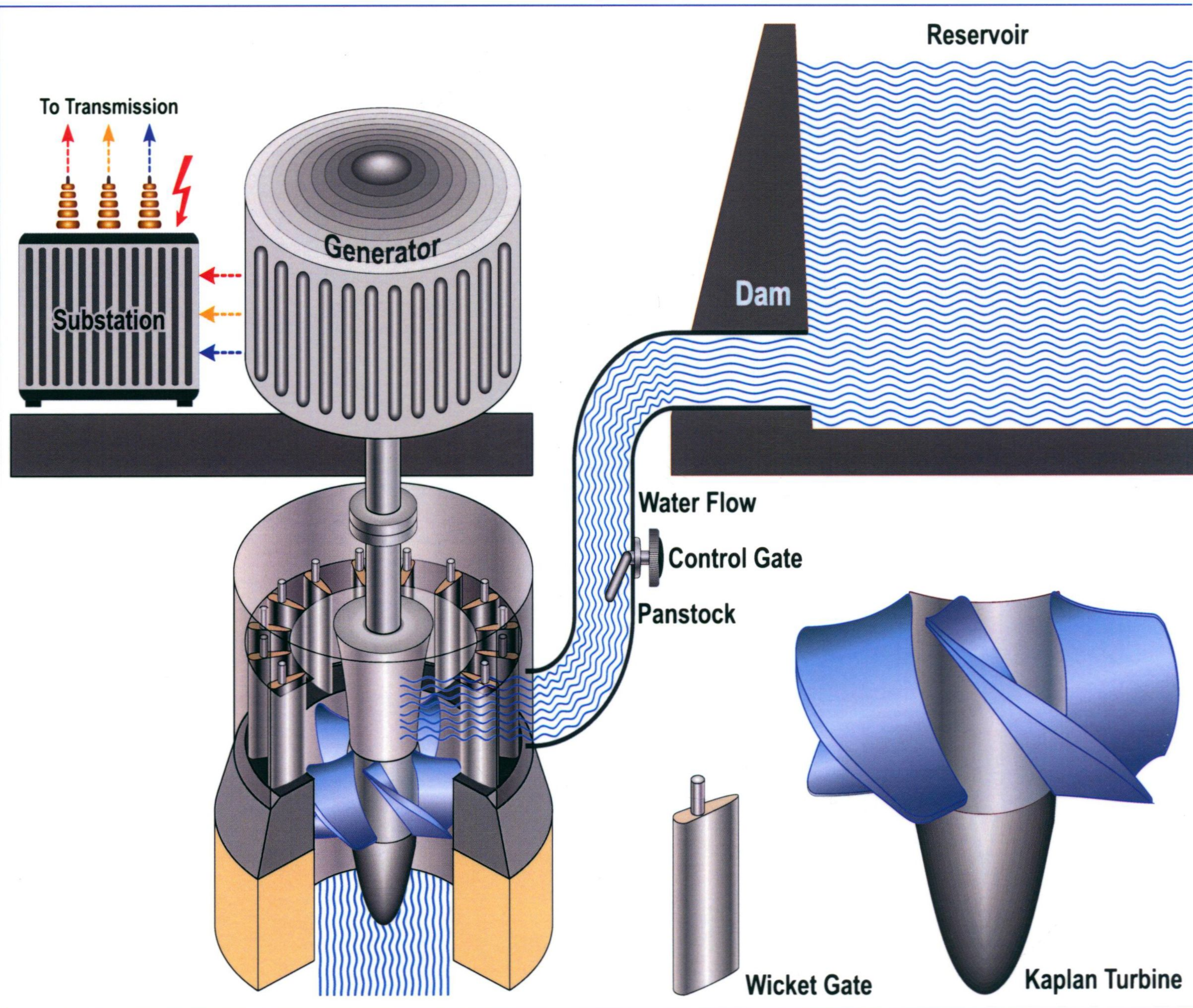
Gas Turbines: Modeling and Performance

Contributors: Barinyima Nkoi, Thank God Ebi Isaiah, et al.



