Current Status of Jet Engines and Their Future on Fuel Efficiency

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Abstract. Recently, regulations on emissions for international aviation has become increasingly strict. In addition, cost of fossil fuel has increased owing to limited non-renewable resource. Therefore, it is important to understand fuel efficiency because this is a practical method to reduce the cost and emissions based on recent technology. In this article, theoretical background of jet engines will be demonstrated, which include structure of jet engines and cycle efficiency. Followed by factors that affect the efficiency of jet engines. Finally, applications of jet engines based on efficiency and methods that improve efficiency are demonstrated, which includes recent technologies and possible future directions.

Keywords: jet engines, Fuel Efficiency, Brayton Cycle, Turboprop Engine, turbofan engines.

1. Introduction

In most recent day, owing to limited non-renewable resource, fossil fuel consumptions have become a critical issue over the world, as well as climate change owing to carbon emission [1]. This problem has affected industries that involve combustion engine including aviation with jet engines. better fuel efficiency has been considered as the most practicable goal that led to lower costs and emissions in most recent day [2]. In addition, owing to improvements on jet engine design, the efficiency and performance of jet engines has been improved up to 85% [3]. Therefore, it is important to understand current statue on jet engines efficiency and possible trending in close future.

In this following work, some typical jet engines and their thermodynamics backgrounds will be introduced. This includes two basic concepts and some typical modifications on the basic model. After that, the efficiency of the jet engine will be demonstrated with some possible factors. Finally, applications of different jet engines based on efficiency and possible future prospects are discussed.

2. Jet Engines and Their Theoretical Backgrounds

2.1. Introduction of Turbojet Engines and Their Thermodynamics Properties

Recently, owing to the high-power-to weight ratio and lightweight, gas turbine engines are commonly used to power aircraft [4]. Their cycle also called the jet-propulsion cycle, whose model known as turbojet engines. In order to understand jet engines, ideal Brayton cycle will be briefly introduced in this session, followed by turbojet engines.

2.1.1 Ideal Brayton Cycle.

An open system gas turbine engine is demonstrated as figure 1, whose cycle is demonstrated as the Brayton cycle. Normally, this theoretical cycle consists of 5 components: compressor, two heat exchangers, turbine, and working fluid [5]. There are four processes in the Brayton cycle. It begins with isentropic compression (1-2), followed by isobaric heat addition (2-3) and Isentropic expansion (3-4). Finally, it ends with isobaric heat rejection (4-1). The T-s diagram for the ideal Brayton cycle is shown as figure 2.

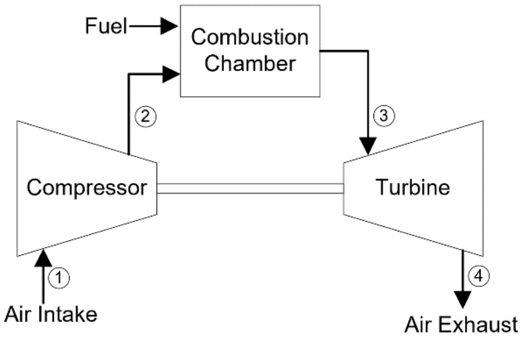

Figure 1. Open system gas turbine engine.

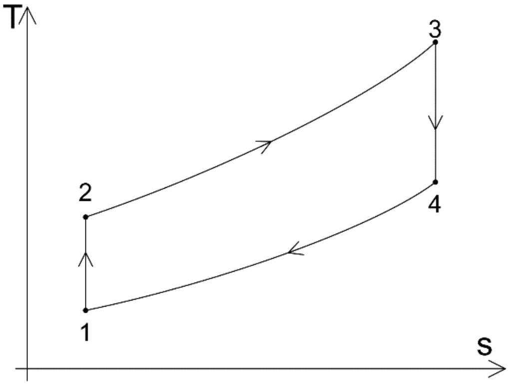

Figure 2. T-s Diagram for the ideal brayton cycle.

