A Review of Power-Generating Turbomachines

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Abstract
A turbomachine is a device which interacts with a continuously flowing fluid by means of a rotor, which results in either the extraction of energy from the fluid (as in turbines), or the addition of energy to the fluid (as in compressors and pumps). Two major applications of turbomachinery include power generation and propulsion. This paper presents an overview of current and past developments of turbomachinery in power generation, as well as a review on research involved in future developments. Specifically, turbines in the steam, gas combustion, hydroelectric, ocean energy, and wind sectors are examined. In addition, a brief description of the historical development of these various turbine types is included, as well as a discussion of their current designs, with an emphasis on the rotor.

Current research topics related to steam turbines include computer modeling of two-phase flow fields to reduce erosion in the machines, as well as the use of unsteady computational fluid dynamics (CFD) packages to assess blade design with respect to aeroelastic instability, with the goal of improving component lifespan and efficiency. In gas combustion turbines, current efforts in sustainability are focused on identifying alternative fuels and reducing emissions, as dictated by ever stricter environmental regulations. Hydraulic turbines employed in hydroelectric power plants are subject to cavitation and its destructive effects. Researchers are using new CFD analysis techniques to handle, reduce, or avoid cavitation in the flow of hydraulic turbines, leading to better performance, efficiency, and cost-savings. On the ocean energy front (a largely undeveloped but very promising source of renewable energy), researchers are adapting blade element momentum theory (BEMT) performance models and the Reynolds-Averaged Navier Stokes (RANS) equations to tidal turbine systems analysis and wave turbine systems with the goal of increasing cost-competitiveness of ocean energy. Finally, the wind sector is addressed with a discussion of current research in offshore wind turbines and wind turbine farm array optimization.

The future development and research portion of the discussion is presented with an underlying emphasis on efficiency, sustainability, and cost-savings.

Introduction

This paper presents electrical-power generating turbines by flow-type; first compressible-flow type turbines are examined in sections 1 and 2, followed by incompressible-flow type turbines in sections 3 and 4, and then wind turbines in section 5. Each section addresses the historical development, current usage and rotor design, as well as the status of current and future research and development for each turbine type. The greatest research discussion is found in the sections covering ocean and wind energy. These two energy sectors are in a state of growth now that steam, gas, and hydraulic turbines are not, as they are older and more established technologies.

1.0 Steam Turbines

1.1 Past

The idea of using steam to produce work has been around for centuries, dating back to the time of Archimedes. It was not until the industrial revolution, however, that steam power started to realize its potential in the form of reciprocating engines and turbines. The first impulse type turbine was created by Carl Gustaf de Laval in 1883. This was closely followed by the first practical reaction type turbine in 1884, built by Charles Parsons. Parsons' first design was a multi-stage axial-flow unit, which Westinghouse acquired and began manufacturing in 1895, while General Electric acquired de Laval's designs in 1897. Since then, development has sky-rocketed from Parsons' early design, producing 0.746 kW, to modern nuclear steam turbines producing upwards of 1500 MW.[1] Today, steam turbines account for roughly 90% of electrical power generated in the United States.[2]

1.2 Current Design

Steam turbines can be designed for either radial- or axial-flow. Modern steam turbines are predominantly axial-flow units, especially in large power plant applications. Steam and gas turbines are both used extensively in power plants to drive electric generators, but steam turbines are generally much larger in size. The rotors are generally multistage arrangements designed to handle high pressures in the first stages and lower pressures in the later stages.[3]

The two major axial-flow turbine stage configurations are impulse and reaction. The distinction is based upon relative pressure drop across the stage, where one stage consists of one row of stationary blades/nozzles, and one row of rotating blades. A design is considered an impulse design if most or the entire pressure drop occurs across the stationary blade or nozzle (a 0% reaction). A reaction design experiences a pressure drop across both the stationary and rotating blades. If the pressure drop is split equally between the stationary and rotating blades, the reaction is 50%.[1] As the steam flows across a stage its kinetic energy does work upon the rotating blades. One tool important to the understanding of energy transfer from steam to rotor is the velocity triangle.

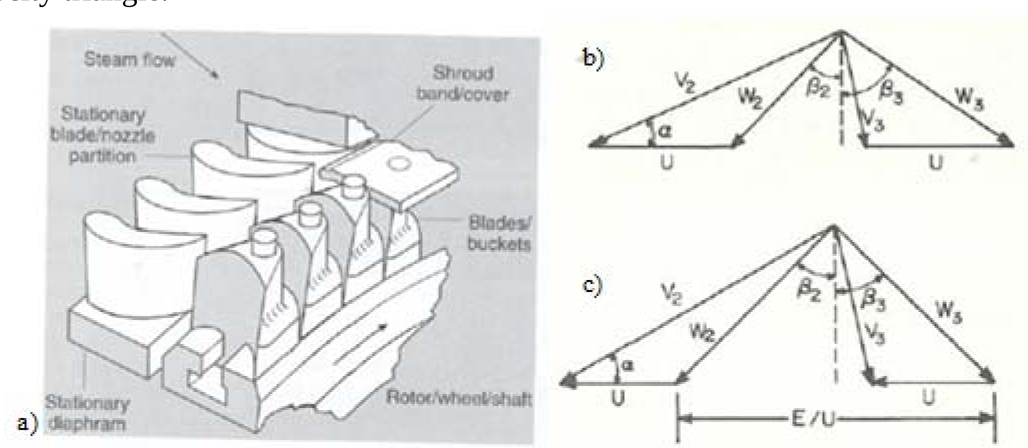


Figure 1: a) Typical steam turbine stage[1] b) Velocity triangle for a reaction turbine c) Velocity triangle for an impulse turbine.[3]

