Applied Energy 138 (2015) 445–449

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Impact of heat transfer on the performance of micro gas turbines

Dries Verstraete *, Carlos Bowkett

School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia

HIGHLIGHTS

- The impact of heat transfer on micro turbine performance is evaluated for different configurations.
- A reduced order one-dimensional lumped capacitance thermal network is used.
- Heat transfer leads to a small loss in output power and thermal efficiency.
- Configuration and material selection impacts the importance of heat transfer.

ARTICLE INFO

Article history:
Received 1 February 2014
Received in revised form 1 October 2014
Accepted 26 October 2014

Keywords:
Micro turbines
Performance
Heat transfer
Configurations

ABSTRACT

The miniaturisation of gas turbine engines poses significant challenges to the performance in heat management due to the close proximity of the hot and cold components. This paper examines the scale and significance of heat transfer within micro gas turbines and aims to quantify the corresponding impacts on performance and efficiency. To study these effects, a reduced order lumped capacitance heat transfer network is developed. Two different micro turbine configurations are investigated and the effect of micro turbine size and material selection is explored. The investigation shows that the choice of configuration and materials influences the impact of heat transfer on the micro turbine performance and heat management is therefore key to achieving the full potential of micro turbines.

1. Introduction

Miniature or micro gas turbines are small, single-stage, low pressure ratio, gas turbine engines that typically employ radial compressor and turbine rotors [1–5]. When designed for a power output of 5 to 15 kW, micro turbines are of interest for various commercial and military applications [1,4–8]. They could provide the power for a household or a small set of units [1,4,6,9], or form the backbone of a distributed backup and peak demand system as they offer an unparalleled flexibility [1–3,6,10–13]. This unique fuel flexibility makes them ideal for both remote power generation at off-grid locations as well as for operation on indigenous fuels in developing countries [2,7,11]. Micro turbines are attractive prime movers as they offer a good power quality, a very high reliability, a long engine life and low maintenance costs [2,4,7,11,12,14]. They produce low noise and vibrations as well as very low emission levels and are thus well suited for domestic use [2,6,10].

The smaller the gas turbine, the harder it is to achieve a competitive efficiency. Turbomachinery efficiencies are, for instance, affected by the small blade height, low Reynolds numbers, tip clearance effects, and surface finish [1,3,10,15]. At the considered power level, manufacturing limitations become significant and heat transfer and fluid leaks start to dominate [1,3,4,9,10]. Components that are in close proximity can operate at significantly different temperatures, resulting in heat fluxes of the same magnitude as the energy involved in compression and expansion [16]. Research on turbochargers of similar size as the micro turbines investigated in this paper shows that the heat flux from the turbine to the compressor leads to a drop in turbine power of around 10% at design point conditions and up to 20 or even 45% at low rpms [17–19]. While the power delivered by the turbine drops, the compressor consumes more power because of additional reheat losses [20,21].

Heat transfer impacts the performance of all micro turbines, but its influence depends to a large extent on the design specifics, both at the component [3,18,22] and configuration level [3]. With a predicted shift to smaller micro turbines, implying lower component efficiencies and an increased impact of heat transfer, reasonable cycle efficiencies can only be obtained through an increase of the turbine inlet temperature while simultaneously limiting the impact of heat losses. Whereas significant development in material science has enabled higher temperatures to be sustained [23], the

* Corresponding author.
E-mail address: Dries.Verstraete@sydney.edu.au (D. Verstraete).

http://dx.doi.org/10.1016/j.apenergy.2014.10.075
0306-2619/

same advances have not been forthcoming in heat transfer management.

This paper intends to raise the level of understanding of heat transfer management in micro turbines by applying a reduced order lumped capacitance thermal network. This type of network is less computationally intensive than a full conjugate heat transfer study but can approximate heat transfer results with a high degree of accuracy [17]. The network includes the heat transfer in the turbine- and compressor rotor, the shaft, the stator, the combustion chamber, and the housing. It also calculates the non-adiabatic flow in the radial compressor and turbine. A lumped capacitance network that consists of conventional correlations employed extensively in turbocharger heat transfer research [16,17,19–22,24–26], is used here to predict the flow and heat transfer in complete micro turbines of different size, material, and configuration. The originality of the paper resides in the application of this type of heat transfer analysis to an entire micro turbine and in the comparison of two different configurations, thereby, for the first time, quantifying the impact of configuration selection on micro turbine performance.

2. Methodology

Steady-state heat transfer between micro gas turbine components is solved through a thermal network based on the so-called electrical analogy [27]. A reduced-order, one-dimensional lumped-capacitance model is developed by simplifying the micro turbine as an assembly of bodies with a known geometry. Heat fluxes between the different bodies, as well as heat fluxes between the working fluids and bodies are taken into account. Several studies on heat transfer inside automotive turbochargers of similar size have demonstrated that this approach provides adequate results [16,17,19–22,24–26].

