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Using exergy for performance evaluation of a conceptual ramjet engine burning hydrogen fuel

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ABSTRACT

Ramjet engines are widely-used devices in the defence industry and have military applications. These engine types, preferred in many fields, are known to act according to the laws of thermodynamics. For this reason, exergy analysis methodology is a beneficial tool for assessing the performance of a ramjet engine, as well as other energy conversion systems. The present study aims to introduce a performance analysis of a hydrogen fueled ramjet engine within the framework of the first and second laws of thermodynamics. At the end of the study, the exergy efficiencies of inlet, combustion zone and nozzle are found to be 3.88%, 7.62%, and 0.03%, respectively, whereas the exergy efficiency of a ramjet engine is 8.85%. The introduced methodology and the results obtained from the current study may be useful for anybody who is interested in thermal sciences and aero-propulsion technologies.

Introduction

The aerospace science and technology industries have made progress in the last decade as a result of the growth in air transportation and military forces worldwide. The interest of mankind in air transportation, rather than that of road, sea, rail and so on, has increased considerably as it provides more comfortable, time-saving and easier access to numerous destinations [1–3]. Nonetheless, the rise in air transportation passenger and aviation fleets has led to more energy consumption and considerable environmental damage. The latest research on environmental issues associated with aviation and aircraft fleets reports a requirement for aviation-induced emissions reduction. From the perspective of sustainable development, it is essential to achieve greener, environmentally friendly and more efficient systems employed in air transportation. If the propulsion system of aerospace systems is considered to be the most energy consuming sub-system, the green engine concept gains importance [4–6].

Recent studies in this field of science have presented evidence as to how hydrogen would fill the gap in providing the energy demands of the future. The most promising progress up until now has been achieved by benefitting from hydrogen as a main fuel in combustion systems as well as in fuel cell technology. Being environmentally-friendly and offering clean combustion are prominent specifications of hydrogen as a main fuel compared to conventional fuels, such as gasoline, diesel, fuel-oil and so on [7]. The major problem arising out of fossil fuel combustion is the danger of environmental issues.

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Nomenclature

$\dot{m}$	Mass flow rate (kgs^{-1})
$\dot{Q}$	Heat flux rate (kW)
$\dot{W}$	Work rate or power (kW)
V	Velocity (ms^{-1})
h	Specific enthalpy (kJ/kg)
$\dot{E}$	Exergy rate (kW)
e	Specific exergy (kJ/kg)
c_p	Specific heat capacity under constant pressure ($kJkg^{-1}K^{-1}$)
T	Temperature (K)
P	Pressure (kPa)
R	Universal gas constant
x	Molar rate (%)
LHV	Lower heating value of the fuel ($kJkg^{-1}$)
ε	Exergy efficiency (%)
$\dot{IP}$	Improvement potential rate (kW)
χ	Relative irreversibility (%)
δ	Fuel depletion rate
ξ	Productivity lack

From this perspective, hydrogen is considered as a certain solution in reducing carbon emissions especially, in addition to unburned hydrocarbon formation. Within this framework, various energy production systems fueled with hydrogen have recently been investigated by a number of researchers [8–12]. Supplying energy to aerial vehicles and spacecraft using hydrogen burning engines is particularly under discussion. Certain papers have dealt with the 'highs and lows' of hydrogen utilization in aero engines [13–21]. The storage and carriage of hydrogen as a fuel are the most prevalent problems with respect to safe flight conditions. The chemical behavior of hydrogen to make compounds exposes an obstacle in overcoming the storage issue. However, a remarkable development in the liquefying of hydrogen fuel for storage has recently been successful [18,19]. Xu et al. [18] discuss design and analysis of a liquid hydrogen fuel tank for a high-altitude long-endurance (HALE) type aircraft. In the study, a liquefied hydrogen fuel tank is shown to be lightweight and well-insulated to prevent heat loss. Thermal performance analysis and structural assessment of various material preferences are discussed in detail. According to the results, liquefied hydrogen fuel storage is found to be feasible for aerospace applications. In another study [19], the storage of liquefied hydrogen fuel for long space missions is discussed. The study found that conserving liquefied hydrogen in a tank without evaporation during a space mission is possible. Donat et al. [20] present details of a hydrogen fueled scramjet in their studies.

Former studies have shown that utilizing hydrogen as a fuel for aerial vehicles and spacecraft has been under consideration for a long time. The earliest accessible research in this field was carried out within the scope of a secret NASA project in the 1950s. However, technical limitations of liquefied hydrogen storage led to the termination of the project [21]. Fortunately, state of the art advances enable us to seriously consider liquefied hydrogen as a propellant fuel. Liquefied hydrogen powered aerial vehicles are being studied more intensely than ever. Donat et al. [20] present a conception and research into a hydrogen fueled scramjet in their studies. Their work discusses the design process of a scramjet in addition to results obtained from ground and preflight tests. Experimental knowledge including instrumentation and data processing is also given in detail. Ref. [22] deals with an exergy analysis of a supersonic ramjet engine filled with conventional fuel. This parametric study presents an exergy value variation dependent on a variable cross-section area and inlet flow temperature. In Ref. [23], the researchers make use of an exergetic approach to estimate the specific impulse of a ramjet engine parametrically. Similar research has been conducted for aircraft as well as for ramjets and spacecraft [12]. Within this framework, the exergy-based sustainability and performance of a hydrogen fueled turbofan engine is discussed in Ref. [24].

Regarding earlier studies, it has been shown that liquefied hydrogen is a feasible fuel option for aerial vehicles in the near future. From this point of view, the authors of the current study intend to introduce a performance analysis of a conceptually designed and liquefied hydrogen fueled ramjet engine in terms of exergy. In the study, an exergy analysis of a hydrogen fueled ramjet engine is presented for the literature for the first time besides highlighting the significance of hydrogen as a propellant fuel.

Methods and materials

Basics of a ramjet engine

The ramjet engine is an aero-thermodynamic duct containing no rotating component; neither a compressor nor a turbine. Any type of ramjet engine, whether subsonic or supersonic, is comprised of an inlet, combustion zone and a nozzle. At this point, the inlet section is similar to a divergent duct and it implements subsonic compression of air. The combustion zone of the ramjet engine, where air and fuel react chemically, is an advanced passage containing fuel spray nozzles. The nozzle component of the ramjet engine may not be only the convergent type but may also be the convergent-divergent type. While air is passing through the inlet, it loses kinetic energy and the pressure of the air increases as well as the compression process in any type of gas turbine engine. Then pressurized air reacts with the fuel exothermically within the combustion zone. As a result of the combustion process, energy carrying gas runs to the ambient air through the nozzle. The aerodynamic structure of the nozzle leads to the generation of thrust. A schematic illustration of a supersonic ramjet engine is shown in Fig. 1. Fundamental design parameters of the conceptual ramjet engine are also given in Table 1. It is known that performance of ramjet engines is fair under supersonic flight conditions in comparison with subsonic conditions [22–25]. Therefore, the flight Mach number of the ramjet engine was designated to be higher than 1.2.

A cycle analysis of the ramjet engine was conducted according to the design parameters given in Table 1. The methodology used for cycle analysis can be found in Refs. [26,27].

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