In the impulse turbine design, the magnitude of the relative velocity of the steam remains unchanged ($W_2 = W_3$), but the absolute velocity exiting the rotor is greatly reduced ($V_3 << V_2$). The kinetic energy lost in the fluid has been transferred to the rotor and is proportional to the difference in the squares of the velocities V_2 and V_3. The reaction design velocity triangle differs from the impulse design in that W_3 is much larger than W_2. This increase in relative velocity corresponds to a pressure drop across the rotating blades and a loss of enthalpy. A multistage turbine can be designed to have each nozzle row coupled with one moving blade row (pressure compounding), or have one nozzle row direct steam to multiple moving blade rows (velocity compounding). There are also intermediary designs that incorporate both pressure and velocity compounding.

1.3 Future Developments and Research

Recent developments and improvements in three-dimensional Computational Fluid Dynamics (CFD) codes have allowed researchers to gain new insight into steam turbine problems. Reliability is of critical importance in steam power generation[1], and so current research surrounding steam turbines is focused around a few fundamental areas, in particular, multiphase flow and aeroelastics. Two-phase flow in steam turbines poses a significant problem for turbine component lifespan and reliability due to water erosion, particularly in the final stages. Researchers are using three-dimensional numerical simulation to study two-phase flow fields to learn how to minimize water erosion.[4,5,6] Blade flutter due to aeroelastic instability is another significant concern in turbine reliability. These vibrations occur due to tip shrouds on the last stage moving blades during high mass flow, which are necessary for performance reasons. Researchers are using unsteady CFD packages to assess blade design and identify aeroelastic stability margins for safe operation.[7] Steam turbine design will continue to change as CFD packages become more advanced and researchers put them to use.

2.0 Gas Combustion Turbines

2.1 Past

Steam turbines developed first around the time of the industrial revolution. It was not until the 1930s and 1940s that gas turbines began to be developed and utilized as aircraft engines. The 1960s saw the advent of gas turbines for power generation applications, particularly in peaking power plants and co-generation plants (as supplements to the more conventional steam turbine plants). Gas turbine technology increased rapidly to a unit size of 100 MW within 30 years. Modern gas turbines generate upwards of 300 MW.[8]

2.2 Current Design

Gas combustion turbines are similar to steam turbines in that they are generally axial-flow designs. Radial-flow gas turbines are considered simpler, and there are some applications for it, but axial-flow designs are preeminent in aircraft and stationary power plants. The basic gas turbine is comprised of three major components: a centrifugal or axial-flow compressor (to compress the working gas from a state of low pressure to high pressure), the combustor or heat exchanger (to raise the exit gas-fuel mix temperature), and the turbine itself (to extract energy from the working gas, producing mechanical power). The compressor and turbine are generally interdependent, operating off the same shaft.[9]

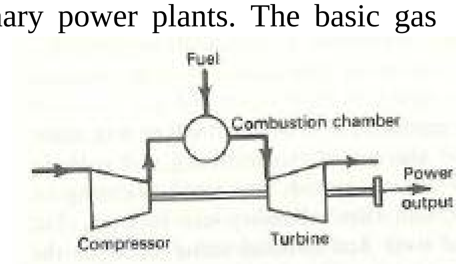


Figure 2: Simple gas turbine system.[43]

Like steam turbines, gas turbines find extensive use in power plants but are typically much smaller in size. What really differentiates gas turbine combustion engines, and indeed where they have made their greatest impact, is their application to aircraft propulsion. In aircraft gas turbines, which are designed for efficiency as well as diameter and weight, a more sophisticated design includes the following components: compressor (centrifugal or axial), fans, combustors, turbine (radial or axial), ducts, air systems, nozzle guide vanes (NGVs), mixers, afterburners, and heat exchangers.[9] Typical configurations include shaft-powered (turboprops and turboshafts, used for fixed-wing and rotary-wing aircraft, respectively) and thrust-propelled (turbojets, turbofans, and ramjets). Typical gas turbine design is similar to that of a steam turbine, with one stage being comprised of a row of nozzle guide vanes, and a corresponding row of rotor blades mounted on a rotor disc connected to the main shaft.

2.3 Future Developments and Research

Aside from improving efficiency, critical areas of research are fuel availability, fuel flexibility, and emissions reduction. There is presently significant research being done on combustion characteristics of alternative fuels such as ethanol[10], palm methyl ester (PME)[11], dimethyl ester (DME)[12], hydrogen/syngas[13,14], and biofuels.[15] Researchers are using 3D CFD codes to simulate alternative fuel combustion flows and flame propagation within turbines and to analyze the fluid dynamic effects.[13,16]

In addition to fuel research, researchers are turning their attention more and more to emissions reduction as tighter governmental regulations necessitate.[17] As turbine efficiency has increased with increasing turbine inlet temperatures, so too has NOx production which tends to increase with inlet temperature. New engine and combustor configurations are being investigated to address these effects.

