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Overview of steam turbines and efficiency

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Abstract. Thermal power plants, which produce energy from the burning of fossil fuels that in turn generate turbine-turning steam, contribute a large proportion of energy in the world. Research on how we could apply fluid dynamic and thermodynamic principles in the design of turbines is crucial to improving their efficiency and fuel consumption. This paper mainly aims to explore and summarize how the power efficiency of turbines is maximized in thermal power plants and analyze the designs of turbines that increase proficiency. Literature and past paper review will be the primary method of this research. The main findings of this research are that efficiency in thermal turbines can be increased in three principal ways: a multi-stage expansion mechanism, the application of alternating blades, and in implementation of a reheating system. Using these methods, efficiency has been increased almost a million-fold in steam turbines. The purpose of this paper is to gain insights into how energy output in thermal power plant turbines is maximized and the specific designs of turbines that improve its efficiency.

Keywords: Fluid mechanics, steam turbine, output maximization, transfer efficiency.

1. Introduction

The burning of fossil fuels comprises 61% of energy production in the world [1], and they rely on the mechanism of heat turbines in which when they meet high-energy, expanding steam, they turn and produce electricity through a series of processes. As the global energy demand steadily rises, the problem of how to better use energy resources is increasingly urgent. The study and research on improving heat turbine efficiency, which is crucial to generating more energy and using fuel more effectively, is thus an important area of focus. Various designs of turbines that operate at a low fuel cost have been formulated and applied to industrial purposes, and they are built in a fluid dynamic and thermodynamic-optimized manner.

This paper mainly focuses on how turbine efficiency is maximized in thermal power plants and on explaining the basic mechanism of heat turbines. Moreover, this research mainly takes on the form of literature research on past papers that examine how efficiency is increased by controlling heat and fluid flow through the generator; The purpose of this research is to understand and present how energy output is maximized in certain designs of turbines.

2. Mechanism of steam turbines

To understand how the efficiency of energy transfer is maximized in modern steam turbines, the design of turbines and the mechanism of how they work must be explained beforehand. Initially built in 1884

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by Sir Charles Parsons in England, the steam turbine is a machine that, in its essence, converts the chemical energy stored in coals to electrical energy manifested in currents that power everyday devices.

There are three fundamental parts of a steam turbine: the boiler, the rotor blades, and the rotating shaft. The boiler uses heat energy that can be created from the burning of fossil fuels like coal to vaporize liquid water, creating high-temperature and high-pressure steam. However, other fuel sources such as natural gas, biomass fuel, petroleum, and nuclear fuel can also be used for the generation of heat for steam turbines. Due to the reason that a variety of fuels can be used by it, the steam turbine is a suitable energy source in a wide range of areas. As the U.S. Department of Energy points out, "Steam turbines are well suited to medium- and large-scale industrial and institutional applications where inexpensive fuels such as coal, biomass, solid wastes and byproducts (e.g., wood chips), refinery residual oil, and refinery off-gases are available" [2]. The exhaust from the boiler will be emitted into the atmosphere.

The steam is pressurized in the boiler for it to have enough pressure energy to turn the blades, and it passes through a nozzle and into the turbine casing, which encloses the blades. The blades in the turbine harness the kinetic energy in the high-pressure, expanding steam and rotating. The kinetic and pressure energy of the steam is converted into rotary mechanical energy. The reason why a linear stream of steam can rotate the blade is due to the reason that the blade has the shape of an airfoil. One surface of the airfoil is more curved than the other, which creates a velocity difference and therefore a pressure difference according to Bernoulli's principle that manifests as a lift force that, from a macroscopic view, is rotary motion. The steam can move faster on the curved surface because mass needs to be conserved for the incoming steam and the exiting steam, and equal flow rates at the two surfaces will result in mass not being conserved throughout the process of turning the blades. The rotation of the blades will cause the rotation of the shaft that acts as the axis of rotation as they are connected. The blade of the turbine is also designed to withstand high pressures, heat, as well as mechanical stress. According to Zhu, the material used for blades depends on its stage (an effective measure to increase efficiency that will be discussed later); for instance, blades under high and medium pressure are usually made of stainless steel from 12Cr, because stainless steel has better properties at high temperatures. Titanium alloys, especially Ti-6Al-4V, have been used in low-pressure turbines since 1960 [3].

Finally, the low-pressure exhaust steam exits the turbines and is discharged through a joint that connects the turbine and the condenser. The condenser condenses the steam back into liquid water, which can be reused in the boiler to create hot, high-pressure steam again. In addition, as the Savree encyclopedia states "Heat sinks are required to transfer the thermal energy from the exhaust steam to the environment. A typical heat sink may be a lake, river, or ocean. If a large body of water is not available to act as a heat sink, cooling towers are used, and the cooling water is recirculated" [4]. The excess heat can also be cooled by air or a surface heat exchanger.

3. Methods to increase turbine efficiency

The core mechanism that the steam turbine uses to generate electrical energy is far from complex; however, the question lies in how we can maximize its efficiency. Engineers have come up with ways that make the machine transform the maximum amount of energy from the high-pressure and temperature steam, and they are based on principles of fluid and thermodynamics.

