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Thermodynamic Concepts on Efficiency of Aircraft Engines

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Authors' contributions

This work was carried out in collaboration between both authors. Author FF designed the study, wrote the protocol and wrote the first draft of the manuscript. Author EY managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Along with the development of engine technology to be able to produce maximum efficiency in aircraft jet engines, various modifications were made to the machine tools. Modifications are made by taking into account four main factors, namely: maximum power output, reduced engine weight, low fuel consumption and maximum aircraft payload. This research uses a meta-analysis method, namely the analysis of several research results in line with what has been done previously regarding the efficiency of aircraft jet engines. The thermodynamic concept related to the heat engine which implements the brayton cycle that maximum efficiency can be done by reducing wasted heat energy and maximizing the work produced. From this concept, several attempts to maximize aircraft efficiency, such as modification of design that have a significant impact on weight reduction, fuel barrier design with low fan pressure, high bypass design ratio are also carried out in an effort to reduce aircraft noise levels. Aircraft noise levels can also be minimized by modifying the nozzle and ejector on the engine.

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1. INTRODUCTION

News of the Sriwijaya Air SJ-182 airplane crash on January 9th, 2021, which has caused quite a lot of speculation. Some of them stated that the wrong cause of the accident occurred because the plane was 26 years old. Based on the Decree of the Ministry of Transportation Number 115 of 2020 which states that "the age limit for aircraft that is registered and operated for the first time in Indonesia is provided that aircraft in the transportation category for passenger transportation are at most 20 years old" [1].

The Boeing 737-500 aircraft used on this flight were known to have flown for the first time on May 13th, 1994, with a maximum capacity of 112 passengers, according to various sources. This type of aircraft is included in the Boeing 737 Classic family produced by Boeing Commercial Airplanes and is the second generation of the Boeing 737-100/200.The Boeing 737-500 is the smallest variant and was first flown in 1989 and then began serving passengers in 1990. Although smaller than the 300 and 400 series, the Boeing 737 series 500 engines are more fuel efficient than 737-200 by up to 25 percent. The aircraft relies on two CFM56-3C1 engines made by CFMI, a joint-owned company of France's Safran Aircraft Engine and GE Aviation of United States. With a load of around 1,000 kilograms, the B737-500 can fly up to 4,444 kilometers with a fuel capacity of up to 23,830 liters.

Some aviation experts say that the age of an airplane is not a major factor in the occurrence of airplane accidents. One of the factors that can cause an aircraft to be unfit for flight apart from weather and crew performance is a technical factor. The technical factor referred to here is aircraft maintenance [2]. Aircraft engine maintenance includes structure of the frame engine, electrical system, radio installations and instrumentation. Machine maintenance is carried out regularly and non-routine [3].

Aircraft engine maintenance is an important thing, because several engine tools that are related to each other have quite sensitive characteristics. So that when there is one part that has a problem, it will have an impact on other parts. There are several machine tools which, if not carried out routine maintenance, can be subjected to prolonged humidity which in turn can cause corrosion on the machine. If one of the machine tools has a problem or cannot function optimally, it will have a direct impact on the function of the other equipment which results in the machine not working properly [4].

Based on thermodynamic principles regarding optimal work on the engine depending on engine performance. The incoming heat energy is optimally converted into work, and the remaining heat from the exhaust is small. The lower the heat output produced, the more work a machine can produce. A jet engine is a machine that can power an airplane that applies the brayton thermodynamic cycle. This jet engine, known as a gas turbine engine, requires high speed. Various modifications to jet engine used in aircraft such as turbojet and turbofan engines, rocket engines, ramjets and pump jets.