About the Book

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Gas Turbines - Modeling and Performance presents contemporary research in the area of gas turbines for different applications. It presents an assortment of topics ranging from basic understanding about the designing and modeling of gas turbines to advanced technologies for their continually increasing efficiency, which is the need of modern gas turbine industries. It will be of comprehensive guide for material scientists, gas turbine engine design and maintenance engineers, manufacturers, mechanical engineers, advanced graduate students and researchers as well as design and maintenance engineers in aerospace and gas turbine industry. In this book, an overview of combustion process and a description of some new pioneer combustor have been presented. As gas turbine manufacturers are looking for continuous operation or stable combustion, satisfactory emission level, minimum pressure loss and durability or life. Hence, the advanced combustor might include all of these criteria, so some of them are selected to discuss in details.

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Preface

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Contents

1

ADVANCED CYCLES LARGE-SCALE AERO-DERIVATIVE GAS TURBINES: PERFORMANCE COMPARISON

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Keywords: Aero-Derivative-Gas-Turbines, Thermal-Efficiency, Intercooled-Recuperated, Fuel-Flow, Heat-Rate

ABSTRACT

This paper aims at carrying out comparative performance analysis of simple and advanced cycles large-scale aero-derivative industrial gas turbines derived from aircraft turbofan engines. The investigation involves technical performances of three large-scale aero-derivative engine cycles based on existing and projected cycles for applications in land based power generation and Combined-Heat-and-Power (CHP). Preliminary design and performance simulation were implemented of a simple cycle (baseline) three-spool 100 MW aero-derivative engine model, intercooled and intercooled/recuperated engine cycles of the same 100 MW nominal power rating. In the analysis, design point and off-design performances of the engine models were established. The results indicate that to a large extent, the advanced engine cycles showed superior performance in terms of thermal efficiency, and fuel flow. In numerical terms, thermal efficiencies of intercooled engine cycle, and intercooled/recuperated engine cycles, over the simple cycle at design point increased by 2.42% and 0.94% respectively, whereas heat rates of these cycles over simple cycle at design point decreased by 2.37% and 0.93% respectively. It is worthy of note that for large-scale aero- derivative gas turbines having power rating of 100 MW and above, intercooled cycle would consume less fuel than intercooled-recuperated and simple cycles. This finding would actually aid good choice of cycle option for large-scale aero-derivative gas turbine designers, manufacturers and users.

INTRODUCTION

Aero-derivative industrial gas turbines (ADIGT) could be grouped into three categories namely: small-scale, medium-scale, and large-scale aero-derivatives, based on different ranges of power ratings. Small-scale ADIGT category can be defined as having the range of power rating from about 0.6 MW up to 5 MW. The range of power rating greater than 5 MW but up to 20 MW could be classified as medium-scale category. Large-scale category would be considered as the class having power rating above 20 MW [1] - [3] . As the name implies, aero-derivative industrial gas turbines (ADIGT) are gas turbines derived from aero-gas turbine engines by means of conversion. The decision to use aero-derivative gas turbines is mainly based on economical and operational advantages. Gas turbine manufacturers have found that to reduce cost of designing and developing new gas turbines, a more effective approach is to develop high performance industrial gas turbines by modifying aircraft gas turbine engines [4] [5] . Also, by introducing aero-derivative's removable gas generator, better flexibility is provided which in turn leads to reducing maintenance operation and enhancing gas turbine availability in industrial applications [6] . More so, implementing aero-derivative technology for industrial gas turbine has resulted in low maintenance downtime, good part-load efficiencies and higher rate of return [4] - [7] .

