ENSY 5400 PROJECT: OVERVIEW OF STEAM TURBINES

Submitted by

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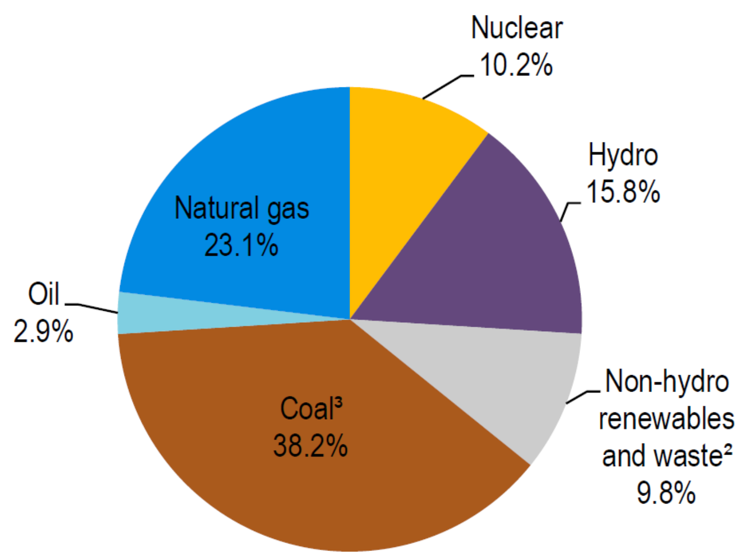
Contents

1. INTRODUCTION

Electricity is universally the most prevalent form of end-use energy consumption and is a cornerstone asset of the modern world. World electricity generation is projected to increase by a factor of 2.05 by 2050, from 21.6 trillion kWh in 2012 to 44.26 trillion kWh by 2050. Key drivers of electricity demand growth are economic growth and electrification development initiatives. To supply sufficient electricity to a continually-growing world market, power generation and systems infrastructure have continued to grow and improve.

Power generation methods can broadly be classified as thermal, nuclear, and renewable. The distribution of electricity generation by each category is shown in Figure 1. Thermal generation includes generation from fuel sources such as coal, natural gas, and petroleum.



1. Excludes electricity generation from pumped storage.
2. Includes geothermal, solar, wind, tide/wave/ocean, biofuels, waste, heat and other.
3. In these graphs, peat and oil shale are aggregated with coal.

Figure 1: Distribution of electricity generation worldwide in 2018, by energy source.

Steam turbines are widely used in thermal, nuclear, geothermal, and solar thermal power plants, making them responsible for the majority of electricity generation worldwide as shown in Figure 2. Therefore, steam turbines play a dominant role in power generation. This trend is expected to continue in the future despite the phasing out of fossil fuel power plants due to their versatility and ability to benefit from related technological developments such as improved design methodologies and manufacturing methods. Accordingly, Figure 3 forecasts relatively steady growth in power generation from steam turbine power plants.

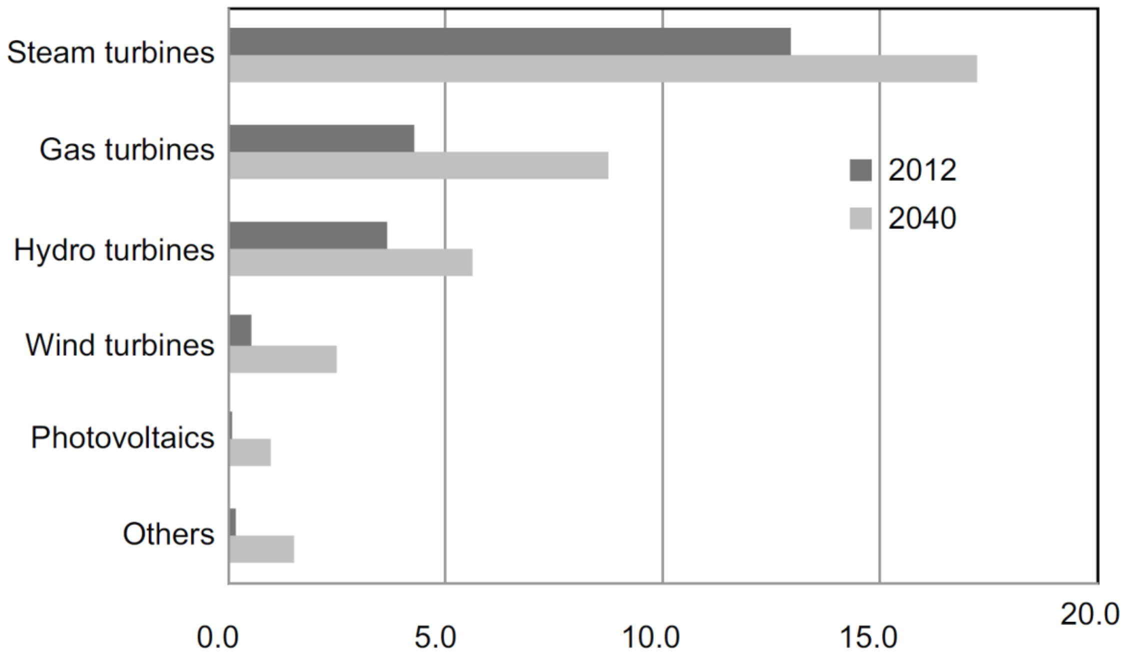


Figure 2: World electricity generation by prime movers in 2012 and projected energy generation in 2040 (trillion kWh). In 2012, the power-generation percentage by prime movers in all power stations was 60% from steam turbines, 20% from gas turbines, 17% from hydropower turbines, 2.4% from wind turbines, and 0.5% from PVs (photovoltaics).

