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Numerical calculation of energy and exergy flows of a turboshaft engine for power generation and helicopter applications

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ABSTRACT

Fuel efficiency of aircraft and helicopter becomes greater concern in recent years caused by rising fuel costs and as well as environmental impact of aviation emissions. Modern helicopters, however, highly complex systems with especially turboshaft engines that produce energy and power. So it is important to gain deeper understanding energy and exergy use throughout turboshaft engine and its components. Concurrently, in this study, energy and exergy-based computational approach applied to a turboshaft engine and its components. Exergy efficiency of the axial, centrifugal compressors and power turbine is found to be between 83.8% and 88.6%, while for the combustor, the corresponding value is to be 80.60%. For the components, the greatest exergy efficiency is calculated to be 91.4% at the gas generator turbine unit. As a result of the study, the exergetic efficiency of the turboshaft has been calculated as 27.5% with 1500 kW product exergy. It is expected that numerical formulation based on energy and exergy is beneficial for assessing turboshaft performance for future rotorcraft development.

1. Introduction

A turboshaft engines are similar to turboprop engine, except that the hot gases are expanded to a free or power turbine, therefore providing greater shaft power. A turboshaft engine is designed to produce only shaft power and used in helicopters, ships, trains, tanks, pumping units, and various industrial gas turbine applications. Industrial gas turbines are defined as all gas turbines other than aircraft gas turbines. Industrial gas turbines are basically turboshaft engines [1,2].

With the increase of world's energy and air transportation need, the number of aero gas turbines and turboshaft engines increases the year to year [3]. The fast growing energy demand and air-travel has presented gas turbine manufacturers with the challenge of minimizing the environmental impact. The task is made more challenging by strategies to reduce noise, limit pollution and use less energy can have adverse effects on each other [4–6]. When we investigate optimum energy and exergy balance of air gas turbines and turboshaft engines, first consideration can be formulated in a common work of the first and second laws of thermodynamics. The importance of first and second law of thermodynamics is also linked to environmental problems [7–9].

Energy-based methods are the fundamental concept that energy flows into and out of a system through work, mass flow and heat transfer [10,11]. In gas turbine systems, thermodynamic first-law analysis is traditionally design procedure. Essentially, this is energy-based approach. Exergy-based methods applied to the design of gas turbine systems have advantages over traditional methods. Energy must be conserved is the basic premise of the first law. On the other hand, exergy is based on entropy generation minimization. It is, in fact, totally or partially destroyed and not conserved. The main target of exergy analysis is to determine true magnitudes of exergy destructions and their exact locations and help improve the system performance. Exergy destruction is proportional to the amount of entropy generated. It can be caused friction, expansion, mixing, chemical reaction, and heat transfer through a finite temperature difference. Exergy loss occurs when a material or energy stream is rejected to the environment. So, the maximum work may be achieved when the system is brought to the dead state (i.e., the system is at mechanical, thermal, and chemical equilibrium with its environment). Destroyed exergy brings about the component or system inefficiency. Hence, minimizing entropy generation reduces exergy destruction to improve efficiency. Indeed, exergy method can identify the environmental,

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economic and sustainable benefits of gas turbine technologies much better than energy [12–14].

In the open literature, energy, exergy analyses and computational methods for turbomachinery and stationary/aero gas turbines have been reported in the last decades [9,11,15–32]. The original motivation of this work was prompted by a study made to energetic and exergetic numerical calculation of an advanced helicopter turboshaft engine using thermodynamics laws. The turboshaft engine model studied here is very similar to for the Makila1A1 engine used in powering the Eurocopter's AS332 Super Puma, AS532 and SA330 helicopters available for both civil and military operators. Broadly speaking, lack of energetic and exergetic numerical calculation of the turboshaft engine and its components emphasizes the originality of this article. This paper discusses in detail that concept of using energy and exergy tools as an integrated methodology for helicopter and turboshaft matching. In this regard, the main objectives of this contribution are to (i) calculate the energy and exergy flows for the turboshaft engine components, and (ii) analyze the energetic and exergetic metrics of the turboshaft and its components.

2. Methodology

2.1. First law of thermodynamics and energy

Energy-based approach is based on the principle of conservation of energy applied to the system. For a general steady state, steady-flow process, the four balance equations (mass, energy, entropy and exergy) are applied to find the work and heat interactions [11,13,14].

Total enthalpy is defined as the sum of the internal energy, the flow energy, and the kinetic energy and its rate of change can be therefore written as [32]:

$$\nabla\cdot(\rho\delta h_i\mathbf{V}) = \nabla\cdot(\rho\delta e\mathbf{V}) + p_0\nabla\cdot\mathbf{V} + \nabla\cdot(p-p_0)\mathbf{V} + \nabla\cdot\left(\rho\frac{V^2}{2}\mathbf{V}\right) \tag{1}$$

According to the first law of thermodynamics, the steady state total enthalpy equation is as follows [32]:

$$\nabla\cdot(\rho\delta h_i\mathbf{V}) = \nabla\cdot\left(\overline{\overline{\overline{\tau}}}\mathbf{V}\right) - \nabla\cdot\mathbf{q} \tag{2}$$

where the$\mathbf{q}$ is the heat flux by conduction.