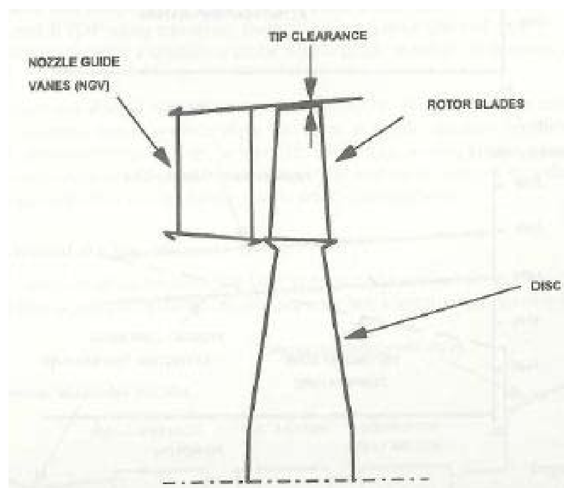


Figure 3: Axial turbine configuration.[9]

Another key advancement to the future of turbine technology is turbine cooling of components in gas turbine engines to achieve higher turbine inlet temperatures.[1] Increased inlet temperatures lead to better performance and lifespan of the turbine. The thermodynamic ideal inlet temperature is around 2000 °C, but even the most advanced metal alloys cannot operate above 980 °C; hence the need for advanced cooling systems. Multiple-use alternative jet fuels are being researched and developed to achieve the desired combustion efficiency, combustion stability, emission levels, and even cooling properties.[18]

3.0 Hydroelectric/Hydraulic Turbines

3.1 Past

Energy has been extracted from flowing rivers and waterfalls for centuries, typically in the form of rotating waterwheels. Today hydroelectric power stations use reservoirs to control and direct flow over massive hydraulic turbines to produce electrical power on a grand scale. Very large unit sizes exceeding 800 MW in capacity have been attained, along with efficiencies upwards of 95%.[19] In 2007 approximately 36% of all renewable energy generated in the US came from hydroelectric power plants (about six times the amount generated by wind and solar power plants combined).[20]

3.2 Current Design

Rotor type and size is largely dependent on the specific speed (a variable resulting from the combination of the head and power coefficients). Axial-flow turbines are best suited for high specific speeds (2.0-5.0 for Kaplan turbines) where large flow areas are desired. They typically operate at low heads with high flow rates. Radial-flow turbines are more suited for low specific speed conditions (0.3-2.0 for Francis turbines) and typically operate at high heads with low flow rates. The Pelton wheel is suited for the highest head applications with very small specific speed in the range of 0.03 to 0.3.[44]

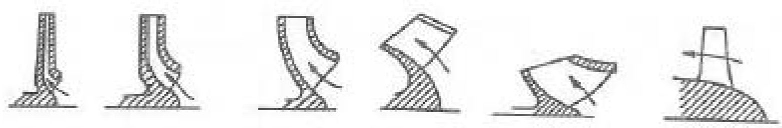


Figure 4: Impeller shape changes from radial to mixed to axial with increasing specific speed.[44]

Specific speed plays an important role in determining rotor geometry. As illustrated by Fig. 4, the impeller shape changes as a function of specific speed. Also crucial to the rotor geometry is the pressure drop seen by the fluid. The pressure drop is the distinguishing factor between two main types of hydraulic turbine: the impulse and reaction turbine.

Impulse turbines, such as the Pelton wheel, are typically employed in situations where a large potential energy is available. The potential energy is converted into kinetic energy as it flows through large pipes (penstock) and finally through nozzles before impinging on the vanes or buckets of the rotor. The force of the fluid impingement on the vanes/buckets creates a torque on the shaft. Thus, all of the energy transfer between the fluid and the rotor occurs through impulse action. The entire pressure drop occurs in the nozzles, resulting in no pressure drop as the fluid flows through the rotor. The rotor, which is composed of multiple ellipsoidal or hemispherical buckets positioned along the circumference, is not enclosed and remains at atmospheric pressure throughout the whole process.[44]

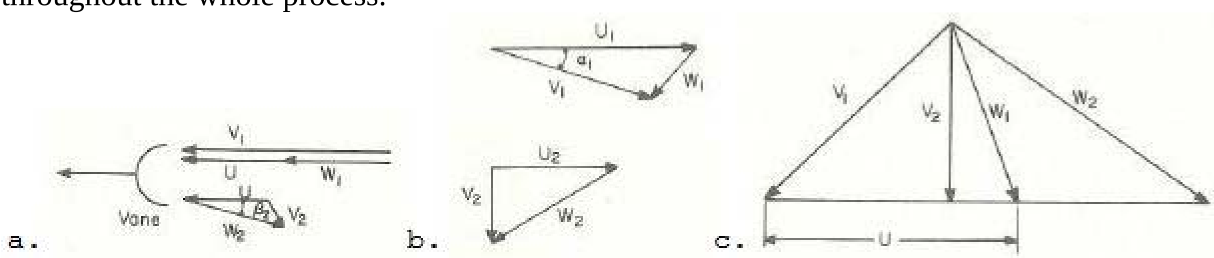


Figure 5: Velocity triangle comparison for the a) Pelton wheel b) Francis turbine and c) Kaplan turbine where V_1 is the absolute velocity of the fluid, U is the vane speed, and W_1 is the relative velocity.[3]