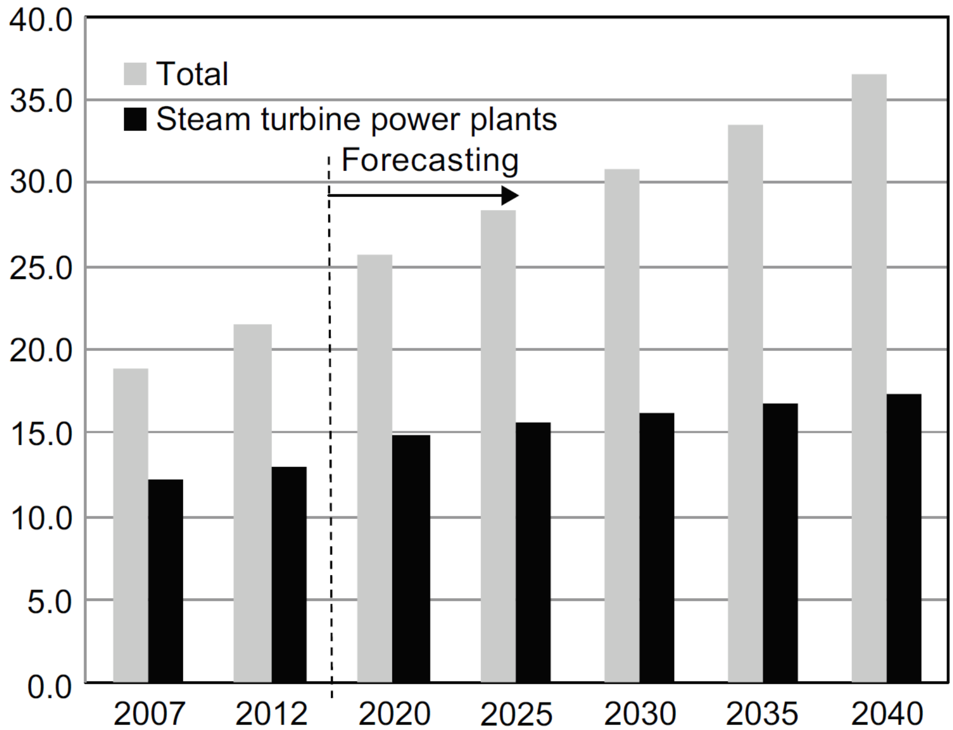


Figure 3: Worldwide power generation of steam turbine power plants (trillion kWh).

2. LITERATURE SURVEY

Steam turbines are a unique class of turbomachinery widely used in electricity generation, process industries, and marine propulsion. Steam turbines were first designed and built in England by Sir Charles Algernon Parsons during the Industrial Revolution in 1884, and have been critical to electricity generation and modern infrastructure ever since. They are an exhaustively studied component of power generation, and detailed literature is available on the subject. In light of scope constraints, this short paper will focus on the usage of steam turbines in electricity generation.

A steam turbine such as shown in Figure 4 is defined as a device that extracts energy from pressurized steam to perform mechanical work on a rotating output shaft. In steam turbines, stator blades accelerate and swirl high-temperature and high-pressure steam provided from boilers around their rotors, and rotating blades receive impulse forces and reaction forces from the accelerated and swirled steam. The rotating blades transmit the torque generated by the steam forces to their rotors. A turbine stage consists of a stator blade row and a rotating blade row. Steam turbines may have multiple stages from single-stage units to multi-stage units with 30 or more stages, allowing for a wide range of capacities from the hundreds-of kW class to the 1900-MW class and a varied range of applications.

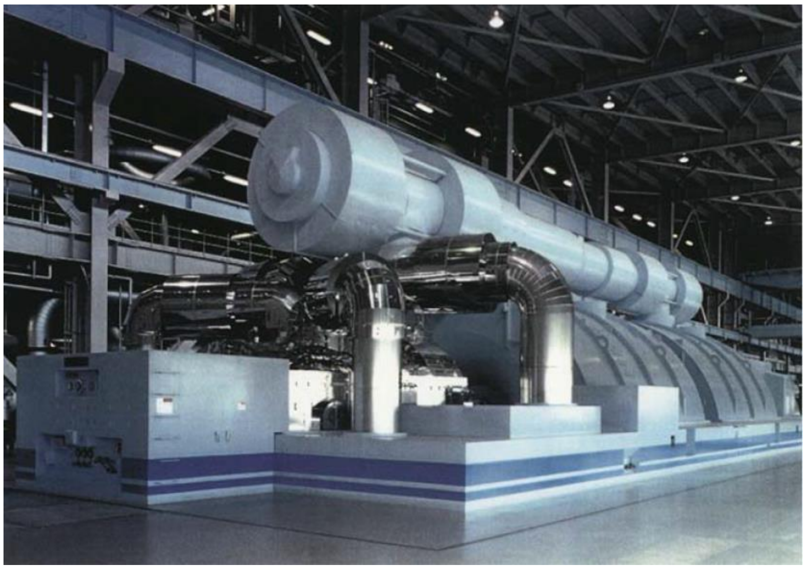


Figure 4: 700 MW class steam turbine in a large-capacity power plant HP (high-pressure) inlet steam: 24.1 MPa 593℃, IP (intermediate-pressure) inlet steam: 593℃.

All steam turbine cycles are fundamentally governed by the Rankine cycle. However, advancements in cycle design have led to improvements upon the original cycle such as the reheat cycle, regenerating cycle, and reheat-regenerating cycle to compensate for major losses in the Rankine cycle as implemented in Figure 5.

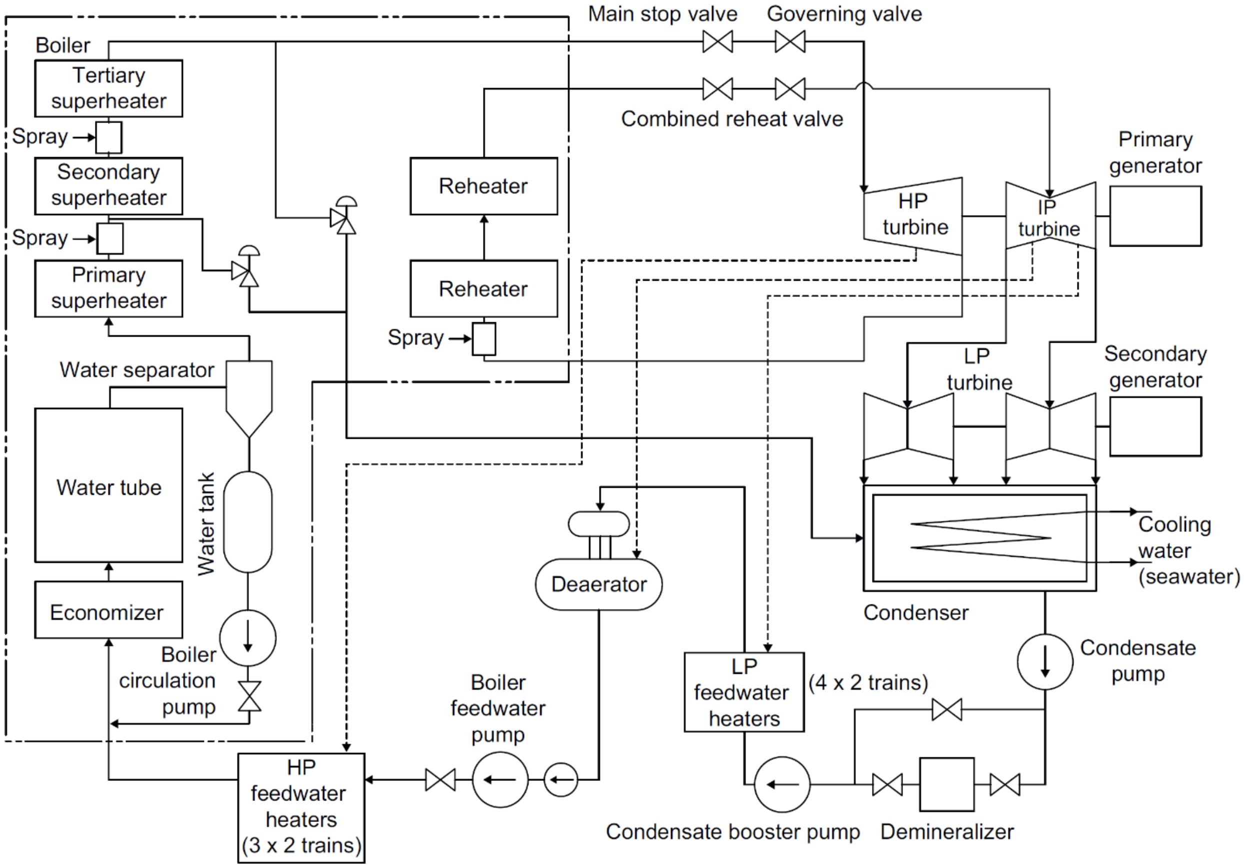


Figure 5: Steam flow diagram of a thermal power station.

