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Tesla Turbomachinery

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Summary

The Tesla-type turbomachinery is distinguished by the fact that the rotor is composed of flat parallel corotating disks, spaced along a shaft. A throughflow of fluid between the disks results in momentum exchange between the fluid and the disks and hence shaft torque and power. Tesla designed, built and tested such machines but was not able to achieve industrial applications of them.

In the subsequent years, many investigations have been carried out to determine the performance and efficiency of this type of turbomachinery. These have been both analytical and experimental. Most of the investigations have had a certain limited application as the objective, with regard to size and speed as well as the nature of the operating fluid. However, some of the investigations have tried to establish the generalized performance of Tesla-type turbomachines. In general, it has been found that the efficiency of the rotor can be very high, at least equal to that achieved by conventional rotors. But it has proved very difficult to achieve efficient nozzles in the case of turbines. For pumps and compressors, efficient diffusion after the rotor has proven difficult to achieve. As a result, only modest machine efficiencies have been demonstrated. Principally for these reasons the Tesla-type turbomachinery has had little utilization. There is, however, a widespread belief that it will find applications in the future, at least in situations in which conventional turbomachinery is not adequate. This includes the use with very viscous fluids, fluids containing abrasive particles, and two-phase fluids.

The flow in the rotor may be either laminar or turbulent, with certain advantages and disadvantages in each of the regimes. It is necessary to carefully distinguish which type of flow is considered in reports by the various investigators.

Herein, the principles of the Tesla-type turbomachinery are reviewed and the problems with nozzles and diffusers (which limit the machine efficiency) are discussed. The analytical methods that have been found useful in modeling and calculating the flow in the rotor are reviewed and the experimental results obtained by some investigators are described. An extensive list of References is presented and summaries are made of the main results and conclusions that have been reported.

Introduction

Tesla is most widely recognized for his outstanding achievements in the fields of generation, transmission and utilization of electrical power. However, he was also the inventor of a unique type of turbomachinery that can be applied as liquid pumps, liquid or vapor or gas turbines, and gas compressors (1). The Tesla turbine was widely recognized in the semi-technical press at the time of the invention (2-7). The Tesla turbomachinery is distinguished by the fact that the rotor is composed of flat parallel corotating disks spaced along a shaft. A throughflow of fluid between the disks results in momentum exchange between the fluid and the disks and hence shaft torque and power. Tesla designed, built and tested such machines but was not able to achieve significant industrial application of them. Figures 1 and 2 are schematic diagrams of a Tesla-type pump and turbine.

As a turbine, the multiple-disk rotor is contained in a housing provided with nozzles to supply high-speed fluid approximately tangential to the rotor. The fluid flows spirally inward and finally exhausts from the rotor through holes or slots in the disks near the shaft. As a pump or compressor, fluid enters the rotor through holes near the shaft, flows spirally outward, and exhausts from the rotor into a diffuser such as a volute scroll. Shaft power is delivered by the turbine and shaft power must be supplied to the pump or compressor. The performance and efficiency of the rotor of such machines is dependent on the combination of shaft speed, disk inner and outer diameters, the spacing between the disks and the fluid properties and flow rate. The performance of the overall turbine is strongly dependent also on the efficiency of the nozzles and the nozzle-rotor interaction. The performance of the pump is also strongly dependent on the interaction of the fluid leaving the rotor with that in the volute and on the efficiency of diffusion in the volute. In general, flow in the rotor may be laminar or turbulent or mixed.

There was little activity concerning the Tesla turbomachinery until a revival of interest began in the 1950s (8-17). Research was widespread after that, particularly in the area of analytical modeling of the flow in the space between two disks in a rotor, and continues at present. References (18-79) are representative. Many attempts have been made to commercialize Tesla-type turbomachinery, especially as pumps, but no widespread applications are apparent. While rotor efficiencies can be very high in this type of turbomachine, there are inherent losses in the fluid flows entering and exiting the rotor. As a turbine, the nozzles are necessarily long and inefficient. As a pump or compressor, the diffuser or volute must handle flow with a very small entering angle which causes the volute to be very inefficient. For these and other reasons actual Tesla turbomachines have efficiencies much less than might be expected from consideration of the flow in the rotor. There is little or no literature devoted to the flows that cause the main losses in Tesla-type turbomachinery. The Tesla-type turbomachinery is variously referred to in the literature as multiple-disk or friction or shear-force (or, nonsensically, boundary layer) turbomachinery.