It has been reported that the introduction of modern, high thrust aero-engines for aircraft propulsion has resulted in the development of a commensurate range of new high power, high efficiency ADIGT. This is illustrated for instance by the Rolls-Royce TRENT. The development of these large, efficient ADIGT offers particular chances for use in power generation and combined-heat-and-power plant [4] . ADIGT gives various advantages over their industrial design counterparts, in technology, project implementation and maintenance. Comparing performance, modern ADIGTs present a very efficient form of simple cycle energy conversion and this is exemplified in the TRENT GT. The high efficiency of the TRENT engine makes it a distinct choice for simple cycle application. With a state-of-the-art technology development from a modern aero-engine, fiscal studies have indicated that the high efficiency aero-derivative version exceedingly counterpoises for higher first cost that could be expected. Modern ADIGTs are also a feasible option for Combined-cycle-gas-turbine (CCGT) and CHP applications where power in the 60 - 120 MW class is anticipated. The TRENT GT, having a combined-cycle efficiency of about 51.5%, is one of the most competitive options available in its class. Modern ADIGT plants are an amply-embraced alternative for energy generation and this progression is expected to advance with the TRENT and future developments [3] - [8] .

Besides, another instance is the GE LM6000 aero-derivative gas turbine series which has undergone some new innovations in technology especially those in the 35 - 65 MW_e range. The GE LM6000 has the latest innovations in the LM6000PG & PH versions. These are denoted as the "PG" for the standard annular combustor (SAC) and "PH" for the dry low emissions (DLE) model. The improved technologies for these new products include new higher temperature alloys and improved cooling pattern to withstand high combustor outlet temperature, LP compressor operating at higher speed and increased mass flow, and higher pressure ratio. The GE LM6000 PG offers a 25% simple cycle power increase compared to the GE LM 2500, its predecessor, owing to advanced technology [9] . The advancement to the GE LM6000 gas turbine produces an 18% increase in the exhaust energy and 25% increase in power, and about 52% combined-cycle efficiency when incorporated into a 2- on-1 reference combined-cycle plant [9] .

More so, aero-derivative gas turbines can meet stringent NOx control requirements because they are suitable for power augmentation by steam injection. For instance, the GE LM series industrial aero-derivative gas turbines are meeting NOx requirements as low as 25 parts per million (ppm) using steam injection. Other merits of aero-derivative gas turbines include low weight-to-power ratio, compactness, and hence, lesser erection and startup time [10] [11] . More so, aero-derivative gas turbine are most suitable for highly efficient cogeneration plants, more flexible combined-cycle plants, and in mechanical drive applications for production and distribution of oil and gas [12] .

Using heat exchangers (both recuperators and intercoolers) in an engine exhibits tremendous potential to cut fuel consumption and thereby reducing CO_2 emissions. It was explained that the recuperator utilizes part of heat from the exhaust gas to raise the temperature of the air entering the combustor [13] . This method achieves the same turbine entry temperature as obtainable in conventional power plants but with the advantage of utilizing lesser fuel [13] . Besides, gas turbine user requirements have, over the years, necessitated technological advancement in engine performance, and comprehensive researches are being conducted to achieve this [14] [15] .

Technically, improvement of thermal efficiency for industrial and aero gas turbines is of paramount importance to the overall performance of the engines. Increase in thermal efficiency depends on certain factors including: Changes in some engine cycle parameters, such as overall pressure ratio (OPR), and turbine entry temperature (TET). Cutting-edge technology of engine components like methods of cooling, efficiencies of components, ducts pressure losses, and introduction of different overall thermodynamic cycle, for example, use of unconventional components like intercoolers and regenerators or recuperators [5] [16] . More so, performance and economic viability of gas turbines are inseparable [15] .

The aim of this paper is to compare the technical performances of large-scale aero-derivative industrial gas turbines. The investigation encompasses comparative assessment of simple (SC), intercooled (IC), and intercooled/recuperated (ICR) cycle options. This sort of analysis would surely aid good choice of engine cycle options in the category of large-scale aero-derivative land based gas turbines. GE Power has developed, manufactured and deployed 100 MW large-scale intercooled aero-derivative gas turbine in the LMS100 series [17] , however, this research introduces analysis of a 100 MW intercooled-recuperated aero-derivative gas turbine and a counterpart simple cycle version. Hence, this research has the advantage of providing wider range of cycle options in this category of aero-derivative gas turbines.