To achieve maximum efficiency, inlet steam pressures in modern steam turbines range from 24.1 to 31.0 MPa.g and temperatures range from 593°C to 600°C for large-scale thermal power plants. Steam turbines under such conditions are known as ultra-supercritical (USC) pressure steam turbines. Typical rotation speeds in large-scale steam turbines range from 1800-3600 rpm for a frequency of 60 Hz with the turbine shaft directly coupled to the generator shaft. For geared turbines used in smaller-scale power plants (less than 40 MW), typical pressure may be up to 120 atm, with temperatures also reaching up to 810 K. A typical rotational speed for geared turbines is 6000 rpm with a generator speed of 1800 rpm for a frequency of 60 Hz.

The full spectrum of design, selection, operation and maintenance, and technology advancements for steam turbines is beyond the scope of this short paper; instead, the focus of discussion will be primarily based on the currently available types of steam turbines, component design, turbine selection, and a brief overview of recent advances in steam turbine technology.

3. STEAM TURBINE FUNDAMENTALS

3.1 Types of Turbines

The basic thermodynamic model of a steam turbine is characterized by the equation

$$\frac{\dot{W}}{m} = h_1 - h_2$$

and the isentropic efficiency is found by the equation

$$\eta = \frac{h_1 - h_2}{h_1 - h_2{}'}$$

where h_1 is the specific enthalpy at the inlet, h_2 is the specific enthalpy at the outlet, and h_2' is the specific enthalpy at the outlet for an isentropic turbine. Different types of steam turbines exist such as condensing, back-pressure (non-condensing), extraction condensing, and mixed-pressure turbines as shown in Figure 6.

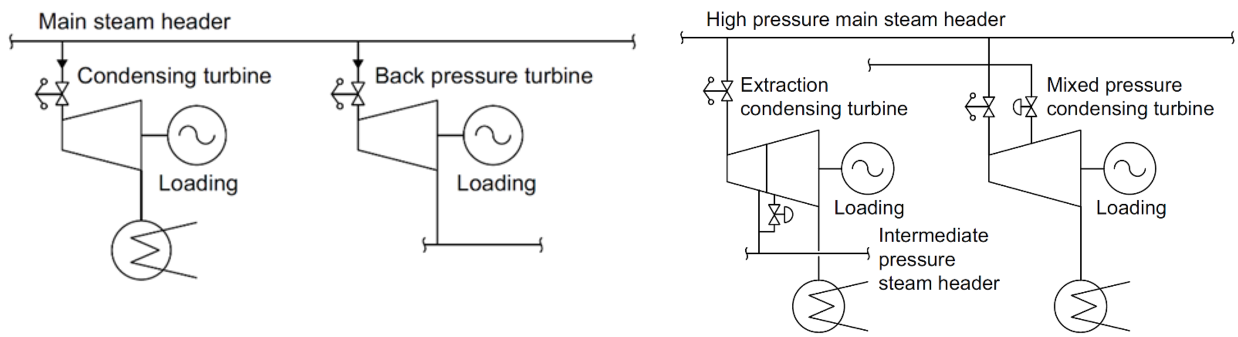


Figure 6: Schematic diagrams for different types of steam turbines.

The primary type of turbine used for power generation is the condensing turbine, as it is capable of maximizing the utility of the total energy in inlet steam flow. However, the condensing turbine has significant amounts of heat discharge loss as all exhaust steam flow is condensed in a condenser that is cooled by cooling water and therefore discharges potentially useful heat to the external environment.

The back-pressure turbine supplies process steam to facilities in private-use power producers, making it useful for both electricity generation and supplying process steam. Exhaust steam pressure is set to be the demand pressure for facility requirements. Since effective heat drop is relatively small as shown in Figure 7, turbine output is also small.

The extraction condensing turbine is capable of adjusting electricity output and process steam flow independently via adjusting inlet and process flows. Adjustment is achieved via an extraction control valve and a main control valve for the inlet.

The mixed pressure turbine, as shown in Figure 8, is designed to effectively utilize surplus medium/low-pressure steam from facilities into the intermediate stage of the turbine. Mixed-pressure turbines may be throttle or nozzle-controlled; throttle control is less efficient at partial load compared to nozzle control, but is a simpler design.

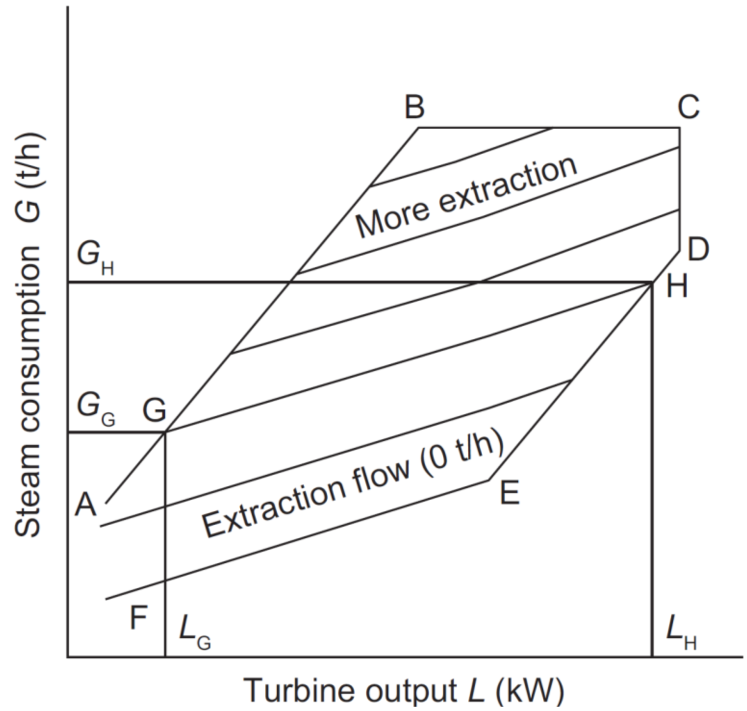


Figure 7: Steam consumption diagram of extraction condensing turbine.