What distinguishes a reaction turbine from an impulse turbine is that a significant pressure drop occurs across the rotor. In a reaction turbine, the rotor is enclosed and completely filled with the working fluid (i.e. water). The water maintains significant kinetic energy and pressure after passing through the rotor. The direction of water flow through in the runner determines the kind of turbine. Francis turbines have water flow in the radial direction, while Kaplan turbines have water flow in the axial direction.

In Francis designs the water flows through the penstock into a spiral casing and is directed by a set of guide vanes on to the turbine rotor, called a runner. After flowing through the runner, the water is discharged into the draft tube. Runner design is determined by certain key variables such as operating head, required runner speed, speed ratio (blade velocity over fluid velocity), and required runner output. In the Kaplan turbine, which is an axial-flow design best suited for high flow rates, water is directed by stay vanes through wicket gates over a propeller turbine. The propeller typically has five to eight blades. After passing through the blades, the water is discharged through a draft tube.[44]

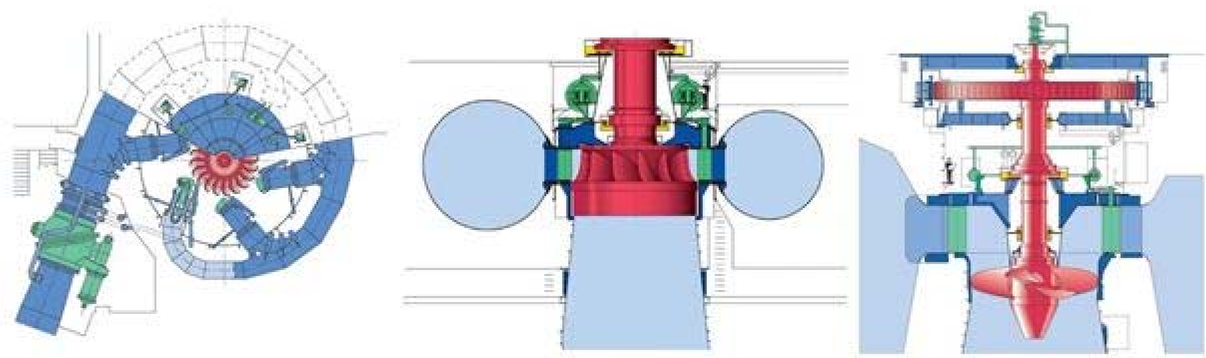


Figure 6: Voith Hydro schematics of the Pelton, Francis, and Kaplan hydraulic turbines (www.voithhydro.de).

3.3 Future Developments and Research

A very important factor in research and development of hydraulic turbines is the handling, reduction, or avoidance of cavitation in the flow, which results in decreased power output and efficiency. Cavitation can also result in unwanted noise and vibration and contributes to gradual erosive wear of the machinery, or even sudden catastrophic failure.[19]

Key to research efforts is the application of computational fluid dynamics (CFD), which began about 30 years ago. CFD analysis has progressed in stages from 3D Euler solutions, to steady RANS simulations using finite volume methods, to the present state of solving unsteady RANS equations with advanced turbulence models.[21] Now these tools are being developed to incorporate two-phase flows, as in cavitation and free surface flow in Pelton turbines, the flow simulation of which is considered "by far the most complex and difficult of all hydraulic turbomachinery simulations".[22]

Research is also prevalent on reaction turbines, which are generally considered more prone to cavitation than impulse turbines. Researchers have applied these tools to the analysis and flow simulation of Francis turbines with promising results that are beginning to converge and accord with the experimental data.[23] Researchers are also carrying out investigations on the acoustical properties of cavitation in order to develop equipment monitoring systems that will accurately estimate erosion level in the turbine.[24]