3.1. Multi-stage expansion

The first way that efficiency in steam turbines can be increased is by separating the process of the steam passing through the turbine into stages. The way that this is done is by designing and arranging turbines with increasing radius away from the nozzle that the steam is injected from. The turbines form a conical shape, with the nozzle connecting the cone's vertex and boiler. The stages are high-pressure, mid-pressure, and low-pressure with the increasing cross-sectional area of the blades, respectively. The main reason that turbines have multiple stages with gradually increasing cross-sectional area is that as the pressure is transferred to the rotary motion of the shaft, the steam cools and expands. To accommodate the expansion of the steam and maintain its velocity so that the maximum amount of energy is extracted from it, a design with a conical shape and the turbines separated into three different stages is used.

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3.2. Alternating blades

The second way that efficiency is increased is by setting stator blades in between rotating blades. Stator blades are approximately identical to rotor blades except in two ways: stator blades are not connected to the shaft and therefore do not rotate with it; the angle of the stator blades are arranged in opposite directions as the rotating blades. Since the incoming jet of steam must impact the rotor blades so that maximum torque is exerted on them (therefore maximum angular acceleration), the steam jet must hit at a specific angle to the blades. The stator blades are set in between rotor blades (hence the stator and rotor blades are alternating) at opposite angles because they direct the flow into the optimal angle, resulting in the maximum amount of energy being transferred.

3.3. Reheating

In multistage turbines, there is often a reheating system installed to raise steam temperatures to the optimal value (at the peak of the thermal cycle). Hence the thermal efficiency of turbines is increased. In between two stages of the turbine, a combustion chamber is installed; fuel droplets are injected into the chamber and are ignited, reheating the steam as it passes through different stages. Another reason that combustion chambers exist is to prevent “damages that could be caused to the blades of the steam turbine by low-quality steam, [as] High content of water droplets can cause rapid impingement and erosion of the blades, which occurs when condensed water is blasted onto the blades” [5]. Thus, reheating steam also increases the life span of turbines.

3.4. Combined cycle turbine

By utilizing a combination of gas turbines and steam turbines (CCPP, short for Combined Cycle Power Plants), a much higher efficiency can be achieved than by using individual turbines [6]. In gas turbines, natural gas is burned to produce hot gases that drive turbines similar to ones in their steam-operated counterparts. However, the gas that exits the turbines still has energy that can be utilized; hence the exhaust gas is directed into a heat recovery steam generator (HRSG), which acts like a boiler in which heat is provided by the exhaust. Steam is generated HRSG and is used to turn steam turbines. By applying this configuration, the efficiency of power plants is greatly enhanced as it minimizes energy waste.

4. Development of steam turbines

The first device that used steam to generate motion was called the aeolipile, invented by Greek mathematician and inventor Hero of Alexandria in 1 AD. It used steam generated by a boiler to create torque on a small metal sphere, which spins under the reaction force of steam. The steam turbine next showed up in 1629 when Giovanni Brance experimented with blowing a jet of steam against a modified water wheel [7]. But before the appearance of modern steam turbines, steam engines, machines that used high-pressure steam to push pistons which also created rotary motion, came into existence. It was improved by James Watt and used in a wide range of applications like railway and sea transportation. Civilization has harnessed steam power.

There wasn’t any development in modern steam turbines until British engineer Sir Charles Parsons saw the advantage of separating the turbine into stages and decreasing the pressure step by step in 1884. Connecting to an electric motor, Parsons built a steam turbine that can produce up to 7.5 kilowatts of power. Although he wasn’t the first one to experiment with blade-turning steam power, his design was significant because it maintained rotation speeds while extracting the maximum amount of kinetic energy from steam jets [8].

As the technology matured, the largest steam turbines in 1900 could produce up to 1,200 kilowatts of power; just a decade later, the capacity reached 30,000 kilowatts. Both the temperature and pressure of the steam fed to the machine were greatly increased as the technology developed. By the mid-twentieth century, the steam turbine could produce 100,000 kilowatts of power. At this point, steam turbines have replaced steam engines as the main electricity source, generating energy for the industrial world. Today, the steam turbine uses a range of sources to produce steam(e.g. natural gas, nuclear, coal), and is capable of generating more than 5 million kilowatts of electricity [9]. The key to continuously increasing the capacity of these machines is to either find new ways to improve efficiency or find new blade materials that can withstand more heat and pressure.

5. Conclusion

The purpose of this research is to introduce the mechanism of steam turbines and explore ways that their efficiency is increased. Also, the history of steam turbines is briefly discussed. The limitation of this particular research is that it does not account for a wide variety of sources, thus some information could be only briefly mentioned or missing. Hence, future studies should focus on a more comprehensive range of sources and take into account more analytical studies to illustrate the efficiency improvements.

Nonetheless, there are seldom contemporary sources that include analytical discussion of steam turbines. This is due to the reason that although steam turbines are fundamentally built on fluid dynamic principles that rely on differential analysis and solving partial differential equations (PDE), it is a very useful machine that mostly engineers instead of mathematicians work on. Hence conducting analytical studies would be immensely difficult for individual researchers, which is the reason why most studies are qualitative. Also, there is no cause to deny the value of number analysis; therefore, I believe that there should be studies that focus on the analytical side of things as they will be able to shed light on the basic principles of steam turbines and potentially stimulate new methods that increase its efficiency. With the world's increasing demand for energy, it is at stake for engineers to find new ways to produce more power.

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