A turbojet engine is a fairly simple type of jet engine. Not only used in aircraft, but this turbojet engine is used on ships. This machine is powerful 28,000 hp with operations that require high speed [5]. Another type of jet engine that is commonly used is a turbofan engine. Turbofan engines are usually used in commercial aircraft and fighter aircraft. In this engine, some of the air is flowed into the combustion chamber, some of it is flowed outside the combustion chamber. In this engine, the air also simultaneously functions as a coolant (lowers the temperature) in the combustion chamber [6]. The next type of jet engine is a turboprop engine. This machine is a turbojet engine equipped with an additional turbine. Apart from being fuel efficient, this machine also has a low noise level. In contrast to a turboprop engine, a turboshaft engine is a type of jet engine, in contrast to a turboprop engine. In this machine is a turboprop engine without using additional turbines. Usually this machine is used on a helicopter [7].

In general, a jet engine is a power-producing engine on an airplane. The components of this machine are the inlet, propulsion turbine, compressor, burner and nozzle. Jet engines have the basic principle of a combustion process that produces heat with high temperatures. As a result of this high temperature, it produces a very fast speed, in other words, from this process jet engine provides/produces a large amount of energy/power. The advantages of a jet engine are that it produces enormous energy, can travel long distances and produces low vibrations. Of the advantages that a jet engine has, of course, there are drawbacks including high fuel consumption, maintenance that requires high costs and also a high level of noise [8].

In a jet engine work system in an airplane can be explained simply by simple thermodynamic concepts. Whereas in general the maximum efficiency in a heat engine can be generated by reducing the heat input and maximizing the incoming heat is converted into work with the smallest possible waste.

2. DATA AND METHODOLOGY

This research uses a meta-analysis research method. In this method, analysis of several research results is carried out in line with what has been done previously by raising similar problems. The data collection process was carried out using documentation techniques in the form of literature related to thermodynamic analysis on jet engines. Several types of literature are used such as articles in scientific journals and the like, both national and international, books related to jet engines and thermodynamic cycles and several published research results. The sampling technique used was purposive sampling technique which was deliberately selected so that the information generated was in accordance with the content of this research.

3. RESULTS AND DISCUSSION

The jet engine is an application of a heat engine whose simple scheme applies the second law of thermodynamics. Specifically, this jet engine has a cycle according to the Brayton cycle [9]. This heat burning machine accelerates the mass of air and produces heat at high temperatures. So that it produces great energy.

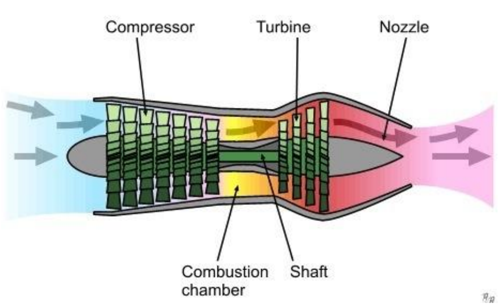

Fig. 1. Aircraft performance system

The rotation of the turbine rotor is caused by the presence of pressurized gas passing through the turbine blades. High pressure gas is obtained from combustion of fuel with air, just before entering the turbine. The expansion of the air from the combustion process is used to move the turbine blades.

Gas turbines use atmospheric air as a working medium. Air enters through the inlet side as a result of being sucked in by the compressor. This compressor serves to compress air to reach a certain pressure. Typically, the pressure at the end of the compressor blade reaches 30 times the compressor inlet pressure. At the end of the compressor compressed air will pass through the diffuser. This diffuser serves to support the compressor to increase air pressure.

The next process is the entry of compressed air out of the compressor to the combustion area (commonly called the combustion chamber). In this area, fuel injection is carried out followed by the process of burning the fuel in the air. This combustion results in expansion of the air so that the volume of combustion air increases, and of course the temperature also increases. The combustion process in the chamber will not increase air pressure, because the increase in air volume due to rapid heating causes the air to expand to the side of the turbine. Meanwhile, the increase in temperature of the combustion air indicates the energy content in the air (enthalpy) which also increases. This energy will be converted into shaft rotation power by a gas turbine.