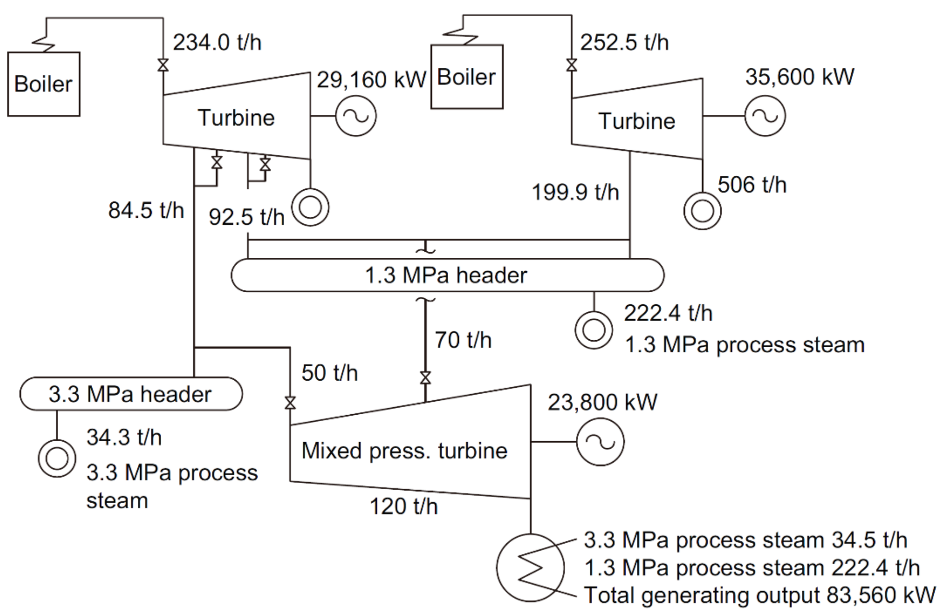


Figure 8: A mixed-pressure turbine at a cogeneration plant.

3.2 Turbine Component Design and Controls

A steam turbine is a complex turbomachinery assembly that requires a high amount of granularity in design analysis. Key components of a steam turbine include a shaft with disks to which moving blades are attached, a casing in which the stationary blades and nozzles are mounted, load-bearing bearings that support the shaft within the casing for stabilization, and seals in the casing to prevent steam from bypassing any turbine stages. Furthermore, a robust control system such as shown in Figure 10 is required to control turbine speed and turbine load and diagnostically monitor the turbine and other plant components.

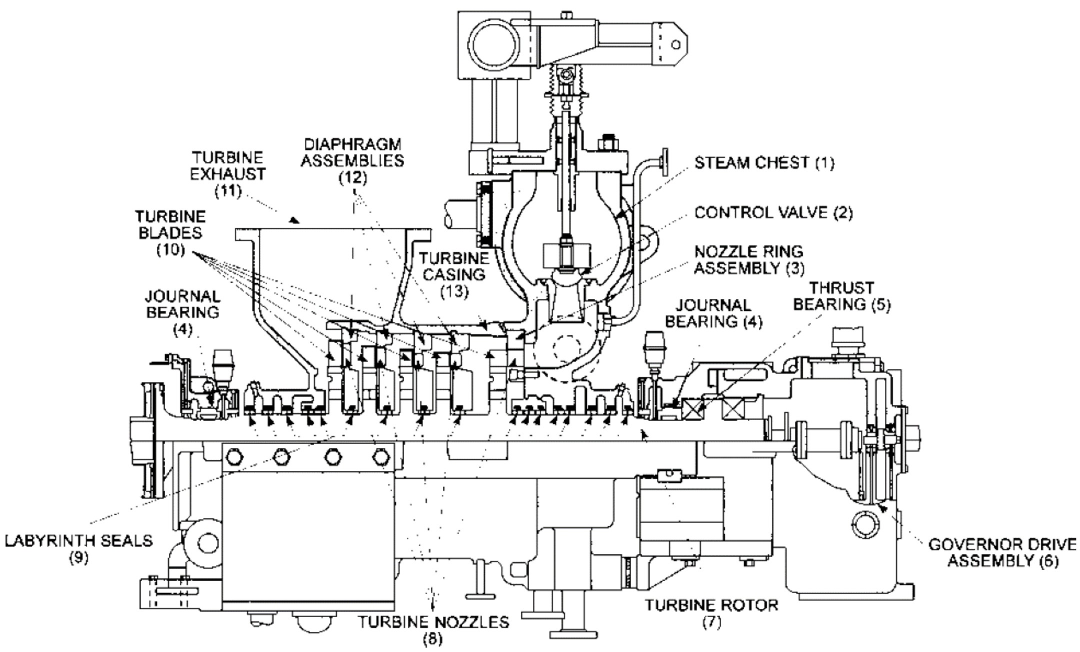


Figure 9: Steam turbine cross-sectional view.

Turbine efficiency and performance largely depends on the design and construction of the blades. As shown in Figure 11, the two turbine stages are impulse and reaction designs. The majority of steam turbine plants use a combination of impulse and reaction forces to utilize steam efficiently, using both impulse and reaction blading on the same shaft. Impulse turbines may be further divided into pressure compounding (Rateau) and velocity compounding (Curtis) staging.

A critical design consideration is the question of how load-bearing components of the turbine such as blades, rotors, and bearings will perform under stress. This is especially true when accounting for the variety of steady-state and transient (alternating, cyclic, or vibratory) mechanical and thermal loads and stresses that turbine blades are typically subjected to.