Heat transfer and work for this cycle can be expressed as:

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) \tag{1}$$

$$w_{cycle} = h_3 - h_2 - (h_4 - h_1) = c_p[(T_3 - T_2) - (T_4 - T_1)] \tag{2}$$

Therefore, based on previous equations 1 and 2, the thermal efficiency is:

$$\eta_{cycle} = \frac{w_{cycle}}{q_{in}} = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{T_2(\frac{T_3}{T_2} - 1)} \tag{3}$$

When specific heat is assumed as a constant, the thermal efficiency can be expressed with the pressure ratio, as:

$$\eta_{cycle} = 1 - \frac{1}{r_p^{(k-1)/k}} \tag{4}$$

This equation suggests that raising the pressure ratio can enhance the thermal efficiency of a Brayton cycle.

2.1.2 Turbojet Engine.

The structure of a turbofan engine is shown as figure 3. The jet-propulsion cycle represents the cycle of the turbojet engine, whose T-s diagram is shown as figure 4. Obviously, the operation of a turbojet engine is similar to the Brayton cycle.

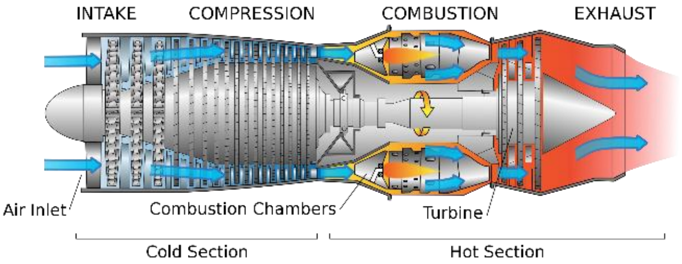

Figure 3. Turbojet engine [6].

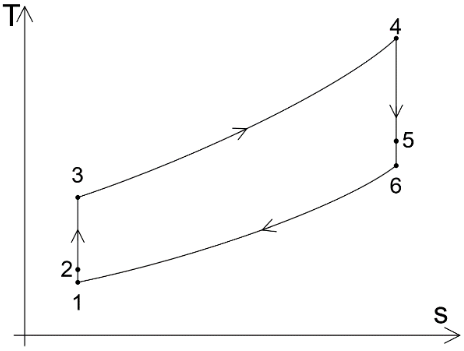

Figure 4. Ideal jet-propulsion cycle.

However, there are two distinctive differences: in the diffuser that in front of the compressor, the air has experienced an isentropic deceleration as process 1-2; In addition, the process 5-6 illustrate an isentropic acceleration which occurs at the nozzle [4].

The efficiency of a turbojet engine can be expressed as:

$$\eta = \frac{\dot{W}_p}{\dot{Q}_{in}} \tag{5}$$

In this equation, $\dot{Q}_{in}$ indicate the heat addition during combustion; $\dot{W}_p$ is the propulsive power, which originally means the power developed from the thrust. According to the Newton’s second law and the equation of power, it can be given as:

$$\dot{W}_p = FV_{aircraft} = \dot{m}(V_{exit} - V_{inlet})V_{aircraft} \tag{6}$$

In addition, the equation of cycle efficiency for a jet-propulsion cycle similar to the for a Brayton cycle. This means increasing pressure ratio is still valid for raising cycle efficiency. However, this cycle efficiency indicates the kinetic energy of thrust instead of the energy that contributes to flying. Therefore, it is inappropriate to evaluate the efficiency of a jet engine with only cycle efficiency.

The turbojet engine was the first gas turbine engine that applied for aviation purpose. However, owing to inefficiency at subsonic condition, it has been generally replaced by others [6].

2.2. Modifications on Basic Model

In order to attain different applications, modifications on turbofan engines are taken, which can be generally classified as two directions. For one case, modifications are taken to increase efficiency specifically at subsonic conditions, such as turbofan engines and turboprop engines. For another, some components are removed to attain higher velocity. Ramjet engine is the typical example of this modification.

2.2.1 Turbofan Engine.

By installing a large fan driven by a low pressure turbine, turbofan engine is invited based on the turbojet engine. This engine is conceded as the most popular variation of the basic gas-turbine engine that widely applied for most airlines [6, 7]. The structure of a turbofan engine is shown as figure 5.

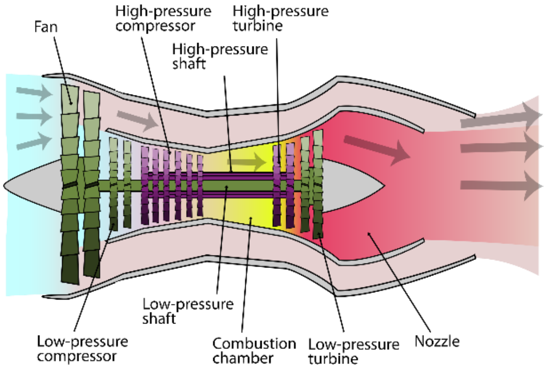

Figure 5. Turbofan engine [6].

