Energy and Exergy (ENEX) Analyses of a MD-80 Aircraft

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***Abstract*—The growth in demand for air transport is a problem for the global and local environment. There are, moreover, fundamental conflicts with sustainable development objectives. Sustainability demands a sustainable supply of energy without causing negative environmental impacts of aircrafts. In this paper, an investigation of energy and exergy analyses (ENEX) is reported for a MD-80 aircraft at take-off phase. In this regard, considering ENEX equations, exergy and energy efficiencies of the aircraft are found to be 29.8% and 11.48% respectively, while take-off thrust and specific fuel consumption of the MD-80 is to be 144 kN and 14.58 g (kN.s)$^{-1}$. In addition, fuel and product exergies of the aircraft are calculated to be 93.92 MW and 28.06 MW.**

***Index Terms*—sustainable aviation, aircraft, green aircraft, exergy, energy**

I. Introduction

Air travel continues to experience the fastest growth among all modes of transportation. Air travel and other high-speed transport accounted for less than 1 percent of world passenger traffic volume in 1950 and for 10 percent in 2005; they are forecasted to account for between 36 and 40 percent by 2050 [1]. The amount of nitrogen oxides around airports, generated by aircraft engines, may rise from 2.5 million tons in 2000 to 6.1 million tons by 2025 [2]. The number of people who may be seriously affected by aircraft noise may rise from 24 million in 2000 to 30.5 million by 2025 [2]. Energy and exergy concepts have been utilized to ensure the environmental, economic and social sustainability. In order to reduce the negative impacts created by the pollutant emissions, the energy sources should be efficiently utilized. If one wants to approach environmental considerations incorporated with sustainability and thermodynamics, there are two methods: energy analysis through the first-law of thermodynamics and exergy analysis through the second-law of thermodynamics.

Therefore, the environmental issues such as noise, emissions and fuel burn (consumption), for both airplane and airport operations, have become important for energy and environmental sustainability.

Minimization of the environmental effects of aircraft fuel emissions, conservation of the air transport fuel energy reserves, improvement of energy consumption reduction strategies for airliners, development of economical flight procedures in air traffic management, and achievements in more efficient air transportation in today's aviation industry substantially depend on an accurate energy modelling for transport aircraft.

Recent advances in computational methods have allowed the modelling and simulations of increasingly detailed aircraft energy systems. Separate disciplines, such as aerodynamics and propulsion, can model complex aircraft systems, provided that a rational set of data are available (physical, geometrical, functional). This knowledge has seemingly not been fully integrated to provide a flight performance simulation model. Ultimately, one needs to look at the whole system, to understand the limitations of the integration between disciplines and the emergence of new knowledge that arises from this integration [3]-[15].

The exergy of an emission to the environment, therefore, is a measure of the potential of the emission to change or impact the environment. The exergy of an emission is zero only when it is in equilibrium with the environment and thus benign. These points suggest that exergy may be, or provide the basis for, an effective indicator of the potential of an emission to impact the environment. There have been various assessment used for waste gases emitted from transportation sectors [3]-[15].

In the present energy and exergy model (ENEX) of a MD-80 aircraft at maximum power is broadly analyzed based on thermodynamics equations. Lack of energy and exergy analysis of a MD-80 ENEX analysis makes the paper original and becomes main motivation for air vehicles during typical flight.

II. System Description and Methodology

The first law of thermodynamics is widely used in energy systems analysis. Many researchers suggest that the thermodynamic performance is best evaluated using exergy analysis. The second law involves the reversibility or irreversibility of processes and is a very important aspect in the exergy method of energy systems analysis. In this regard, exergy analysis appears to be a significant tool for determining locations, types and true magnitudes of waste energy and losses to design more efficient energy systems and distinguishing the quality of energy [16]. On the other hand, technology has a vital role to play in mitigating the environmental impacts of air transportation. At this point of view, exergy efficiency is

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also a useful tool for evaluating aircraft environmental performance. The exergy of an emission to the environment, therefore, is a measure of the potential of the emission to change or impact the environment [17]-[24]. Technically, exergy is measured using thermodynamics principles. Unlike energy, exergy is destroyed due to irreversibilitie's in real processes [25]-[29]. This method is particularly useful for quantifying types, magnitudes of wastes, destructions and losses of energy in the thermal systems. The exergy is a measure of quality and provide the basis for an effective measure of the potential of energy impact to the environment. Exergy can also provide into the efficiency, environmental impact and sustainability of energy systems [30].