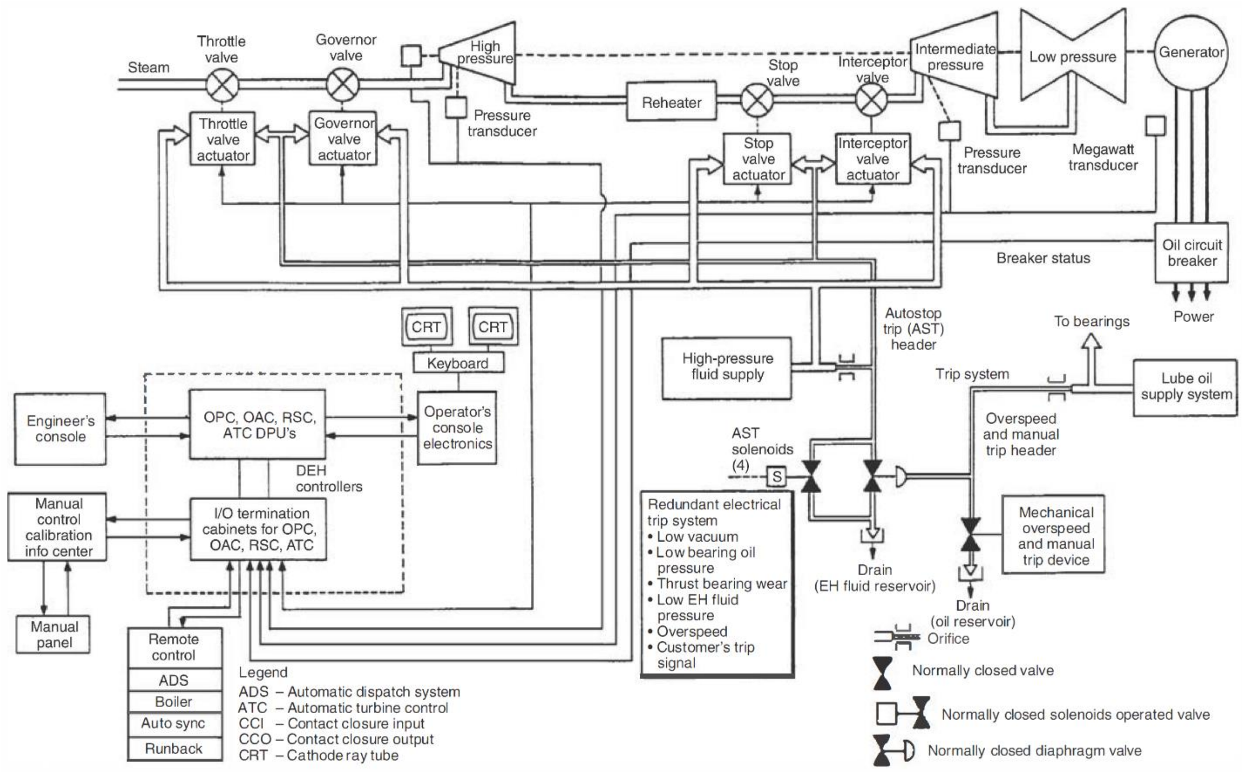


Figure 10: An example digital electrohydraulic (DEH) control system.

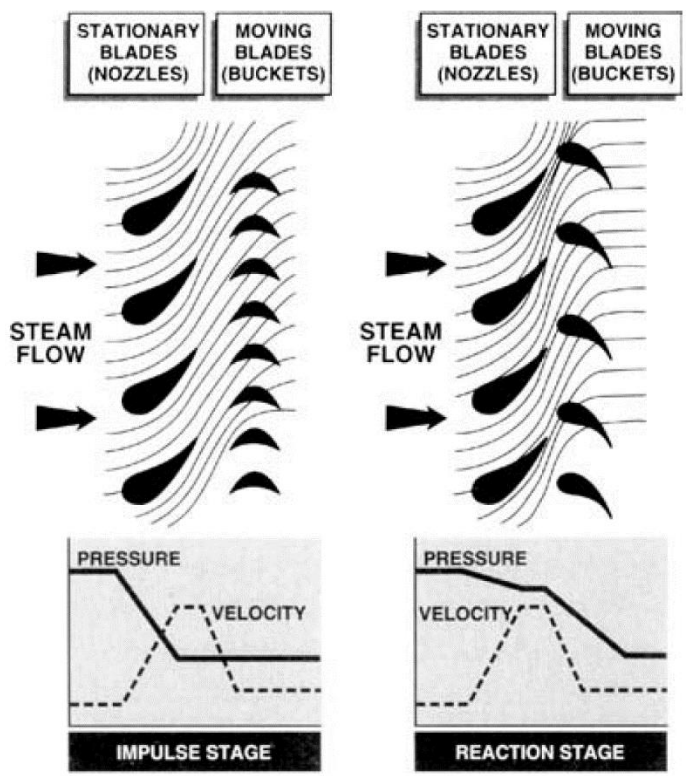


Figure 11: Diagram of simple impulse and reaction turbine stages.

3.3 Turbine Selection

If steam conditions and turbine efficiency are known, the theoretical steam rate (TSR) of a steam turbine may be determined via a Mollier chart and used to determine preliminary power output estimates. Otherwise, usage of manufacturer data is required. A graphical method for selecting turbines is presented below, and is applicable for simple single-stage machines.

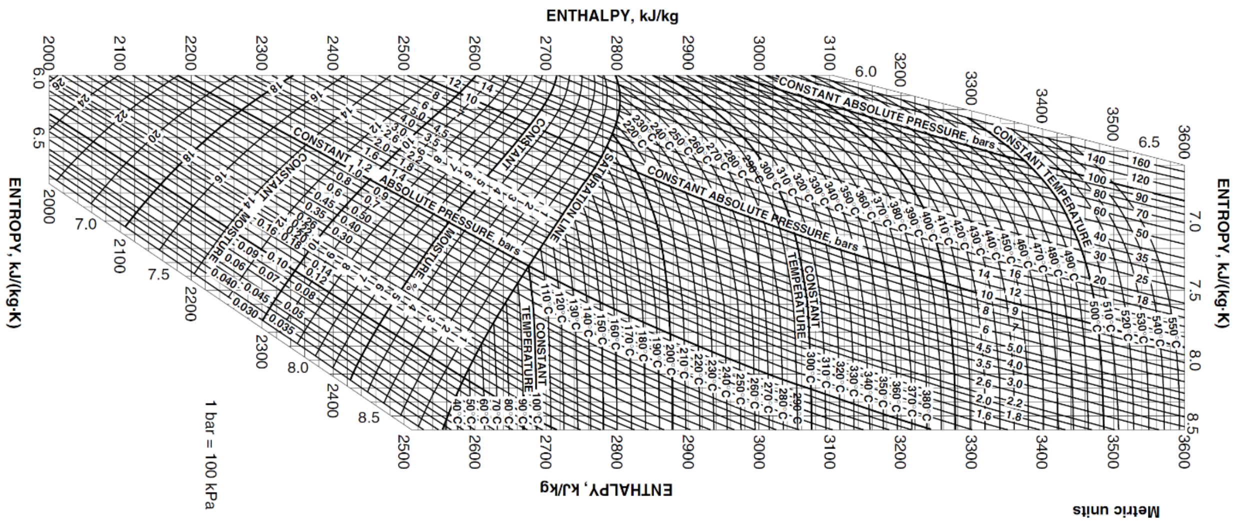


Figure 12: Mollier chart for steam, metric units.

Step 1: Determine the TSR using a Mollier Chart or relevant steam tables and the TSR equation. The TSR equation in metric units is $TSR = \frac{3600}{h_1 - h_2}$ kg/(kWh).

Step 2: Determine base steam rate (BSR) using relevant BSR graphs such as shown in Figure 13, selecting the BSR value from TSR, turbine speed, and turbine frame.