4.0 Ocean Energy Turbines (Tidal and Wave)

4.1 Past

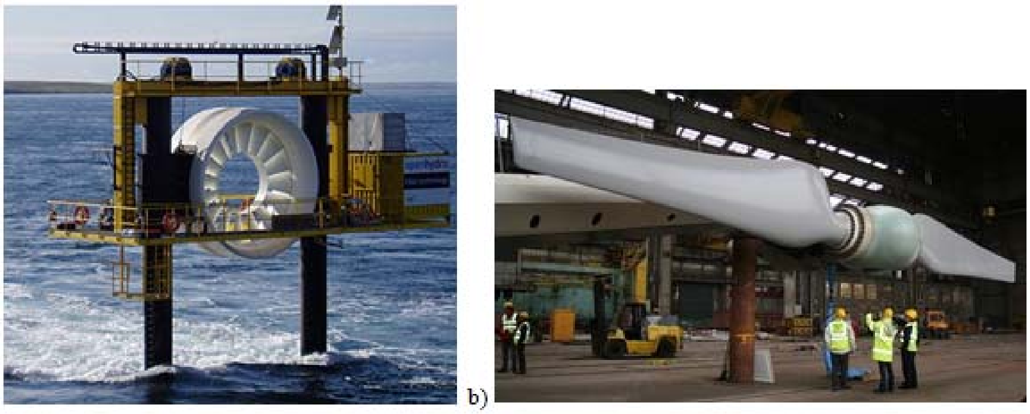
The oceans of the earth represent an attractive alternative energy source. This source is nonpolluting, more predictable than wind and solar, and vastly abundant. In fact, "The projected available ocean power far exceeds the ultimate energy consumption of mankind".[25] Worldwide research and development, however, is relatively limited and lags far behind research into other alternative energy resources.

The ocean stores energy for potential conversion into electricity in two primary ways: thermal and mechanical. Thermal energy is available due to the temperature gradient from the surface of the ocean to its depths. Solar irradiation incident on the ocean's surface can lead to a temperature gradient of 20 °C or more between the surface and depths of about 1000 meters in the equatorial regions of the world's oceans. Ocean Thermal Energy Conversion (OTEC) systems make use of this temperature stratification as a heat engine to power the same kind of low-pressure steam turbines discussed in section 1.2. While there has been promising research in OTEC systems worldwide and especially in the U.S. since the 1960s onward, there are presently too many challenges for OTEC systems to overcome to be economically feasible in the short-term, and the U.S. Department of Energy no longer supports such research.[20]

In the short-term, there is more potential on the mechanical side of ocean energy for future development in electricity-producing turbine systems. The ocean stores tremendous mechanical energy in the forms of waves and tidal action, and both wave and tidal energy harnessing systems have demonstrated economic feasibility for electricity production.[20] The first tidal power station was built in the 1960s on the estuary of the Rance River, off the northwestern coast of France. The station, with an installed capacity of 240 MW, has operated very successfully and reliably for years and yet remained the only industrial-scale tidal power station until the recent completion of the Sihwa Lake tidal power station in South Korea. There are presently tidal power installations in France, Russia, China, South Korea, and Canada. Wave energy systems are even less developed than tidal systems.[25]

4.2 Current Design

Tidal energy is typically harnessed to produce electricity in one of two ways: in-stream tidal turbines and tidal barriers/dams.[25] In-stream tidal turbines, which are relatively new technology, are typically designed as large impellors housed in a shroud or duct. Newer designs, such as those developed by Alstom/Clean Current (www.cleancurrent.com) and Irish company OpenHydro (www.openhydro.com) feature open-center shaftless impellors, which increase both performance and reliability. British company Marine Current Turbines (www.marineturbines.com) has taken another approach, developing an in-stream tidal turbine system that features multiple counter-rotating axial-flow pitch-controlled propeller rotors, similar to those currently used in the wind industry. Other companies such as UEK Corporation in the U.S. and Rotech in Scotland are developing their own unique approaches to harnessing tidal stream energy via turbines.



a) b)

Figure 7: a) Open-center in-stream tidal turbine developed by OpenHydro (www.openhydro.com) b) in-stream tidal turbine propeller rotor manufactured by Marine Current Turbines (www.marineturbines.com).

While in-stream tidal turbine systems use relatively new turbine rotor technology, tidal barriers/dams can utilize conventional hydroelectric turbines. Specifically, the same kind of low-head axial-flow turbines discussed in section 3. In tidal barrier/dam systems, water is collected and stored in a reservoir at high tide, and then released through turbines at low tide. The reservoir is created by a dam-like structure called a barrage and built in an estuary. Tidal systems can also be designed with more complex two-way hydroelectric turbines that generate electricity during both the reservoir charging and discharging stages. These setups rely on a natural resonant inshore frequency for successful operation. Hence, the inshore geological features are critically important. One downside is that power generation depends on the lunar cycle, causing power generation to occur at different times on different days, and therefore not always at the time of peak demand.[20]

Wave energy is less developed than tidal energy, but shows potential. While tidal systems can utilize relatively conventional hydroelectric turbines, there are many different concepts for mechanisms to extract energy from ocean waves. In particular, pneumatic turbines have found application in ocean energy converting systems. Two such pneumatic turbine designs are the Wells turbine and the McCormick turbine, which can be staged in co-rotating or counter-rotating configurations.