Owing to the presence of the fan, more thrust is provided because of extra air intake [2, 8]. Besides, compare with turbojet, the turbofan engine is more efficient in subsonic condition [2]. However, for large bypass ratio engine, the enormous fan diameter limits the installation of this engine [9]. Additionally, owing to the large resistance from excessive area of fan, there is a restriction on velocity to maintain maximum efficiency, as well as fan diameter [7].

2.2.2 Turboprop Engine.

If the fan diameter is continually increases and the cowl is removed from a turbofan engine, another modification is developed named turboprop engine. In a turboprop engine, the propeller is turned by the gas turbine core, which generate mass flow of air and develop thrust with relatively low velocity [10]. Its structure is shown as figure 6.

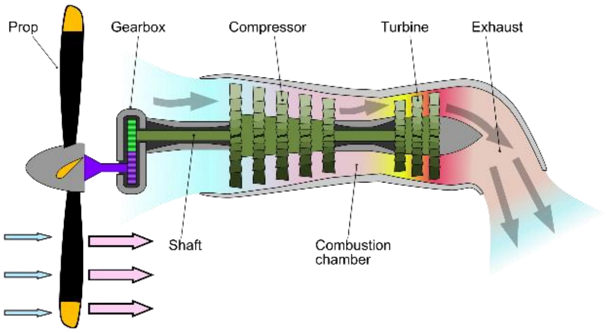

Figure 6. Turboprop Engine [10].

Compare with other jet engines, a turboprop engine is more lightweight and able to provides a better power output per unit of weight [11]. Additionally, owing to the works of propeller, it is possible for an aircraft using turboprop engines to save more energy during takeoff and landing [11]. However, for an aircraft with turboprop engines, there is a limitation on cruising velocity which approximately below 750 km/h, as well as cruising altitude [10].

2.2.3 Ramjet Engine and Scramjet Engine.

It is possible to compress the air at engine inlet without a compressor if the air velocity attains a sufficient level [12]. In this situation, both the compressor and the turbine can be removed from the jet engine. Therefore, based on this theory, ram compression jet engines are developed.

The structure of a ramjet engine is shown as figure 7 below. Owing to the removal of moving parts, ramjet engine is considered as the simplest type of jet engine [13]. In addition, the most efficient velocity for the ramjet engine is around 3 Mach, and the maximum velocity is 6 Mach [13]. However, it is impossible for a ramjet engine operate independently because of disappearing compressor and turbine [12]. Besides, it performs less efficient than turbojet engine than turbofan engine with the same velocity.

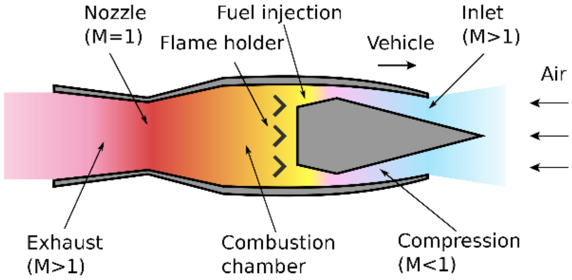

Figure 7. Ramjet engine [13].

A particular variant of ramjet engine is supersonic-combustion ramjet engine, which is considered as the most advanced engine which work at supersonic speed [12, 13]. The structure of a scramjet engine is shown as figure 8 below. The main difference between ramjet engine and scramjet engine is the air flow in the combustion chamber. Owing to the modification on the structure, the air flow in the inlet for scramjet engine is not compressed and maintain at supersonic speed [12].

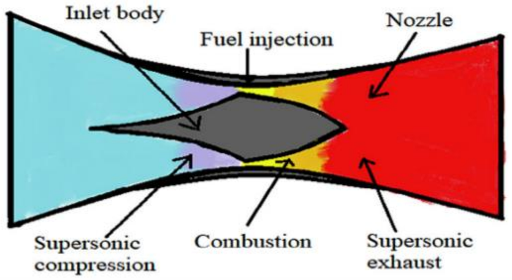

Figure 8. Scramjet engine [12].