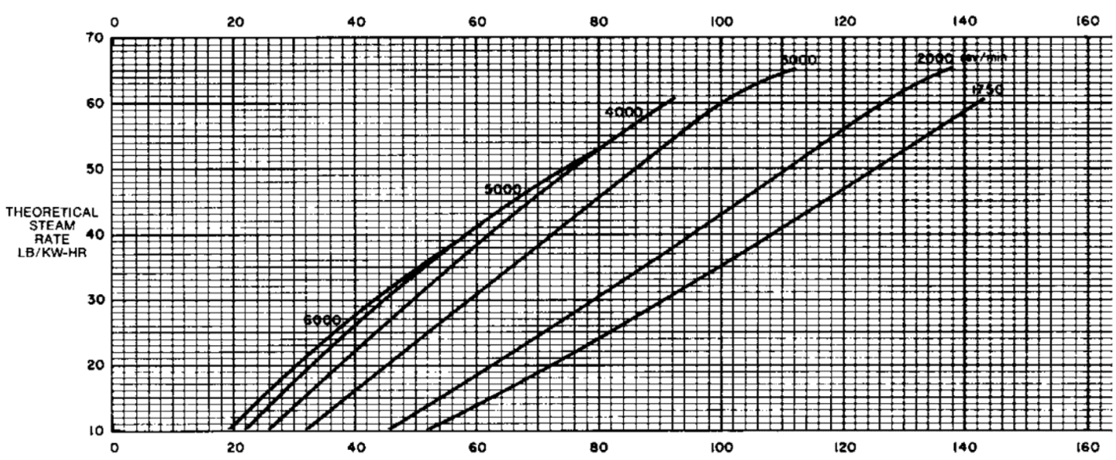


Figure 13: Base steam rates of single-valve, single-stage steam turbines, 8 in/200 mm exhaust, 1400 hp/1050 kW.

Step 3: Determine the mechanical loss using relevant loss graphs, selecting based on turbine speed, exhaust pressure, and turbine frame.

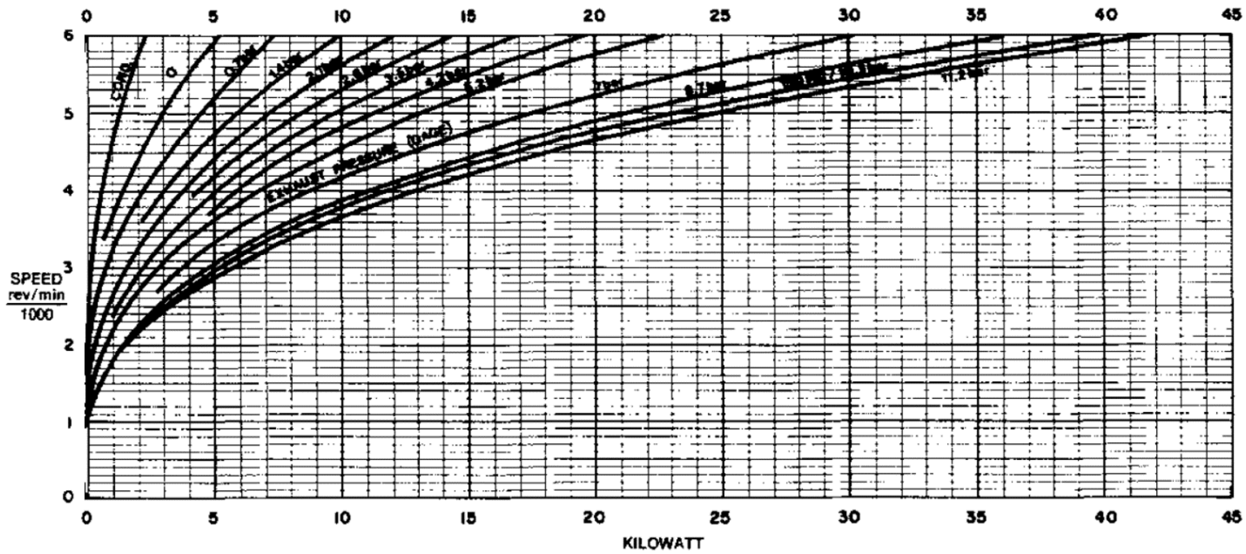


Figure 14: Mechanical losses of single-valve, single-stage steam turbines, 8 in/200 mm exhaust, 1400 hp/1050 kW.

Step 4: Determine superheat based on steam tables for dry and saturated steam.

Step 5: With superheat and TSR, determine the superheat correction factor (SCF) from the relevant SCF graph such as shown in Figure 15.

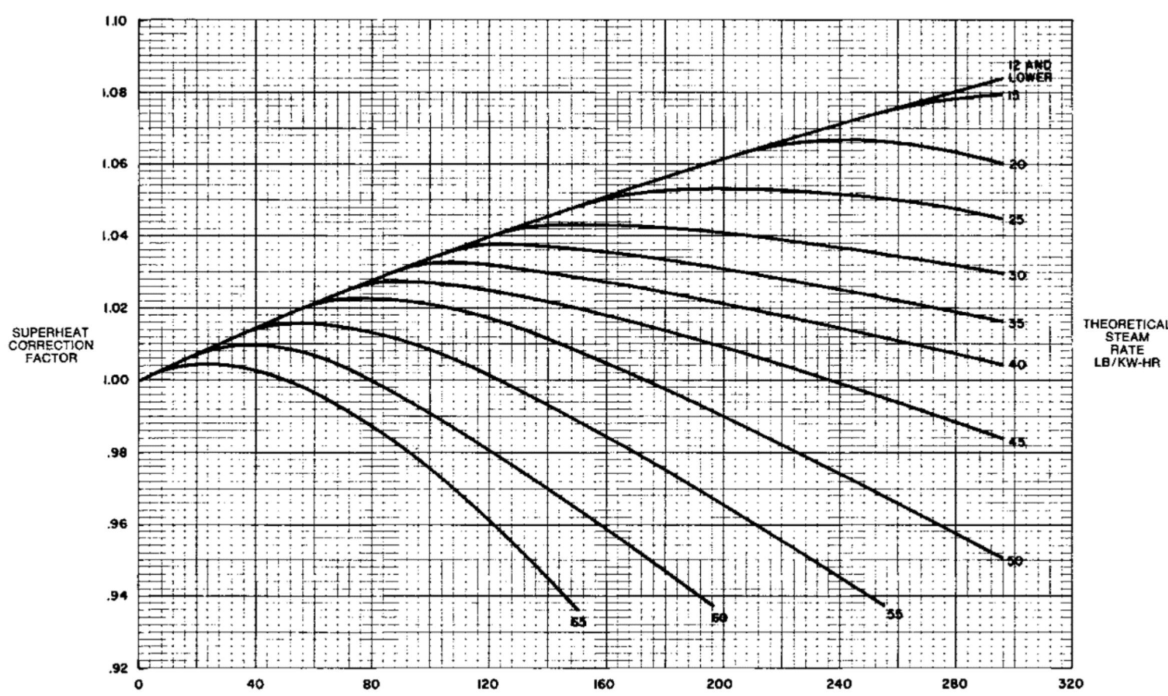


Figure 15: Superheat correction factors for single-valve, single-stage steam turbines.