Multiple-Disk Rotors Having Laminar Flow ~

A way of analytically modeling the flow in a multiple disk rotor known as bulk-parameter analysis, was used by early investigators (7, 9-11, 16, 17, 21, 24, 49). It is usable for both laminar and turbulent flow. In this method of analysis, the frictional interaction between the fluid and the disks is represented in terms of an empirical fluid friction factor. This results in ordinary differential equations which, together with simple boundary and entrance conditions, constitute a problem easily solved using computer-implemented step-wise calculations. The method is limited in usefulness by the inadequacy of the friction factor concept.

In the case of laminar flow, much better analytical modeling can be achieved. Partial differential equations can be established rather simply together with appropriate boundary and inlet conditions. Because the flow path is long compared with the disk spacing, order-of-magnitude arguments can be made to simplify the equations somewhat and reduce them to pseudo-parabolic form. The problem can then be solved by any one of several available means.

Some investigators have used truncated series substitution methodology to make solutions (23, 25, 29, 32) but the method has accuracy limitations. A much more widely used method is to solve the problem using computer-implemented finite difference methods; references (19) and (33) are typical examples. Integral methods have also been used, mainly to shorten the computer execution time required for solution (38). Most of the literature has considered the fluid to be incompressible although some investigators have calculated compressible flows (48, 53, 65, 71).

Wu (78) in 1986, made detailed comparisons of results from all of the available literature. It was found that when the results of investigations using similar solution means were compared there was close agreement, within accuracy limitations. It was also concluded that the finite difference solutions all obtained good accuracy and produced essentially the same results and such solutions are recommended to be used.

It is also clear from the literature that the calculated results for laminar flows between corotating disks are in excellent agreement with experimental results for such flows (35, 44). While future efforts may lead to increased efficiency or shorter computer execution time, present published methodology and results are sufficient for use in the design of laminar flow multiple disk rotors for pumps, compressors, and turbines. Some generalized information for such rotors has been presented. (45, 46)

The results of a solution of a flow consist of detailed knowledge of the distribution of the velocity and pressure throughout the flow between the disks. From this, the relationship between the mass flow and the pressure change from inlet to exit become known and allow determination of design facts such as the number of disks required for an application of interest. The solutions are parameterized using the following or equivalent parameters: for outward flows (pumps), Reynold's number, flow rate number and radius ratio; for inward flows (turbines) the additional parameter (vo/omega ro : average disk-disk radial component of velocity, at outer radius of disk / angular velocity of pair of disks x outer radius of disk) is required. The results can be arranged to provide values of dimensionless torque, dimensionless pressure, dimensionless power, rotor efficiency, etc.

With proper use of the analytical results, the rotor efficiency using laminar flow can be very high, even above 95%. However, in order to attain high rotor efficiency, the flowrate number must be made small which means high rotor efficiency is achieved at the expense of using a large number of disks and hence a physically large rotor. For each value of flow rate number there is an optimum value of Reynolds number for maximum efficiency. With common fluids, the required disk spacing is dismally small causing laminar flow to tend to be large and heavy for a prescribed throughflow rate.

Extensive investigations have been made of Tesla-type liquid pumps using laminar-flow rotors (64). It was found that overall pump efficiency was low even when rotor efficiency was high because of the losses occurring at the rotor entrance and exit earlier mentioned.