The combustion air then enters the side of the turbine. The gas turbine consists of several blade stages. The first stage through which the combustion air passes is called the high pressure stage (high pressure), while the last blade is called the low pressure stage (low pressure) side. The blades of each steam turbine stage function as nozzles, which convert the heat energy contained in the combustion air to become energy for motion. In addition to the rotor side, turbine blades are also on the stator side.

The compressor in the gas turbine system is located on one shaft (shaft) with the turbine. Part of the mechanical energy in the form of shaft rotation produced by the turbine is used to rotate the compressor rotor. In power plants, some of the mechanical energy is used to rotate the generator which is also on the same axis as the turbine and compressor.

In contrast to airplane turbojet engines, a small portion of the hot energy of combustion air is used to rotate the turbine, which is then used to rotate the compressor. Most of the heat energy in the combustion air of the jet engine is used to propel the plane, where the turbine output is in the form of a nozzle. This nozzle serves to increase the thrust speed of the exhaust gases, so as to get a greater thrust for the aircraft.

The brayton cycle, which is applied to a jet engine, consists of 4 stages of the thermodynamic process [10].

3.1 Isentropic Compression Process

In isentropic compression, air enters the gas turbine system through the compressor inlet. From the compressor, the air is compressed at a certain pressure followed by a narrowing of the volume of the combustion chamber. In this process the entropy in the system is considered constant [11]. Based on a reversible process according to the first law of thermodynamics, work is generated in this process [12]:

$$dQ = dW + dU \quad (1)$$

Where is the isentropic process

$dQ = 0$ and $= nc_v(T_2 - T_1)$:

$$dW = -dU$$

$$W_1 = -\int dU = -\int_{T_1}^{T_2} nc_v\, dT = nc_v(T_2 - T_1) \quad (2)$$

3.2 Isobaric Combustion Process

In the isobaric combustion process, compressed air enters the combustion chamber, the heat energy from the combustion is absorbed by the air, increasing the air temperature and increasing the air volume. In this process the pressure is constant because there is no pressure increase because the air from combustion is free from expansion to the side of the turbine [11]. Work generated in this process:

$$W_2 = p\,(V_2 - V_1) \quad (3)$$

3.3 Isentropic Expansion Process

In this isentropic expansion process, where the compressed air from the combustion products expands through the turbine. Turbine blades which are small nozzles function to convert the hot energy of the air into kinetic energy in the form of propulsion of the aircraft by a large nozzle at the end of the turbn gas output. [11]. Work generated in this process:

$$W_3 = -\int dU = -\int_{T_1}^{T_2} nc_v\, dT = -nc_v(T_1 - T_2) \quad (4)$$

In this case $T_1 > T_2$.

3.4 Isobaric Heat Dissipation Process

Pada proses pembuangan panas, dimana udara dibuang ke atmosfer. Panas yang diseap oleh udara bebas, sehingga siklus udara siap untuk kembali masuk ke tahap kompresi isentropic [11]. Work generated in this process:

$$W_4 = p\,(V_2 - V_1) \quad (5)$$

Referring to the brayton cycle concept, the calculation of engine efficiency can be calculated. The total work that can be generated in accordance with the Brayton cycle is the total number of all 4 processes that occur in the cycle. The efficiency of a heat engine describes the work performance of the engine. The greater the efficiency value, the better the working performance of the machine. Based on the second law of thermodynamics which states related to the efficiency of a heat engine where the amount of heat energy that comes later from that energy will produce work which will later be used to carry out every process on the heat engine so that it becomes a cycle. During work, of course there is a waste of energy. The relationship between work efficiency, namely [13].

$$\eta = \frac{W}{Q_H} \quad (6)$$

where η is efficiency, W is action dan Q_H is the amount of incoming heat energy. From the relationship of these equations, to obtain maximum efficiency, of course, you must minimize waste energy and maximize the energy that goes into work. In this concept, in simple terms, the efficiency of the machine can be maximized.