Step 6: Determine the corrected steam rate via the formula

$$\text{Corrected steam rate} = \frac{\text{base steam rate}}{\text{superheat correction factor}} \times \frac{\text{kW+kW loss}}{\text{kW}} \text{ (SI units)}$$

Step 7: Determine steam flow via the formula

$$\text{Steam flow} = \text{corrected steam rate} \times \text{kW}$$

Step 8: Determine the required inlet size using the relevant graph such as shown in Figure 16, using steam flow and turbine inlet pressure and temperature.

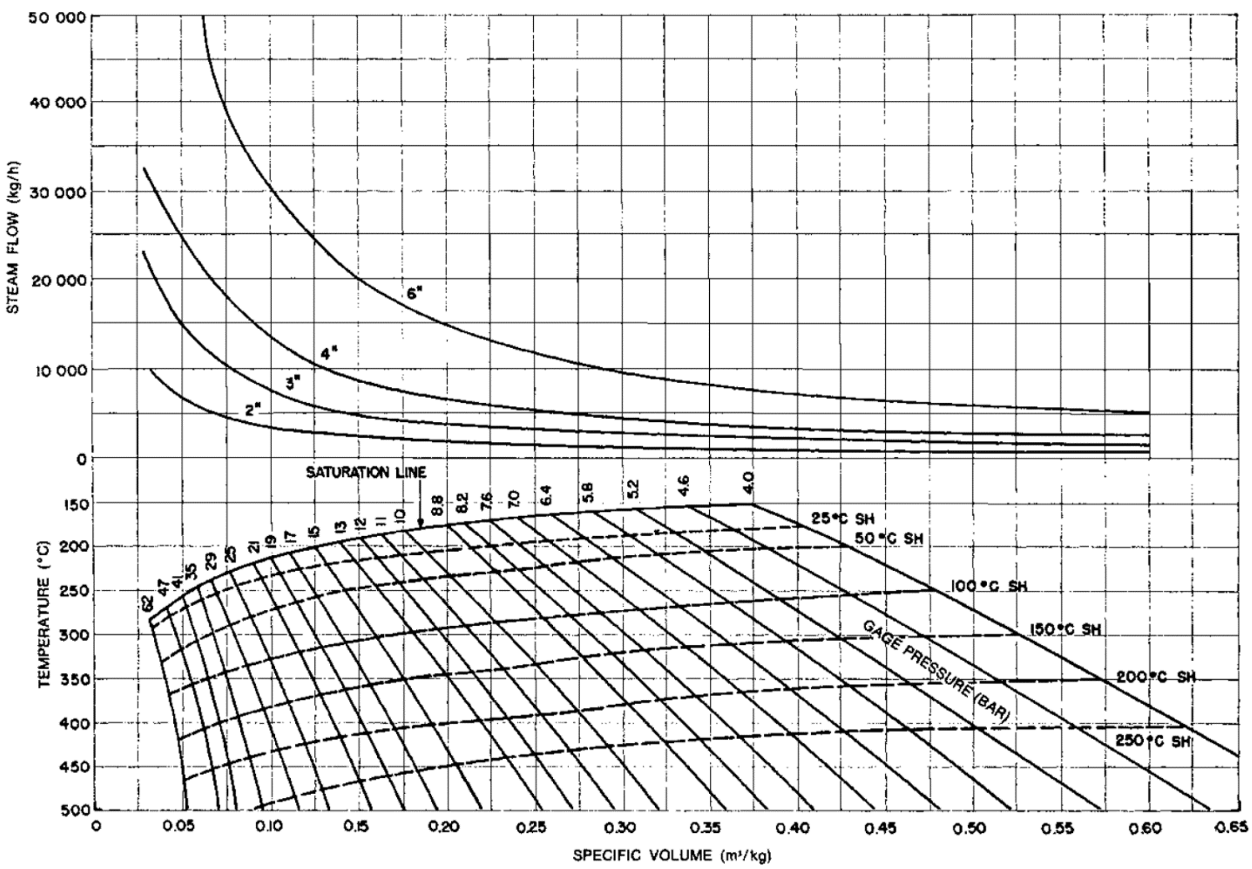


Figure 16: Inlet size requirements for single-valve, single stage steam turbines.

Step 9: Determine the required exhaust size using the relevant sizing graph as shown in Figure 17 using steam flow and exhaust pressure.

Used in conjunction with performance and physical data information from manufacturers, steam turbine selection is possible. Similar procedures for single-valve, multistage steam turbines and multivalve, multistage steam turbines (Elliott shortcut selection method) may be used to select steam turbines for power generation.

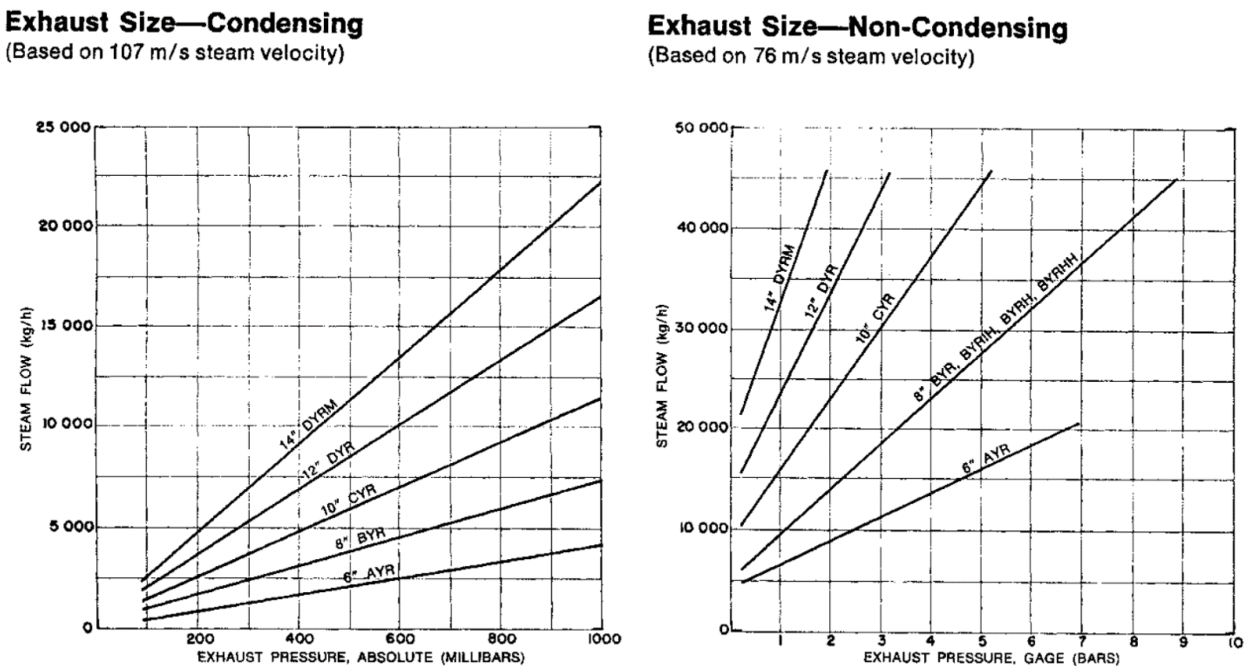


Figure 17: Exhaust size requirements for single-valve, single-stage steam turbines in SI units.

