operation requires a simple and robust rotor geometry and construction. Therefore, a permanent-magnet machine has been chosen. The cylindrical permanent-magnet is encased in a retaining sleeve in order to limit the stresses on the brittle magnet. The eccentricity is minimized by shrink-fitting the sleeve on the permanent magnet and grinding the rotor. The rated speed is set in between two critical bending modes.

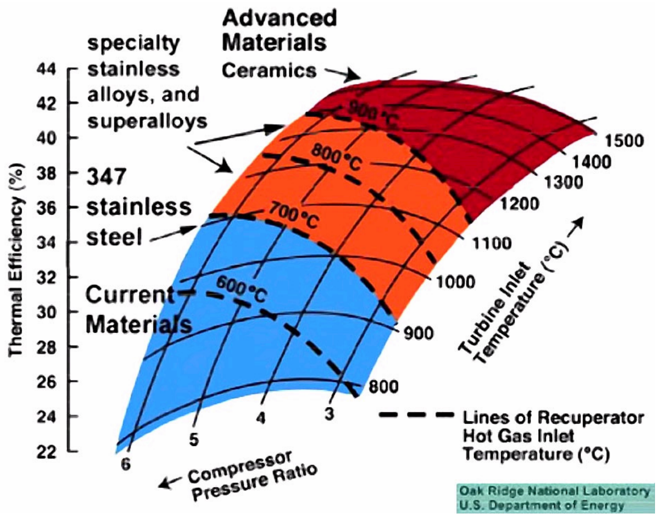

Figure 5. The recuperator hot-gas inlet temperature determines materials selection.

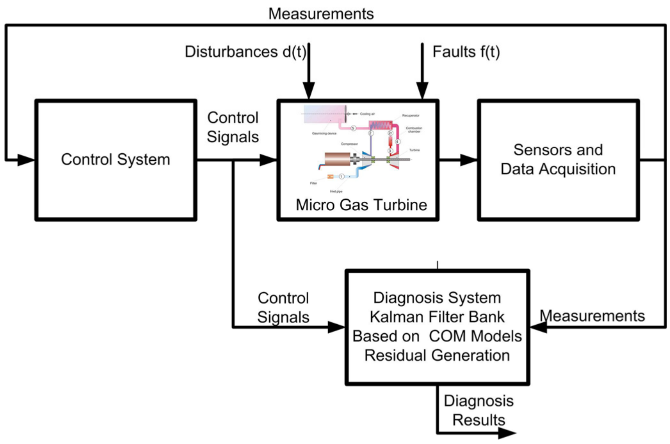

Figure 6. Model-based and control-oriented diagnosis of the micro gas turbine.

The main challenges in the electromagnetic design are the losses due to the high frequency in the stator core and winding. They are reduced with choosing an appropriate magnetic material and a litz wire winding.

6.2. Power and Control Electronics

The power and control electronics need to be able to start the turbine and then switch to generator mode and rectify the generator currents and voltages to a dc output. This is realized with a power stage of six MOSFETs and a controller implemented on a digital signal processor. Since the fundamental frequency already is 8.3 kHz the requirements on current measurement and control are extremely high and the switching frequency exceeds 100 kHz. In addition, the electronics should be small and lightweight.

6.3. Realized Hardware

A test bench setup has been realized including all the parts of the electrical system. The individual parts are shown in Figure 7. The weight of the electronics is approximately 20 g and the stator weighs 25 g.

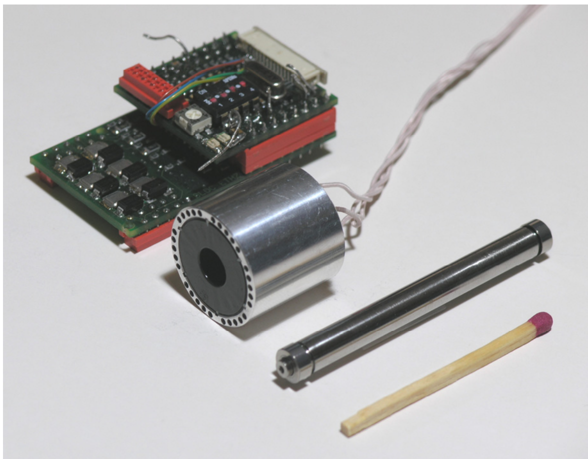

Figure 7. Rotor including two permanent-magnets and assembled high-speed ball bearings, stator with three phase winding, power and control electronics.

7. Simulation Toolbox

The achievable performance and efficiency of very small thermal machines depends strongly on a good temperature management of the system: Short distances between hot and cold parts with little space for insulation result in high heat flows between parts, smaller pipes have a higher surface-to-volume ratio which increases the heat exchange between parts and the gas flow.

In order to get an estimate of the performance of such machines a Simulink library for the simulation of small thermal machines has been developed. The library consists of configurable model blocks for the all basic machine parts (pipes, turbines, shafts, insulation layers, heat exchangers etc.) with connectors for all relevant energy and mass flows. With these components it is possible to easily create Simulink models of different machine designs and permits to quickly estimate the effect of changed component parameters (like changed part dimensions or materials etc.) on the performance of the whole system. Figure 8 shows the temperature distribution in the shaft of a miniaturized single shaft gas turbine machine model for two cases. The only difference between cases 1 and 2 is a change in the machine layout near the compressor which leads to a higher heat flow from the hot shaft (and hot piping) into the gas flow near the compressor. Apart from the welcome effect of a lower shaft temperature this also results in a 20% reduction of the overall system efficiency due to the changed operation points of the compressor and the turbine. Most of the heat is brought into the shaft in the turbine although the losses generated in the bearings and the generator has some influence as well.

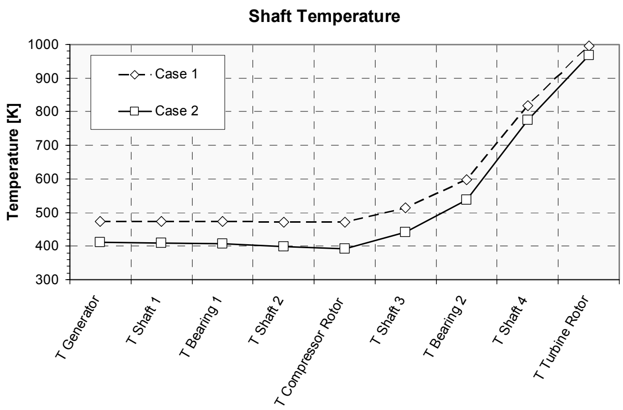

Figure 8. Simulated temperature distribution in the shaft for two slightly different machine layouts.

8. Summary

The design of a mesoscale gas turbine generator imposes significant challenges to all the disciplines involved. Particularly the small size and the high-speed operation require a special thermal, mechanical and electrical design and demand for ceramic materials and catalytic combustion. An existing turbine and compressor are downscaled and the electrical system is analyzed on a test bench.

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