The Wells turbine is unique in that its blades have a symmetric profile. The overall reaction force developed on the blade is perpendicular to the overall approach flow, which is the vector sum of the air flow velocity through the column and the approach flow due to rotation. The useful component of the overall reaction force is the component in the direction of rotation and that component is the driving force. Because of the symmetric profile, once the turbine begins rotating it will maintain its rotation even if the direction of the air flow through the column changes. Wells turbines also find application in Oscillating Water Columns (OWCs), another kind of wave energy device currently subject to much research.[26,27]

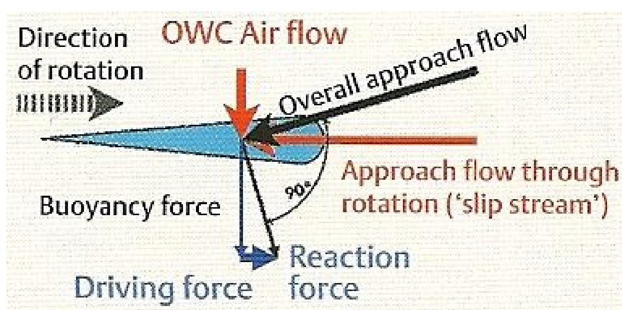


Figure 8: Velocity triangle diagram of the forces developed on the symmetric blade of a Wells turbine.[39]

Another method to harness wave energy, used in Norway and developed by the Norwegian firm Norwave, is the tapered channel method. This method employs a tapered channel to push water over a barrier, where it is collected in a reservoir and then released through a low-head Kaplan hydroelectric turbine. This method is similar to the tidal barrier method, however it is specifically designed to use surface waves, which enter the channel and subsequently grow in height as the channel narrows.[25]

4.3 Research and Future Developments

The previous three sections (1-3) covered the more traditional electricity-generating and well-established technologies of steam, gas, and hydroelectric turbines. While research in these fields is still active, the research and development in the ocean energy and wind energy fields are much more prevalent right now, and accelerating rapidly.

Much of the research in ocean energy turbines is centered on adapting blade element momentum theory (BEMT) performance models (long used in aircraft propulsion and wind turbine models) and the Reynolds-Averaged Navier Stokes (RANS) equations to tidal turbine systems analysis and wave turbine systems with the goal of increasing performance and cost-competitiveness of ocean energy. Researchers in the UK have recently applied the RANS-BEMT approach to model the wakes around tidal turbines and to study their effects on performance in turbine arrays.[28,29] Their studies have identified highly effective strategies for lateral and longitudinal turbine row spacing to enhance energy production, and in general have furthered understanding of turbine wakes and their effects in different turbine array configurations.

Other researchers have adapted these BEMT models to incorporate the turbulent inflow conditions present in coastal waters, where tidal stream turbines are likely to be deployed.[30] Such models allow engineers to accurately predict power output and other performance characteristics without actual deployment. Similar research has been able to extend the models to account for other real-world phenomena, such as tip and hub loss corrections.[31] Such improvements and specific-case modifications to BEMT models can lead researchers to ever more accurate models and calculations of turbine performance in real-world flow conditions, driving up performance and driving down cost for an overall increase in cost-competitiveness of ocean energy, which is necessary for it to compete with existing fossil-fuel power plants.

Other researchers in Canada have developed numerical models to study the performance of different configurations of twin-turbine tidal systems. Their model has been validated by experimental tests and shown that power output of optimally-configured twin-turbine systems can be more than twice the output of a single tidal turbine. They have also identified optimal configurations for counter-rotating and co-rotating twin-turbine systems.[32]

Researchers have applied CFD codes to the analysis of Wells turbines in wave energy converting systems. Examinations of the flow-fields around the turbine blades have yielded insights into effects on performance by different tip clearances (uniform and non-uniform), with non-uniform tip clearances generally leading to overall better performance.[33]

As tidal and wave turbine systems continue to grow in relevance to the world's energy portfolio, it is important to gauge their life cycle properties and determine how they compare to existing technologies. Researchers in the UK have carried out cradle-to-grave assessments (including emissions from starting materials all the way through the decommissioning and recycling of the devices) of tidal and wave turbine systems and shown them to have comparable energy payback periods, CO_2 payback periods, and energy and carbon intensities when compared to each other. They are also comparable to established technologies, such as wind turbines, and quite low when compared to typical fossil fuel technologies. All ready at acceptable levels, life cycle properties of tidal and wave systems only stand to get better as their construction methods and deployment efficiencies improve.[34]

5.0 Wind Turbines

5.1 Past

Wind turbines are unique because, unlike the previously discussed turbomachines, they are not enclosed and the rotor blades almost always lacks a stator, as well as other common components like multiple stages, nozzles, inter-stage guide vanes, and compressors. These differences cause some to not regard them as true turbines; however, they are operating under the same principles and for the same end-purpose of electrical power generation. The modern wind turbine evolved from the windmill (a purely mechanical device), which has been in use for centuries, most notably in Europe. In the very late 1800s to early 1900s, the windmills were first adapted to convert wind energy into electricity, creating the first true wind turbines.[35] Electrical generators, however, will not be addressed here. Wind turbine technology remained relatively dormant for many years until the 1970s when research and development accelerated rapidly. Today, wind turbines are viewed as a maturing technology with over 200 GW of installed electrical capacity in over 80 countries.[36]

While onshore installations are now well-developed, many countries are now directing their attention to offshore installations. The offshore wind resource is relatively untapped worldwide and holds enormous potential for electricity-generating capacity.[37] While offshore wind turbines have been conceptualized for many years, the first realized offshore wind farm was not built until 1992 off the coast of Denmark. The first large, utility-scale offshore wind farm was not commissioned until 2002. Today there is over 1000 MW of installed offshore wind capacity[35], but offshore wind remains a largely untapped source of renewable energy and offers many opportunities for research and development.