Advantages and disadvantages of the scramjet engine are similar to the ramjet engine. The maximum working velocity for scramjet engine is higher than the ramjet that up to 15 Mach [12]. However, in order to produce sufficient thrust, the operate speed should be greater than 5 Mach [12]. In addition, due to the high temperature and operating velocity, materials selection for scramjet engine are particularly challenging [12].

Although both engines are modified originally from the turbojet engine, their applications on aviation are scarce even for military purpose. Instead, ramjet engines are commonly installed in missiles [12].

3. Efficiency Factors

In previous section, the turbojet efficiency is defined as propulsion power divided by head addition. Therefore, efficiency other jet engines can be defined similarly, which called overall efficiency. The overall efficiency can be calculated as:

$$\eta_o = \eta_c \eta_p \eta_T \tag{7}$$

3.1. Cycle Efficiency

η_c represent the cycle efficiency, which directly related to thermodynamics parameters, such as pressure ratio, maximum or minimum temperature [6]. In addition, it is possible for the efficiency of each components have an impact on the cycle efficiency [6].

For one case, it is impossible to achieve 100% isentropic process in reality, which is the main reason for reducing cycle efficiency. For jet engines, there are mainly four components involved: diffuser, compressor, turbine, and nozzle. Owing to extra heat transfer, more work required for compressor, and less work output for turbine. Therefore, the cycle efficiency reduced, and isentropic efficiency is used to compare the actual performance with the idealized circumstance [4]. T-s diagrams for compressor and turbine with comparison between the isentropic and the actual process are shown as figure 9 and figure 10 respectively.

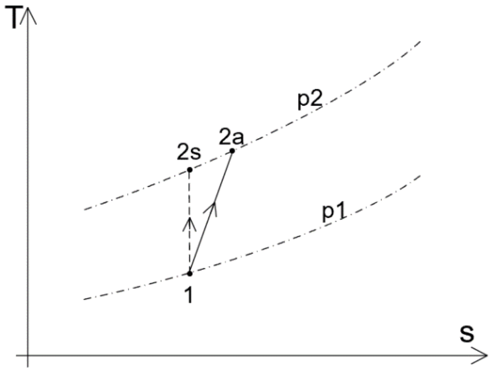

Figure 9. T-s diagram of isentropic and actual compression process for compressor.

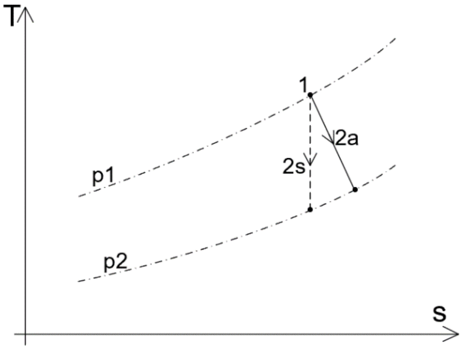

Figure 10. T-s Diagram of isentropic and actual expansion process for turbine.

For another, pressure drop during combustion is unescapable. Owing to the pressure drop of fluid, the actual heat addition is less than ideal process. Besides, pressure difference between air flow from inlet and outlet has an impact on heat rejection. Finally, it is possible for incomplete combustion to affect the heat addition, which probably has an impact on cycle efficiency.

Therefore, the actual T-s diagram for a turbojet engine derived from the ideal diagram is shown as figure 11.

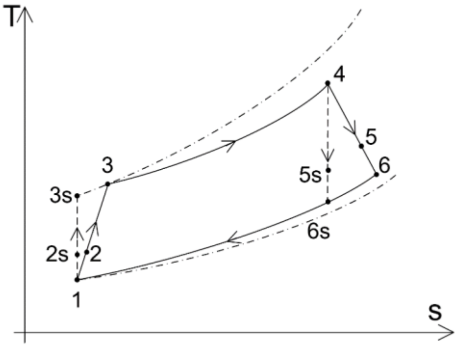

Figure 11. T-s diagram for the cycle of turbojet engine with ideal and actual processes.

3.2. Propulsive Efficiency

η_p indicate the propulsive efficiency, which indicate the propulsive power compare with kinetic energy from jet [6]. In figure 12, propulsive efficiency for different jet engines is shown regarding the velocity.