MATERIALS AND METHODS

Design Point Performance (DP)

The Design Point of a gas turbine could be defined as the very condition in the operating range of a gas turbine when the engine is running at the very mass flow, speed, and pressure ratio for which the components were designed [18] . In establishing the design point of the engine, pressure ratio and TET that results in an overall highest thermal efficiency are normally determined from preliminary cycle calculations. After this is done, other appropriate design parameters of the gas turbine system may be allotted. Then, detail design of different engine components can be done in order to provide the specified requirements of the complete system when operating at the DP. There are many requirements from a gas turbine engine. These may be referred to as design priorities, and always these requirements are in conflict. The design of the engine is greatly influenced by a set of these priorities depending on the engine application [5] [15] [19] [20] .

Off-Design Performance (OD)

Besides the DP performance of the gas turbine, it is mandatory to ascertain its general performance over the entire operating range of power output and speed. This is known as Off-Design (OD) performance [18] . Component characteristics as indicated by component maps of compressor, turbine, and combustor, are very useful in ascertaining off-design behaviour of the gas turbine system. At steady state operation of the engine, corresponding operating points on the component maps are matched and can be plotted on the compressor characteristic diagram to form an equilibrium running line [20] .

Various performance plots of power output, specific fuel consumption (sfc), thrust, specific thrust or power, etc could be made once the operating conditions of an engine have been determined. It is important to note that off-design performance is very much affected by factors such as ambient conditions of temperature and pressure, altitudes, flight speed (for aero engines), etc. The off-design performance analysis is normally achieved by the use of computer model simulations of engines [20] [21] .

TURBOMATCH

Engine components operating point matching to establish OD performance is normally a tedious and time consuming task since it is an iterative process. Computer based simulation is normally employed to accomplish the task. TURBOMATCH is an in-house gas turbine engine performance software developed and established at Cranfield University (CU). It is employed to simulate the DP and OD performances of a broad range of aero and industrial gas turbines. Simple single shaft engines, complex multi-spool engines, as well as novel cycle engine configurations can be modelled adequately using the scheme [15] - [16] [18] - [20] .

In the scheme, different engine components (intake, compressor, combustor, turbine, nozzle, etc) are repre- sented by bricks (building blocks of the programme). These bricks are pre-programmed routines deployed to simulate, on a modular basis, the performance of the various engine components they represent. The cycle thermal efficiency, specific fuel consumption, power, or thrust of the engine, etc. are essential performance output parameters that are obtained as desired results of the simulation. Besides these overall cycle results, individual component performance characteristics, and the working-fluid properties at various stations within the engine are also outputted [15] [18] [22] [23] .

Simple Cycle Three-Spool Turboshaft Engine with Free Power Turbine

In this paper, three-spool turboshaft engine with a free power turbine (FPT) was considered in which a high pressure compressor (HPC) is driven by the high pressure turbine (HPT) and a low pressure compressor (LPC) is driven by an intermediary low pressure turbine (IPT). The schematic representation of such engine is shown in Figure 1 indicating station numbers.

The T-S diagram of the simple cycle is shown in Figure 2 considering isentropic efficiencies of compressors and turbines. With the notations of Figure 1 and Figure 2, and applying steady flow energy equation, heat flow into the cycle in the combustion chamber (process 4 - 5) per unit air mass flow is given by Equation (1).

$$q_{\text{in}} = h_5 - h_4 = c_{pi}\left(T_5 - T_4\right) \tag{1}$$

where c_{pi} is the specific heat capacity at constant pressure, which varies with temperature at the given engine component station i.i represents engine station numbers 1, 2, 3, 4, 5, 6 etc.