The mass balance equation can be expressed in the rate form as [11,13,14]:

$$\sum\dot{m}_i = \sum\dot{m}_o, \tag{3}$$

where $\dot{m}$ is the mass flow rate, and the subscript in stands for inlet and out for outlet.

The general energy balance can be expressed below as the total energy inputs equal to total energy outputs [11,13,14].

$$\sum\dot{E}_i = \sum\dot{E}_o \tag{4}$$

Energy conservation suggests that for a steady-state process the First Law may be represented by Refs. [11,13,14]:

$$\sum(h+ke+pe)_i\dot{m}_i - \sum(h+ke+pe)_o\dot{m}_o + \sum\dot{Q} - \dot{W} = 0 \tag{5}$$

where $\dot{m}_{in}$ and $\dot{m}_{out}$ denote the mass flow rate across the system inlet and outlet, respectively, $\dot{Q}$ represents the heat transfer rate across the system boundary, $\dot{W}$ is the work rate (including shaft work, electricity, and so on) transferred out of the system, and h, ke, and pe denote the specific values of enthalpy, kinetic energy, and potential energy, respectively [11–14].

2.2. Second law of thermodynamics and exergy

The Gibbs function gives a relation between entropy and internal energy. In time averaged form, it can be given as follows [32]:

$$T\nabla s = \nabla e + p\nabla\frac{1}{\rho} \tag{6}$$

Inserting the steady-state expression of the internal energy [32]:

$$\nabla\cdot(\rho\delta e\mathbf{V}) = -p\nabla\cdot\mathbf{V} + \left(\overline{\overline{\overline{\tau}}}\nabla\right)\cdot\mathbf{V} - \nabla\mathbf{q} \tag{7}$$

whereas energy is a conserved quantity, exergy is not and is always destroyed when entropy is produced. In the absence of electricity, magnetism, surface tension and nuclear reaction, the total exergy of a system $\dot{E}x$ can be divided into four components, namely (i) physical exergy $\dot{E}x^{PH}$ (ii) kinetic exergy $\dot{E}x^{KN}$ (iii) potential exergy $\dot{E}x^{PT}$ and (iv) chemical exergy $\dot{E}x^{CH}$ [12].

In the perspective of producing work, we can write that [32].

$$Energy = Exergy + Anergy \Leftrightarrow Total = Useful + Useless \tag{8}$$

For an open system, Eq. (8) can be written mathematically as [32].

$$ex = (h_t - h_{t0}) - T_0(s - s_0) = \delta h_t - T_0\delta s \tag{9}$$

Time-averaged change in exergy can be written as [32]:

$$\nabla\cdot(\rho ex\mathbf{V}) = \nabla\cdot(\rho\delta h_t\mathbf{V}) - T_0\nabla\cdot(\rho\delta s\mathbf{V}) \tag{10}$$

If we neglect the heat transfer across the outer boundary as well as viscous,

$$-\int_{S_A}\rho ex(\mathbf{V}\cdot\mathbf{n})dS = -\int_{v}\nabla\cdot\rho ex\mathbf{V}dv + \int_{S_O}\rho ex(\mathbf{V}\cdot\mathbf{n})dS + \int_{S_W}\rho ex(\mathbf{V}\cdot\mathbf{n})dS \tag{11}$$

From above equations, following exergy balance can be written [32]:

$$\dot{E}x_{eng} + \dot{E}x_q = W\dot{\Gamma} + \dot{E}x_m + \dot{E}x_{th} + \dot{A}_{tot} \tag{12a}$$

Left-hand-side terms represent exergy sources supplies, whereas right-hand-side terms represent exergy outflows and sinks, except for$W\dot{\Gamma}$, which is a reversible accumulation/restitution of exergy. The rate of exergy outflow is decomposed into$W\dot{\Gamma} + \dot{E}x_m + \dot{E}x_{th}$, and the total anergy generated within control volume ($\dot{A}_{tot}$) [32],

$$\dot{A}_{tot} = \dot{A}_{\Phi} + \dot{A}_{\nabla T} + \dot{A}_W \tag{12b}$$

The aircraft surface has been split in two surfaces: one solid body surfaceS_B, which may be non-adiabatic, and one permeable engine or propulsion surface S_{eng}, on which $\mathbf{V}\cdot\mathbf{n}\neq 0$. Note that $S_A = S_B \cup S_{eng}$[32].

The rate of exergy supplied by an engine is:

$$\dot{E}x_{eng} = \int_{S_{eng}} -\rho\delta h_t(\mathbf{V}\cdot\mathbf{n})dS - T_0\int_{S_{eng}} -\rho\delta s(\mathbf{V}\cdot\mathbf{n})dS \tag{13}$$