In the literature, ENEX analyses have not been calculated for the MD-80 aircraft with JT8D turbofan engine. The MD-80 series was the second generation of the DC-9. It was originally called the DC-9-80 series and the DC-9 Super 80 and entered service in 1980. The MD-80 series was then developed into the MD-90 entering service in 1995. The last variant of the family was the MD-95, which was renamed the Boeing 717-200 after McDonnell Douglas's merger with Boeing in 1997. The DC-9 family is one of the most successful jet airliners with a total of over 2,400 units produced; it ranks third behind the second-place Airbus A320 family with over 4,000 produced, and the first place Boeing 737 with over 7,000 produced [31].

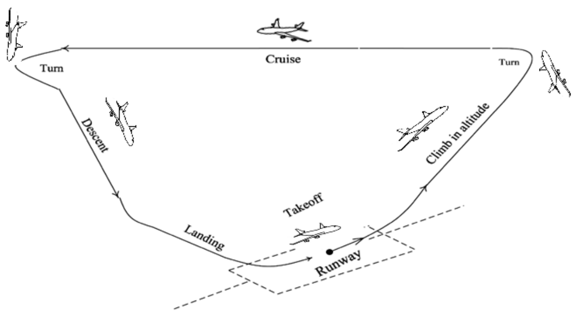

Figure 1. Typical flight phases for a passenger airplane

Thrust is the force for propelling an aircraft in different flight regimes. Thrust, drag, lift and weight represent the forces that govern the aircraft motion. An aircraft engine must identify the different requirements for all flight phases (Fig. 1) such as takeoff, climb, cruise and maneuvering, descend and landing. During the cruise, the four forces are in equilibrium in pairs-thrust and drag as well as lift and weight. Thrust force is used in braking the aircraft via thrust-reversing mechanism during landing. [32], [33]. In the absence of electricity, magnetism, surface tension and nuclear reaction, the total exergy of a system 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 ($\dot{E}x^{CH}$) [34].

$$\dot{E}x = \dot{E}x^{PH} + \dot{E}x^{KN} + \dot{E}x^{CH} + \dot{E}x^{PT} \tag{1a}$$

Although exergy is extensive property, it is often convenient to work with it on a unit of mass or molar basis. The total specific exergy on a mass basis may be written as follows [34]:

$$ex = ke + pe + (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + ex_{CH} \tag{1b}$$

where *ke* is the specific kinetic energy of the system and *pe* is the potential energy per unit mass due to the presence of any conservative force field. *T*, *p*, *u*, *v*, *s* and ex_{CH} are the temperature, pressure, specific intermolecular energy, specific volume, specific entropy and specific chemical exergy, respectively. The terms with the subscript *0* are the properties of the exergy reference environment.

The general exergy balance can be written as follows [34]:

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} = \sum \dot{E}_{dest} \tag{2a}$$

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,in} - \dot{E}x_{mass,out} = \dot{E}x_{dest} \tag{2b}$$

$$\dot{E}x_{work} = \dot{W} \tag{2c}$$

$$\dot{E}x_{mass,in} = \sum \dot{m}_{in}\psi_{in} \tag{2d}$$

$$\dot{E}x_{mass,out} = \sum \dot{m}_{out}\psi_{out} \tag{2e}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k at location k and $\dot{W}$ is the work rate.

The flow (specific) exergy is calculated as follows [34]:

$$\psi = (h - h_0) - T_0(s - s_0) \tag{3}$$

where *h* is enthalpy, *s* is entropy, and the subscript zero indicates properties at the restricted dead state of P_0 and T_0.

The rate form of the entropy balance can be expressed as [34]:

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0 \tag{4}$$

where the rates of entropy transfer by heat transferred at a rate of $\dot{Q}_k$ and mass flowing at a rate of $\dot{m}$ are $\dot{S}_{heat} = \dot{Q}_k / T_k$ and $\dot{S}_{mass} = \dot{m}s$, respectively [34].

