Energy 89 (2015) 545–557

Contents lists available at ScienceDirect

Energy

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

Development and validation of a full-range performance analysis model for a three-spool gas turbine with turbine cooling

Yin Song [a, b, *], Chun-wei Gu [a, b], Xing-xing Ji [a]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

[b] Collaborative Innovation Center of Advanced Aero-Engine, Beijing 100191, China

ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form
3 June 2015
Accepted 5 June 2015
Available online 27 June 2015

Keywords:
Gas turbine
Performance analysis
Cooling
Multi-spool
Part-load

ABSTRACT

The performance analysis of a gas turbine is important for both its design and its operation. For modern gas turbines, the cooling flow introduces a noteworthy thermodynamic loss; thus, the determination of the cooling flow rate will clearly influence the accuracy of performance calculations. In this paper, a full-range performance analysis model is established for a three-spool gas turbine with an open-circuit convective blade cooling system. A hybrid turbine cooling model is embedded in the analysis to predict the amount of cooling air accurately and thus to remove the errors induced by the relatively arbitrary value of cooling air requirements in the previous research. The model is subsequently used to calculate the gas turbine performance; the calculation results are validated with detailed test data. Furthermore, multistage conjugate heat transfer analysis is performed for the turbine section. The results indicate that with the same coolant condition and flow rate as those in the performance analysis, the blade metal has been effectively cooled; in addition, the maximum temperature predicted by conjugate heat transfer analysis is close to the corresponding value in the cooling model. Hence, the present model provides an effective tool for analyzing the performance of a gas turbine with cooling.

1. Introduction

Gas turbines are used for a variety of applications, such as electrical power generation, marine power plants, driving pumps and compressors. The thermodynamic modeling and performance calculation of a gas turbine is necessary for both its design and its operation; not only the design condition but also the off-design (or part-load) condition should be of concern. Moreover, the research and evaluation of novel gas-turbine-based systems (such as a solid oxide fuel cell/gas turbine hybrid system [1], a solar hybrid combined cycle system [2], the combined cycle with Carbon Dioxide bottoming cycle [3], and the combined cooling, heating and power systems [4]) also require an accurate and reliable method to predict the full-range performance of gas turbines.

Because of its significance, the full-range performance analysis of a gas turbine has been of concern over the years. For example, Zhu and Sarvanamutto [5] developed a full-range mathematical model for the three-spool LM-1600 gas turbine using the so-called “hot end method” for component matching, which assumed the choking of the LP turbine, and began from the hot end to determine the compressor operating point. Al-Hamdan [6] studied the modeling and simulation of a single-spool gas turbine engine for power generation; this researcher matched the compressor and the turbine by superimposing the turbine performance map on the compressor map, whose axes were made identical. Rodgers [7] studied the part-load fuel consumption characteristics of single, two-shaft recuperated, and two-spool intercooled recuperative small 300-kW class gas turbines and compared the performance with that of an advanced diesel engine. Haglind [8] compared two models for predicting the part-load performance of aero-derivative gas turbines, i.e., a complex model using component maps and a simple model using constant turbine constants, and this researcher determined that both methods were able to provide good predictions of the mass flow and pressure ratio characteristics, but the thermal efficiency and exhaust temperature below 60%–70% load cannot be correctly predicted using the simple model. Haglind [9] further discussed the effects of variable geometry on the part-load performance of the gas turbine used in marine combined cycles and assessed the combined cycle performance [10]. Lee [11] developed a performance simulation program for an IGCC gas

* Corresponding author. Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China. Tel.: +86 10 62781739.
E-mail address: songyin@tsinghua.edu.cn (Y. Song).

http://dx.doi.org/10.1016/j.energy.2015.06.015
0360-5442/

turbine; this simulation is based on a stage-stacking method for evaluating the compressor characteristic and an off-design efficiency variation function for the turbine characteristic, which are useful in the absence of component maps. Tsoutsanis presented a novel method of compressor map generation by deriving a generic form of the equations used to represent the lines of constant speed and constant efficiency for a generic compressor [12] and applied the method to the performance analysis of a GE LM2500+ aeroderivative gas turbine [13]. Aguilar [14] used a component-based off-design calculation program GSP to analyze the regulation methods of a combined heat and power plant based on two-spool gas turbines. For the turbojet engine, Kurzke [15] proposed a method to establish an engine performance model from a limited amount of data, and Sankar [16] et al. developed an engine simulation model for a twin-spool turbojet engine using GSP and performed an analysis related to an engine run at the design point and at off-design points, as well as the engine acceleration deceleration cycles.