5.2 Current Design

The geometry of the rotor, which consists of a hub and blades, determines the basic classification of a wind turbine. There are two basic classifications of a wind turbine: the horizontal-axis wind turbine (HAWT) and the vertical-axis wind turbine (VAWT), distinguished by the orientation of the rotor axis with respect to the oncoming flow of air. The rotors in HAWT devices, which are more common than VAWT devices, are classified according to several factors including rotor orientation, hub design, rotor control (pitch or stall), blade number (2 or 3), and yaw system.

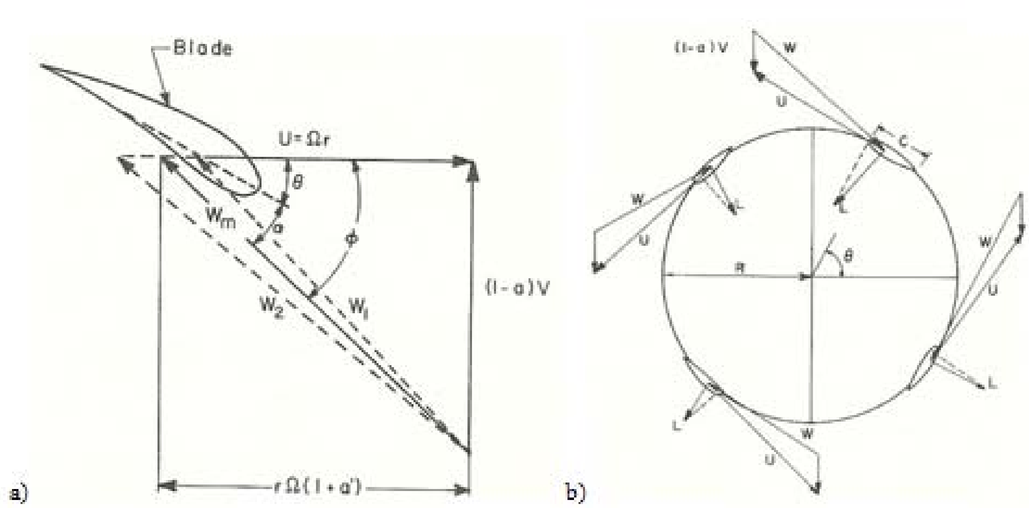


Figure 9: a) Example velocity triangle diagram for a horizontal axis wind turbine b) example velocity triangle diagram for a vertical axis wind turbine.[3]

While rotors can be designed to operate off the aerodynamic forces of lift or drag, the lift force is the preferred method because lift-driven devices can achieve much higher apparent wind speeds and thus can approach the theoretical maximum efficiency of 59% (the Betz limit).[37] The approach to rotor design in wind turbines has undergone an evolution in the last three decades. The prevailing trend beginning in the 1980s was to maximize the design power coefficient of the rotor for each given set of airfoils, but this resulted in undesirable efficiencies when operating in off-design conditions. The 1990s saw a transition to rotor design centered on maximizing the energy capture of the rotor by modifying blade characteristics to account for varying operating conditions. The last decade saw a transition to rotor design centered on minimizing cost of energy via complex optimization models, which factor in relevant data such as manufacturability and site-specific environmental data.[35]

The rotor is the most important component of the wind turbine; therefore its design is critical. Rotors can be designed as either upwind or downwind and typically have two or three blades, but the most common configuration for the HAWT is the upwind rotor with three blades.[35] Power limitation is important in wind turbines, which have naturally fluctuating loads, and so rotors must be designed with speed-regulation in mind. Two common designs for this are stall-regulation and pitch-regulation. In stall-regulated designs, the blades are designed such that at a certain critical wind speed the flow will separate from the low-pressure side of the blades, resulting in stall. In pitch-regulated designs, the blades are designed such that they can be rotated into and out of the wind in order to limit power. In recent years, pitch control has come to be the dominant control mechanism.

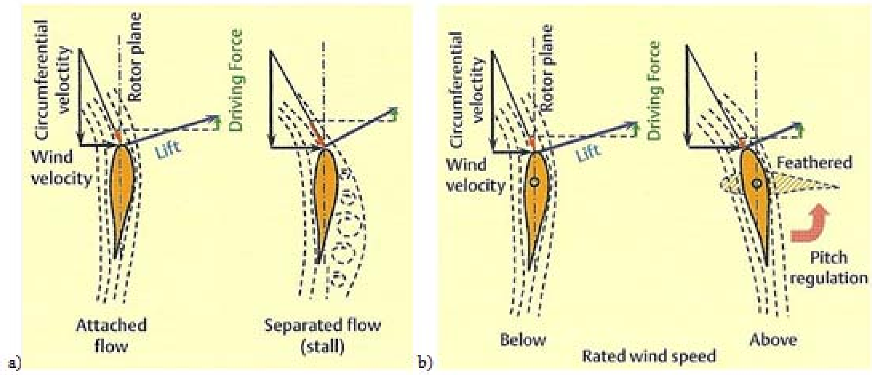


Figure 10: Power limitation methods in wind turbine rotors: a) stall-regulation b) pitch-regulation.[37]

Also critical to rotor design is the choice of blade material. Fiberglass and carbon fiber reinforced plastics (GRP and CFRP) are the most popular choice, with wood/epoxy laminates finding use in some applications. Blade design is complex and depends on a number of different design considerations: aerodynamic performance, structural strength, manufacturability, safety, noise reduction and cost are just a few.[35]

5.3 Research and Future Developments

Wind turbine technology has experienced rapid growth over the last three decades and is now considered a mature technology, especially in comparison to the more nascent ocean energy sector. There remains little room for improvement in blades optimization and available land is running out in the areas where wind energy is most developed, such as northern Europe. These facts are necessitating two key areas of research: 1) wind farm layout optimization to make best use of the land that is available and 2) offshore wind farm development.