The ratio between the volume of compressed air and the volume of energy wasted has a major effect on the combustion efficiency that occurs in a jet engine, causing a thrust. Where in a jet engine, the gas generator is the main power producer in a jet engine. Jet engine performance is influenced by several factors, namely jet fuel, electricity, hydrogen, aerodynamics, atmospheric conditions, altitude, temperature, humidity and weather [14]. The efficiency of the machine is divided into 5, namely:

1. Thermal efficiency comes from an understanding of the ideal cycle which explains the ratio of energy in the form of work (W) to energy in the form of incoming heat (Q_H). where work (W) is the result of reducing the incoming heat (Q_H) with wasted heat energy (Q_C).
2. The thermal efficiency indicator is the thermal efficiency value of the actual cycle indicator diagram. The work of the indicator diagram is the work generated and the incoming heat energy is calculated based on the combustion process per kilogram.
3. Effective thermal efficiency is the ratio of shaft power or effective power to the heat input rate.
4. Mechanical efficiency is the ratio of shaft power and indicator power where the indicator works for each unit of time which will be converted into shaft work per unit time.

Of course, based on the thermodynamic concept, in order to maximize engine efficiency it is necessary to pay attention to several main factors that can move the aircraft, namely the amount of power generated and the weight of the engine. The heavier the machine, of course the greater the power required [15]. In terms of aircraft fuel usage, if the power used in the engine is very large, of course the fuel consumption is also large [16]. In terms of the load that the aircraft can carry, the lighter the aircraft engine, the more cargo the aircraft can carry [17]. Currently, there have been many modifications to aircraft engines taking into account these factors [18,19]. For example, the T70 Turbocharger has a radial type of turbine that has an efficiency value of 60% which will be modified into a turbojet engine. To get a higher efficiency value on a turbojet engine. This single stage axial turbine is expected to have an efficiency of 87% and can supply power to a compressor of 120,000 Watts [20]. In addition, the hot core engine compartment of the turbojet engine is cooled by the rated flow of coolant air exhaled through the nacelle laminar flow system. This arrangement reduces the need to remove bypass ram air from the engine performance cycle for cooling purposes and thereby improves specific fuel consumption and engine efficiency. A turbocompressor pump driven by airflow from the core engine compressor draws cooling air through the laminar flow nacelle system and pumps air into the manifold surrounding the core engine [21].

Apart from improving the performance of the aircraft engine such as producing maximum power, fuel consumption and a slight reduction in engine weight, it is necessary to pay attention to external impacts that can be generated such as noise. Airplane noise has a serious impact on human health [22]. Significant advances are being made with noise reduction for turbofan engines [23]. Modifications were made to such as the LSU-02 unmanned aircraft developed by Pustek LAPAN with modifications to the length and width of the muffler on the 3W28i engine. the wider (larger diameter) of the muffler by approximately 80 mm contributes to a 21.587 dB reduction in sound levels. A modified muffler length with a diameter of 80 mm and a length of 130 mm can contribute to a noise reduction of 20.929dB [24]. Additionally the noise cancellation can be modified from the combination of the mixing nozzle and the ejector. After being tested tested on two full scale turbojet engines. Reduces the maximum sound pressure level by 12 dB and reduces the sound power level by 8 dB [25]. Noise reduction can also be done at the junction plane between the air intake structure and the aircraft turbojet fan casing [26].

4. CONCLUSION

Based on the thermodynamic concept related to heat engines that apply the Brayton cycle, maximum efficiency can be done by reducing wasted heat energy and maximizing the work produced. From this concept, the desire to seek maximum engine efficiency results in many jet engine modifications by maximizing the function of the main factors of engine efficiency such as: Producing large power, low fuel consumption and striving for a light engine weight so that the aircraft's payload capacity is maximized. Current modification steps such as design changes that have a significant impact on the reduction of aircraft weight and the design of the fuel limit with low fan pressure, high design bypass ratio will reduce aircraft noise levels.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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