4. ADVANCES IN STEAM TURBINE TECHNOLOGY

Several technological developments contribute to the advancement of steam turbine technology. General technology trends for steam turbines include but are not limited to:

- Increasing steam temperature and pressure to develop Ultra Supercritical (USC) and Advanced USC (A-USC) plants
- Development of highly efficient last-stage long blades to improve efficiency in high-pressure and intermediate-pressure turbines
- Enhancement of operational availability in low-load conditions and load-following capability to stabilize fluctuations in electricity
- Improving integration of steam turbines into combined-cycle power plants
- Adapting steam turbines for compatibility with nuclear and renewable (geothermal and solar-thermal) power plants.

In terms of developments in analysis, measurement, and monitoring, advancements in finite-element analysis (FEA) and computational fluid dynamics (CFD) technologies have played a major role in optimizing turbine design. This reduces the cost of development via virtual prototyping and results in improved aerodynamic efficiency as well as enhanced turbine durability under various loading conditions.

Furthermore, improvements in solid particle erosion analysis, the development of performance testing methods such as the ASME Power Test Code, and advancements in sensor instrumentation contribute positively to smooth operation and maintenance of steam turbines. Improvements in sealing techniques, material science, bearing design, lubrication, and manufacturing techniques have resulted in turbines that are more durable and resilient, allowing for the development of A-USC plants that push the limits of current turbine technology.

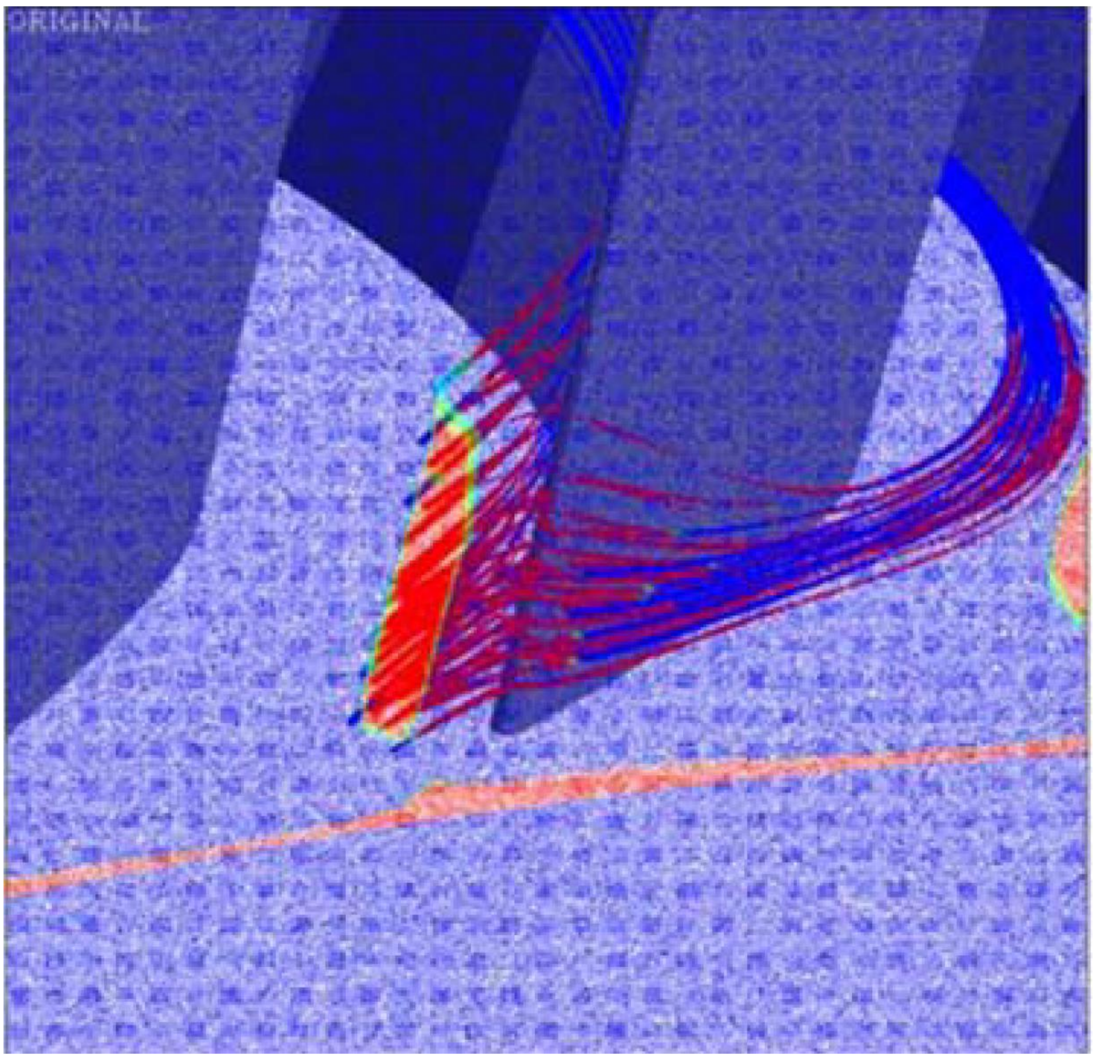


Figure 18: CFD simulation and visualization of calculated steam lines and entropy generation contours near an end-wall of a developed turbine stage.

5. CONCLUSIONS

Steam turbines are a mission-critical component of steam and combined-cycle power plants. They are complex assemblies that require careful design and production by manufacturers, appropriate selection by plant engineers, and regular maintenance and monitoring by operators. Steam turbine usage is expected to continue increasing steadily to fulfill continuously growing energy infrastructure requirements, and steam turbine technology contributes positively to energy security and economic growth in modern society. Furthermore, as turbine efficiency improves over time and fossil fuel power plants are phased out in favor of other thermal energy sources, steam turbines contribute to environmental conservation.

In light of promising steady growth and technological resilience due to continual improvement as related technologies such as analytical methods and material science develop, this paper has attempted to provide a high-level short overview of steam turbine technology. In doing so, the primary focus has been on turbine classifications, components and control, unit selection, and technological advancements. As steam turbine technology is an extremely broad topic with many more avenues for discussion, further content such as manufacturability considerations and economic viability calculations have not been covered due to scope constraints. A detailed presentation of quantitative calculation methods for all primary individual parts in steam turbines have similarly been omitted. Exploration of these topics are highly recommended for any deep dive into the literature of steam turbines.

Further literature recommendations include a survey of steam turbine integration into plants utilizing renewable energy sources such as solar thermal energy, improvements to the modern reheat-regeneration steam turbine cycle, and the software used to model steam turbines in various ways.

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