The efficiency of the turboprop engine increase most significantly and reach the top of 80% while the air velocity saturated approximately at 560 km/h (350 mph). After that, the efficiency plunges to around 40%. This indicates the turboprop engine is the most efficient engine when aircraft in low velocity, which probably below 720 km/h (450 mph).

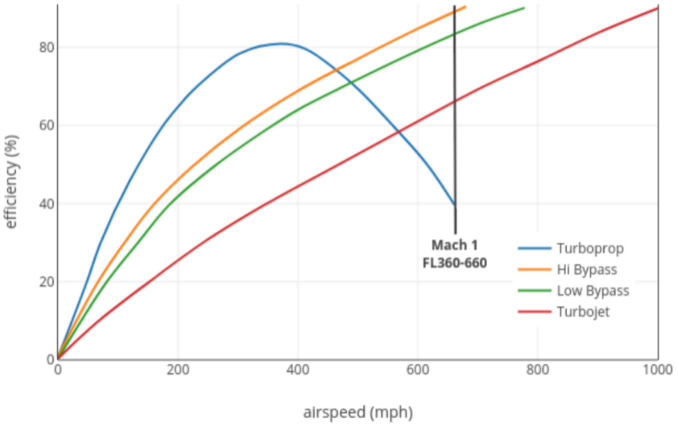

Figure 12. Propulsive efficiency vs air velocity for different jet engines [6].

Both efficiency of the turbofan engine and the turbojet engine shows purely increasing trending. The turbofan engine is more efficient than the turbojet engine with the same velocity. In addition, a turbofan engine with lower bypass ratio less efficient than with greater bypass ratio. However, higher speed is available for turbojet engine, and it can perform similar efficiency as turbofan with higher speed.

3.3. Transmission Efficiency

Since the bypass engine such as the turbofan and turboprop engine has been applied to improves propulsive efficiency, it is possible for losses occurs in itself [6]. These losses originally because of inefficiencies in the added turbine and fan [6]. Besides, pressure losses in the bypass duct and propelling nozzle exists [6]. Therefore, transmission efficiency is used to evaluate these losses.

4. Discussions

4.1. Current Applications of Engine

Turbojet engine was the earliest gas turbine engine that was applied for aviation. However, owing to the inefficiency of turbojet engines, it has been mostly replaced by turbofans and turboprops, with scarce applications on supersonic conditions [6].

Recently, the most widely used engine for both civilian and military purpose turbofan engines. However, owing to the different priority, their configurations are different. For most commercial aircraft, their velocity operates at the range from 500 km/h to 1000 km/h, which is the most efficient range for turbofans with high-bypass ratio [8]. For example, the CFM LEAP-1A engine and GE9X with the bypass ratio of 11:1 and 9.9:1 respectively [6]. However, in terms of military purpose, performance and motility is considered as priority for fighter aircraft, instead of fuel efficiency. Therefore, low-bypass turbofans are the most prevalent engines for these aircraft, with approximately 2:1 bypass ratio [6].

In terms of the turboprop engines, it is widely installed in small subsonic aircrafts with short distance, because they are most efficient below 720 km/h. Besides, it is used by some large military aircrafts or helicopters that probably require frequent takeoff or landing, because it consumes less fuel than other engines during takeoff and landing.

4.2. Improvements on Efficiency and Its Prospects

There are mainly directions on improving efficiency. Firstly, to improve cycle efficiency, compression ration tends to be increases. However, this indicates durable alloys are required to sustain high pressure in combustion chamber. Secondly, for those commercial aircraft that benefits from high-bypass turbofans, the fan diameter tends to be increased, and optimization on fan structure and material is considered to improve efficiency [2, 7]. Finally, for those military aircraft using low-bypass turbojet, afterburner is installed to improves fuel efficiency as well as remaining similar velocity.

5. Conclusions

In general, turbofan engines are the most prevalent engine that used for both civilian and military purpose, its efficiency perform best when velocity between 500 km/h and 1000 km/h. Followed by turboprop engines, which generally used for short distance airlines with low velocity. This is because the efficiency and fuel consumption of turboprop engines perform best with velocity below 720 km/h. Finally, application of turbojet engines is less popular than turboprops and turbofans. This is because turboprop engines can only achieve reasonable efficiency with sufficient velocity that not operated by most aircraft.

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