In an effort to optimize wind farm layouts and wind farm power density, researchers in the state of New York are developing a new methodology called Unrestricted Wind Farm Layout Optimization (UWFLO) which optimizes farm layouts with varying turbine rotor diameters to maximize net power output. The methodology employs a standard wake model, a must for farm layout or grid optimization, and a stochastic optimization algorithm called Particle Swarm Optimization (PSO). The new methodology has resulted in 30% increases in total power generation via layout optimization and 43% increases via turbines with differing rotor diameters.[38] The vast majority of productive wind farms worldwide utilize HAWTs because of their vast size, high power coefficient and multi-MW power output per unit, but such units require significant swaths of land to operate properly. Researchers in California have turned their attention to optimization of VAWT arrays, which require significantly smaller land area for sizable power output and also utilize less vertical space, meaning less visual and radar impact. The researchers conducted field studies of 10-meter tall VAWT arrays, arranged in counter-rotating layouts and discovered that such layouts can utilize adjacent turbine wakes to actually enhance performance. Power densities ranged from 21 to 47 W/m^2 at wind speeds above the cut-in speed, compared to the 2 to 3 W/m^2 achieved by modern HAWT farms. This order-of-magnitude enhancement bodes well for future efforts to efficiently use dwindling land resources and to access land not suited for large HAWTs (typically on the order of 100 meters in height).[39] Additionally, these researchers have shown that bio-inspired VAWT spatial arrangements based on the studies of shed vortices in the wakes of schooling fish can lead to a significantly improved array performance coefficient, whereas HAWT array performance always suffers due to closely spaced turbines.[40]

As available land for traditional wind turbines diminishes, focus turns to offshore wind energy. Near-coastal regions of the ocean offer 40 to 50% more energy yield compared to good coastal sites and ample available space.[37] There are many differences between offshore wind turbines and land-based wind turbines that must be considered, such as undersea electrical transmission, wind farm design and layout, offshore operation and maintenance, and the characteristics of the wind resource itself. One pronounced obstacle in designing offshore wind turbines is designing suitable support structures, and this is one area where much current research is directed. The two most common types of support structure are the monopile and gravity structure, which both involve pile-driving into the seabed to support the turbine towers. Researchers at the National Renewable Energy Laboratory (NREL) in Golden, Colorado have used finite-element and aeroelastic computer codes to analyze the modal dynamics (loads and instabilities) of these systems, which must be minimized for successful operation.[41] Floating support structures are less common but may be necessary for wind farm installations in deeper seas. Researchers at NREL have recently conducted dynamic-response analyses of several different floating support structure concepts for a 5 MW turbine. Their results show that tension-leg platforms slightly outperform semisubmersible and spar buoy support structures, and all three of these concepts outperform barge support structures in terms of the loads experienced by the turbine and tower.[42]

Wind energy, an old technology, lay dormant for many years. The last 3 decades, however, have witnessed a resurgence in wind turbine technology and it is far from over. The researchers at the University of Massachusetts - Amherst, known for its wind energy research center, are currently developing wind farm layout optimization (WFLO) models for offshore farms. Compared to land-based wind farms, offshore models call for different optimization routines because of their very different operation and maintenance characteristics and also different wind availability. Two professors and researchers at the university, James Manwell and Jon McGowan, have identified the following areas of research for future wind development:

- improvements in electricity transmission from remote sites to end-use locations
- reducing cost of energy at lower wind speed sites
- commercial viability for turbine use in remote communities
- offshore wind energy (still in its infancy with tremendous potential but many obstacles)
- improvement of cost-effectiveness
- new materials to increase turbine life (i.e. carbon fiber)[35]

Researchers at NREL and Sandia National Laboratories have outlined similar goals and are currently working alongside industry to meet them. In addition to these research goals, the general sizing of turbines stands to increase significantly in the future, with 5 MW turbines already operational, 7 MW turbines soon to arrive, and possibly turbines with capacities of 10 and 20 MW not too far off.

Conclusion

Turbine technology is central to energy-producing efforts, whether they be well-established such as steam, gas, or hydroelectric turbines, or new and emerging such as wave, tidal, and wind turbines. Industry drives the research and development behind these technologies and as such, most of that effort is directed towards cost-savings (increased efficiency, reliability, and component lifespan), sustainability (alternative fuels, lower emissions), and cost-competitiveness (particularly for the emerging technologies). One tool key to advancements in much of this research is Computational Fluid Dynamics.

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