Criteria for the Occurrence of Laminar and of Turbulent Flow in Multiple-Disk Rotors
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It is established that a wide range of types (or regimes) of flow can occur between corotating disks including wholly laminar flow, laminar flow with regions of recirculation, wholly turbulent flow, and turbulent flow proceeding through "reverse transition" or "relamination" to laminar flow. There is experimental evidence concerning these flows (26, 27, 31, 35, 42, 44) and the hydrodynamic stability of laminar flows between corotating disks has been investigated (31, 66). Wu (78) considering all available experimental and analytical evidence, concluded that the visco-geometric number alpha proposed by Nendl (42, 55) most adequately characterizes the flow regime, where alpha = uh2/vr. While the data of the various investigators are somewhat contradictory, a reliable guide appears to be that flow is laminar for alpha < 10, in transition for 10< alpha < 20 and turbulent for alpha > 20. Various investigators introduce rather pragmatic and differing definitions of "laminar" and "turbulent" which further complicates the matter. It is desirable that it be explored further both experimentally and by additional hydrodynamic stability analysis.

Multiple-Disk Rotors Having Turbulent Flow ~

The bulk-parameter (friction factor) type of analysis of flow in a multiple-disk type of rotor was referenced in the foregoing discussion of laminar flows. It has been used extensively to calculate turbulent flows but with mostly unknown degrees of adequacy. The transition criteria presented is not applicable for bulk-parameter use and the hydraulic diameter concept is required and the assumption must be made that pipeflow frictional correlations are valid for flows between corotating disks. Nevertheless, such analyses has been the only analytical prediction method available until relatively recently and methods now becoming available are not yet well-established. Wu (78) gives an extended comparison of the results of various bulk-parameter methods of analysis with several sources of experimental data for turbulent flows between corotating disks.

Momentum integral equation methods have been and continue to be used to calculate the subject turbulent flows (26, 34, 36). In these methods, ordinary differential equations describing the flow are written based on assumed distribution forms for the velocity and on empirical expressions for the stresses in the flow. Some of these rely on experience and/or specialized experimental results and are found not to be universal. Within carefully noted bounds however these methods can be very successfully used by an experienced investigator and have yielded strong insights into and design information for the turbulent flows of interest.

In principal, the set of partial differential equations applicable for turbulent flow can be written, provided with appropriate boundary and entrance conditions, and then solved in some manner using computer-implemented calculations. In practice, there are several aspects of the process that cannot be executed with confidence that the calculated results will agree with reality. Principally among these is that a model or mechanism describing the turbulent transport of linear momentum must be prescribed. Furthermore, the partial differential equations are much more complicated for turbulent than for laminar flow. In the entrance region, the equations must be solved in elliptical form before changing over to simplified pseudo-parabolic equations to continue the calculations.

Truman (73) carried out calculations for turbulent flow between corotating disks using eddy-viscosity/mixing-length turbulence (stress) modeling, and using a finite-difference method for solving the partial differential equations. Wu (78) used a slightly modified version of the computer-implemented calculations provided by Truman, to compare calculated results with experimental data for turbulent flow due to Bakke (26) and Kohler (34). In general, agreement was good but with some qualifications and reservations discussed in detail by Wu (78). It was noted that at high rotor angular speeds the calculations indicated recirculation in the turbulent flow that could not be detailed since the pseudo-parabolic equations are not applicable for recirculating flows.

Truman, et al.(76) have also calculated similar flows using an anisotropic two-equation turbulence model. More analytical study and much more experimental investigation of the turbulent flow between corotating disks is needed to establish the most applicable methods for calculating the flows with confidence and for the results to be useful in the design of turbomechanics. Wu (78) has outlined an experimental apparatus and procedure that might provide the next needed insights for progress in this area.

Actual Tesla-Type Turbomachinery ~

Many individuals and groups attempting to commercialize Tesla-type turbomachines have designed, constructed and operated them. Pumps have received the most interest but compressors and turbines have also been built and operated. While much useful test data has no doubt been recorded, very little has been published or otherwise made known because of the perceived need for keeping information proprietary. Thus, this large body of information is not available to most investigators.

Most Tesla-type turbines and pumps have been designed using intuition and simple calculations or empirical experience and rules-of-thumb. This has almost always led to the use of large spaces between the disks corresponding to turbulent flow between the disks.