A simplified schematic of the lumped capacitance model is shown in Fig. 1 (not drawn to scale). As the model shows, the working fluids are the fresh air taken by the compressor (T_C), the combustion gases in the combustion chamber (T_{CC}), the hot gases expanding through the turbine (T_T) and the ambient air (T_{amb}). The housing has been separated into four different bodies (H1 to H4) due to its complicated geometry. Each body has been introduced in the model as one or more metal nodes representing its surface temperature and is assumed to have a uniform wall thickness [17,22,24,25]. The turbine (T) and compressor (C) impellers are shown as single nodes in Fig. 1 but are in reality split into three nodes each to improve accuracy and to better capture the effect of reheat on the required compressor power. Each compressor and turbine impeller node has a corresponding fluid node and it is assumed that heat from the corresponding impeller and housing

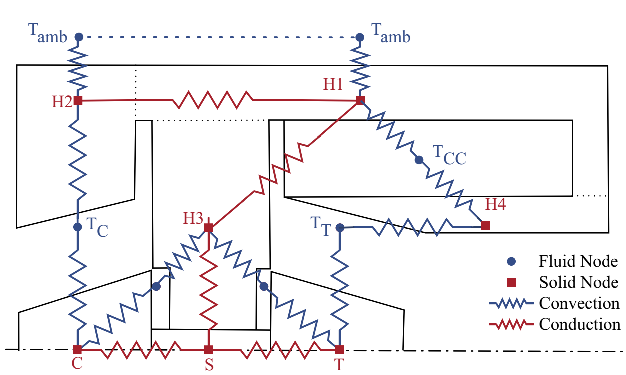

Fig. 1. Simplified schematic of the one-dimensional heat transfer network (configuration not to scale).

nodes is added before the fluid enters the respective fluid node [28]. Splitting the turbomachinery components ensures that the Biot number of each section is lower than 0.1 so that the lumped capacitance assumption is valid [27]. Additional nodes are included in the cavities between the turbomachinery impellers and housing body 3, and on the surfaces of both the impellers and housing body 3 adjacent to those cavities (not shown in Fig. 1 for clarity). Conduction along the rotor shaft is accounted for through the addition of a solid node that represents the shaft (S).

As shown in Fig. 1, metal nodes in the lumped model are connected between them by means of solid conductance and connected with the working fluids by means of a convective conductance. Forced convection coefficients for the compressor and turbine are determined based on the (turbulent) Sieder–Daast correlation [24,25,27,29]:

$$Nu = C \cdot Pr^{1/3} \cdot Re^{4/5} \quad (1)$$

where Nu is the Nusselt number and Pr is the Prantl number which takes temperature variations into account. Re represents the Reynolds number, which is related to mass flow rate variations and is based on the length of the boundary layer establishment [30]. For the combustion gases entering the turbine, it is assumed that there is no conservation of boundary layer thickness at the exit of the combustion chamber [30]. The coefficient C in Eq. (1) is derived from conjugate heat transfer simulations on a similar micro gas turbine [31]. A value of 0.0695 was found for both the compressor and turbine.

The convection coefficients for the rotor and stator cavities are determined in a similar fashion [30]. Conduction calculations are performed using Fourier's law [27] between the metal nodes and external radiation is included by applying the Stefan–Boltzmann law with a temperature-dependent emissivity for the different materials [27]. Natural convection is considered for the housing too [27].

The one-dimensional lumped thermal model is added to an existing object-oriented library for gas turbine simulations, developed in Ecosimpro [32]. The tool contains objects for a range of gas turbine components and its suitability and accuracy has been demonstrated for a variety of applications [33–36]. Thermal ports and geometry information have been added to the different components of the library.

3. Results

Heat transfer computations are performed on different test cases. The first, baseline, case represents a typical micro turbine configuration used in power generation applications [31]. The impact of material conductivity and micro turbine size is analysed for this baseline configuration. An alternative configuration, with the combustion chamber mounted between the compressor and turbine is also investigated and a comparison with the baseline configuration is made.

3.1. Baseline configuration

The baseline configuration is based on a micro turbine on which conjugate heat transfer results are performed [31]. The micro turbine consists of a 20 mm compressor and turbine impeller mounted on a 8 mm long, 5 mm diameter shaft. The combustion chamber is aft-mounted and has an outer diameter and length of 65 mm. The original micro gas turbine uses a recuperated cycle for increased thermal efficiency [31]. For the current study the recuperator and generator are omitted to simplify the thermal network and to avoid inaccuracies due to axial conduction along the length of the recuperator. Whereas this results in a configuration