Heat rejected at constant pressure (process 8 - 2) in the exhaust is given by Equation (2).

$$q_{\text{out}} = h_8 - h_2 = c_{pi}\left(T_8 - T_2\right) \tag{2}$$

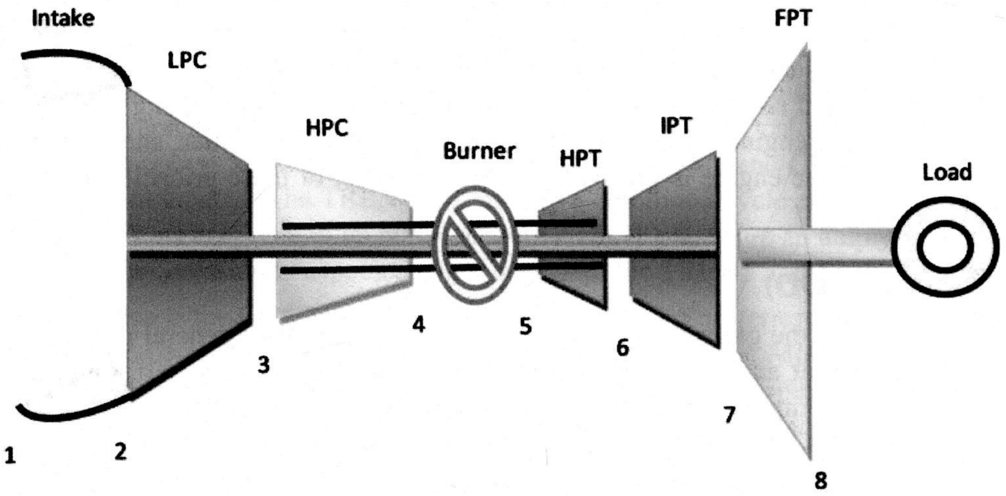

Figure 1: Schematics of a three-spool turboshaft engine with free power turbine.

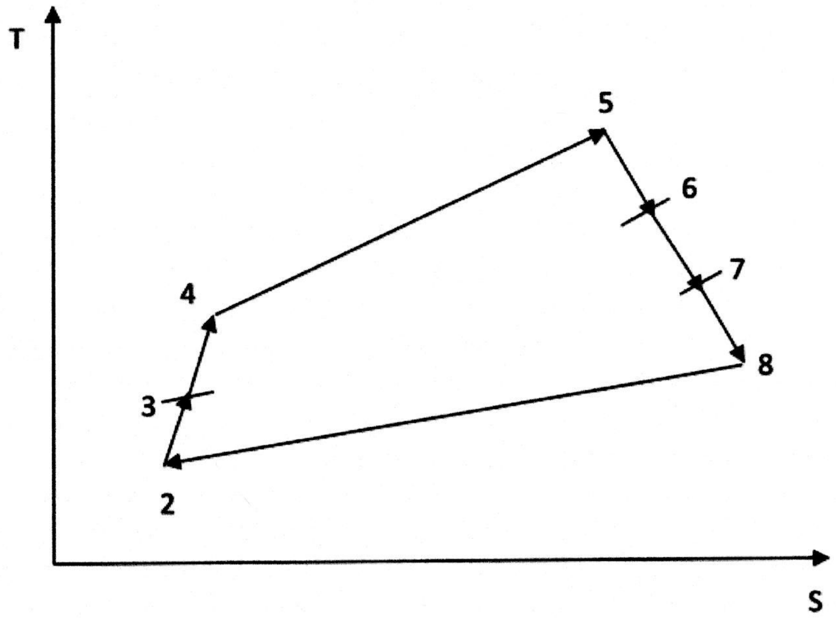

Figure 2: T-S diagram of actual simple cycle three-spool turboshaft gas turbine.

Equation (3) or Equation (4) gives the total compressor work (CW) (process 2-3-4) per unit air mass flow, where process 2 - 3 occur in the LPC and process 3 - 4 occur in the HPC.

$$CW = LPCW + HPCW = \left(h_3 - h_2\right) + \left(h_4 - h_3\right) \tag{3}$$