The published information concerning actual Tesla-type pumps includes references (17, 18, 20, 21, 28, 34, 37, 47, 49, 50, 54, 59, 64, 67). All of the information presented shows lower efficiency than was desired. In general, the pumps designed with little prior calculated rotor design information showed efficiencies below 40%. Adequate calculated rotor design information resulted in higher efficiency but still in the range of 40 to 60%. All things considered, it seems probable that Tesla-type pumps of reasonable size, operating with common fluids, will not exceed an efficiency of 65% at best, with careful attention to volute/rotor matching. Many Tesla-type pumps intended to be commercially competitive have not been provided with a volute or any other type of diffuser.

A number of Tesla-type turbines have been constructed for use with steam, gas and water. Very few data have been published concerning them. The published information includes references (2-6, 8-11, 13, 16, 24, 51, 63). As with pumps, the turbine efficiencies have been low and the machine sizes large per unit of power delivered. All of the turbines reported probably operated with turbulent flow in the rotor.

Most recent pumps and turbines of the Tesla-type have used rotors composed of disks with a central hole rather than the spoke construction used by Tesla. The disks are carried on throughbolts extending from a thicker masterdisk fastened to the shaft; thus the rotor is overhung. Although most machines have used thick disks, there seems to be little reason to do so since the disks have only small forces acting on them and are not required to be perfectly flat.

Many design questions remain unanswered at this time. Whether the disks should be rough or smooth, for best performance, is controversial as is the question concerning appropriate rotor-to-housing seals. There are some ideas concerning ways to improve volute or nozzle performance that remain undemonstrated. An early idea of improving performance of rotors by composing them of nested cones rather than flat disks has been shown to produce no performance advantages and to introduce structural handicaps (20, 79).

Conclusion ~

Tesla-type turbomachinery probably cannot prove competitive in an application in which more conventional machines have adequate efficiency and performance. Thus, they cannot be expected to displace conventional water pumps or conventional water turbines or gas turbines. Tesla-type turbomachinery should be considered in applications in which conventional machines are inadequate. This includes applications for small shaft power, or the use of very viscous fluids or of non-Newtonian fluids. There is some reason to believe that multiple-disk turbomachines can operate with abrasive two-phase flow mixtures with less erosion of material from the rotor. For that reason they should be further investigated for applications to produce power from geothermal steam and particle-laden industrial gas flows. There may also be unique applications possible using ceramic disks. There is considerable evidence that multiple disk turbomachinery can be quieter in operation than is conventional machinery and that the noise is more nearly "white" without a prevailing sound signature. Multiple-disk pumps are well-known to resist cavitation (20, 49). It is the only type of turbomachinery that can be easily constructed in a relatively primitive machine shop.

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Nomenclature

h	spacing between disks
r	general radial coordinate in space between disks
r_i	inner radius of disk
r_o	outer radius of disk
Q	volume flow rate between two disks
$\overline{u}$	average (disk-to-disk) radial component of velocity
$\overline{v}_o$	average (disk-to-disk) tangential component of velocity, at outer radius of disk
ν	kinematic viscosity of fluid
μ	viscosity of fluid
Ω	angular velocity of pair of disks
ρ	density of fluid

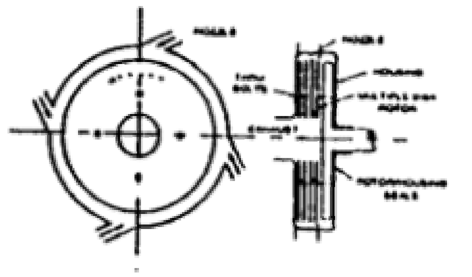

Figure 1 Schematic diagram of a Tesla-type turbine

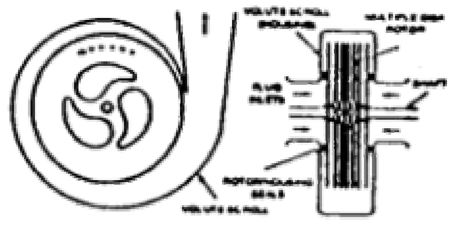

Figure 2 Schematic diagram of a Tesla-type pump

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