With the increase of the turbine inlet temperature, air cooling has been generally applied in modern gas turbines to reduce the metal temperature to below the temperature limit. As a result, cooling-induced loss has been a major source of thermodynamic losses in gas turbines, and the cooling air requirement varies with the engine load because of the variation in the hot gas temperature, which will significantly alter the engine performance. Thus, the prediction of the cooling air requirements is extremely important for the accurate performance calculation of modern gas turbines. Various researchers have proposed approaches for calculating the cooling effect and predicting the coolant requirements. For example, Holland and Thake [17] derived a semi-empirical model that calculates the cooling performance using empirical correlations between the cooling effectiveness and the non-dimensional coolant mass flow. El-Masri [18] presented a general model to investigate the impact of different types of cooling technologies on the cycle performance, including internal air cooling, transpiration air cooling and internal liquid cooling. Consonni [19] regarded the entire cooling blade as a heat exchanger subjected to a constant external temperature and derived an analytical model for predicting the cooling flow. Chiesa and Macchi [20] analyzed and compared the electrical efficiency of combined cycle power plants using different turbine cooling approaches, in which a revised version of Consonni's model is used to account for convection and film cooling.

However, in the above mentioned line of research, coolant modeling is only proposed for the cycle calculations, i.e., only the design-point condition of the gas turbine is considered; currently, in the full-range performance analysis of gas turbines, which is obviously more complex than the design-point cycle calculation, the cooling air flow rate is still set in a relatively arbitrary fashion. Kurzke [15], Haglind [8] and Sankar et al. [16], as noted above, directly predefined the fractional cooling air flow rate in their performance calculations. Al-Hamdan [6] assumed the amount of cooling air bled from the compressor to be equal to the fuel flow. Kim [21] used simple relationships to estimate the cooling requirements at the design and off-design conditions; his method was also used by Lee [11].

In the present research, a full-range performance analysis model considering the prediction of the cooling flow rate is established for a three-spool gas turbine. A hybrid turbine cooling model is embedded, which aims to provide an accurate prediction of the cooling flow rate and its influence on the gas turbine performance, thereby removing the uncertainty induced by the arbitrary value of cooling flow rate used in the existing full-range models for gas turbines. Because detailed full-range test results of gas turbine engines are relatively scarce in the open literature due to commercial confidentiality issues, a rig test was performed for the gas turbine studied in this research; the test results are used for validation of the calculation results. Three-dimensional multistage CHT (conjugate heat transfer) analysis for the turbine components is also performed to verify the prediction of the coolant requirements further.

The rest of this paper is organized as follows. In Section 2, the studied three-spool gas turbine and the measuring condition are described. In Section 3, the full-range performance analysis model with the turbine cooling model is established. In Section 4, the calculation results are presented and validated with the test data and the CHT analysis. Section 5 concludes the paper.

2. Description of the three-spool gas turbine

The diagrammatic view of the studied gas turbine is shown in Fig. 1, which illustrates a three-spool structure and a simple cycle. This gas turbine was derived from a MW-class vehicle gas-turbine engine and is currently used for distributed power applications. Detailed data of this gas turbine are summarized in Table 1.

A conventional open-circuit convective cooling system is used in this gas turbine, and the coolant is extracted from the high-pressure compressor and sent to cool the stator of the first-stage high-pressure turbine. Due to the cooling technology adopted in the turbine, the design-point high-pressure turbine inlet total temperature T_3 is near 1300 K. During the rig test, the power turbine is connected to an electricity generator, and its rotational speed is fixed at 3000 rpm, which corresponds to the power grid frequency in China.

The part-load control strategy of the present three-spool engine is as follows. At part-load running conditions, the fuel flow rate is decreased, and the power spool is maintained at a constant rotational speed, while the rotational speeds of the HP and LP spools automatically decrease, and less air is breathed by the LP compressor. The turbine inlet temperature decreases during this process.

The test of this gas turbine involved obtaining detailed performance data at various loads, which will be used to validate the calculation model established in the present work. The test rig is shown in Fig. 2. The measured quantities and the respective measurement errors are summarized in Table 2. The measurement errors were determined from the instrument properties.

3. Full-range performance analysis model

3.1. Gas properties

The influences of temperature and fuel/air ratio on the gas properties are considered in the present research. The specific heat c_p, enthalpy $\hat{h}$ and the thermodynamic property function ϕ are all expressed as piecewise polynomial functions of the temperature and fuel/air ratio, and the detailed functions can be found in Stull [22].

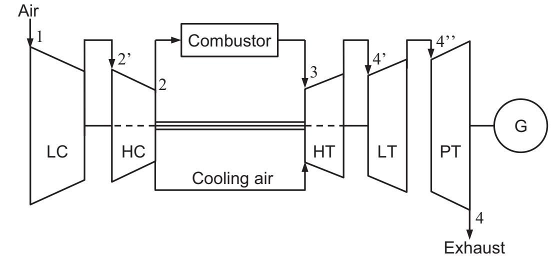

Fig. 1. Diagrammatic view of the three-spool gas turbine.