Taking the positive direction of heat transfer to be to the system, the rate form of the general entropy relation given in Eq. (7) can be rearranged to give [34].

$$\dot{S}_{gen} = \sum \dot{m}_{out}s_{out} - \sum \dot{m}_{in}s_{in} - \sum \frac{\dot{Q}_k}{T_k} \tag{5}$$

Also, it is usually more convenient to find $\dot{S}_{gen}$ first and then to evaluate the exergy destroyed or the irreversibility rate $\dot{I}$ directly from the following equation, which is called Gouy–Stodola relation [34]:

$$\dot{I} = \dot{E}x_{dest} = T_0\dot{S}_{gen} \tag{6}$$

Assuming air to be a perfect gas, the specific physical exergy of air is calculated by the following relation [34]:

$$\psi_{air,per} = C_{p,a}\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) + R_a T_0 \ln\frac{P}{P_0} \tag{7}$$

Numerous ways of formulating exergy (or second-law) efficiency for various energy systems are given in detail elsewhere. It is very useful to define efficiencies based on exergy. There is no standard set of definitions in the literature. Here, exergy efficiency is defined as the ratio of total exergy output to total exergy input, i.e. [34]

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{8}$$

where ‘‘out’’ stands for ‘‘net output’’ or ‘‘product’’ or ‘‘desired value’’ or ‘‘benefit’’, and ‘‘in’’ stands for ‘‘given’’ or ‘‘fuel’’ as shown in Fig. 2 [34].

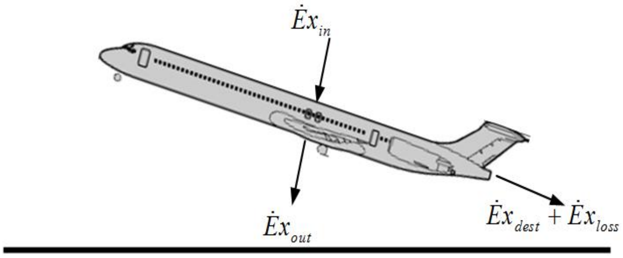

Figure 2. Exergy balance diagram for MD-80 aircraft.

III. Conclusion

The main conclusions that can be drawn from the results of the MD-80 aircraft at take-off phase are as seen in Fig. 3. The other results of the study are as following: Considering ENEX equations, exergy and energy efficiencies of the aircraft are found to be 29.8% and 11.48% respectively, while take-off thrust and specific fuel consumption of the MD-80 is to be 144 kN and 14.58 g $(kN.s)^{-1}$. In addition, inlet and outlet exergies of the aircraft are calculated to be 93.92 MW and 28.06 MW.

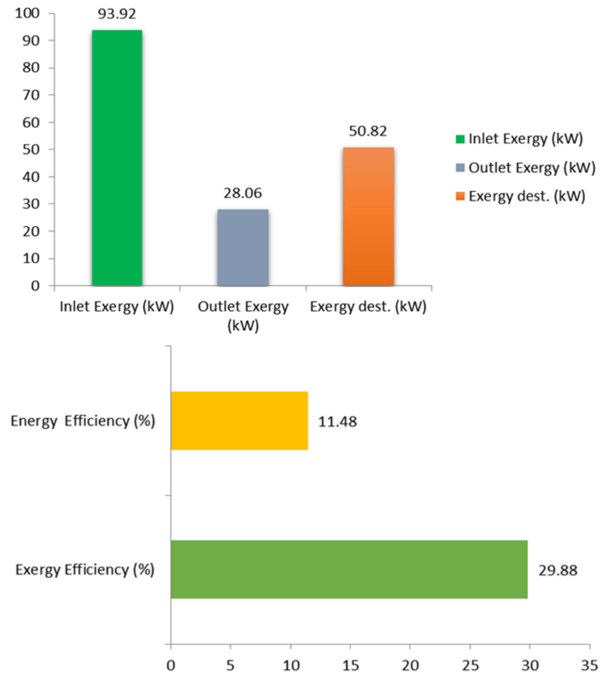

Figure 3. Summary of exergy flows and ENEX efficiencies of a MD-80 aircraft at take off.

For analysis, the use of ENEX assessment appears suitable in many instances for accurately guiding improvement efforts, as the locations of the greatest losses and the causes of these losses are properly characterized for an aircraft. The results are expected to be useful for any kind of aircraft and helicopters. To better define the role of exergy particularly in the area of in regional aircraft and helicopters; further research appears to be needed. In order to minimize the negative impact of aircraft on the environment sustainability, some new exergy-based sustainability parameters of the aircrafts may be developed and calculated experimentally and parametrically for the next studies.

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