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The fluid dynamics of the rotating flow in a Tesla disc turbine

Abhijit Guha *, Sayantan Sengupta

Mechanical Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur 721302, India

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ABSTRACT

The flow induced by rotating discs has attracted some of the greatest minds in fluid dynamics like von Kármán and Batchelor, and still is a vigorously active research area. In comparison, the available analysis of the rotating flow in the narrow gaps among closely-spaced co-axial multiple discs of a Tesla turbine, which produces power, is limited. In this paper a simple theory has been presented that describes the three-dimensional fields of velocity and pressure in the Tesla disc turbine. The theory gives the torque and power output which have been verified by comparing the theoretical predictions with recently published experimental results. The governing conservation equations have been cast in a form that makes it possible to formulate analytical solutions and to develop clear physical interpretation for each term in the equations. Thus the roles of each of the centrifugal, Coriolis, inertial and viscous forces in generating torque and power, and in establishing the pressure field have been comprehensively investigated and explained here. This physical exposition of the rotating flow in a Tesla disc turbine has been achieved for the first time in the present paper. Several subtle flow physics and fluid dynamic behaviors have been elucidated. As an example, it is shown here that a Tesla disc turbine may generate net torque and power even when the tangential fluid speed at the disc periphery is less than the local tangential speed of the disc. The subtle role of the Coriolis acceleration in establishing such flow conditions, which involve flow reversal and complex pathlines, has been explained.

1. Introduction

The Tesla disc turbine is a kind of turbo-machinery in which the rotor is constructed by a series of co-axial, parallel flat discs rather than blades. This bladeless turbine was invented by the famous scientist Nikola Tesla [1]. The discs are arranged such that a small gap is maintained between any two successive discs, and they are attached to a central shaft. The combination of discs and shaft is placed inside a cylindrical casing with a small radial and axial clearance. One or more nozzles are used to guide the working fluid to enter nearly tangentially from the periphery of the discs. There are exit ports near the shaft at the center of each disc. As the fluid passes through the narrow gaps between the discs it approaches in a spiral path (usually, but see the new findings regarding complex non-spiral relative pathlines in Section 4). The working fluid travels from the inlet up to the central exit due the difference of pressure between the periphery and the central exit, and the component of inward radial velocity. The radial velocity gradually increases towards the central exit due to the gradual decrease of flow area. On the other hand, from inlet to exit, the tangential velocity may increase or decrease, depending on the local balance of various components of forces (see Section 3).

Initially the Tesla turbine did not have much commercial success and eventually succumbed to other emerging types of turbines. Research into Tesla turbines has however been conducted since the 1950s [2,3] and recently there has been a resurgence of interest [4]. The main disadvantage of the Tesla disc turbines is that the present values of their efficiency are lower than that of conventional turbines. Tesla turbines, however, have several advantages (mentioned below) and may find niche applications in the future. Moreover, it is hoped that the current surge of research would improve the efficiency of the disc turbines – reference [5], for example, has developed an improved design of the nozzle, greatly improving the efficiency and achieving uniformity in the velocity profile of the jet. (The loss in the nozzle is generally recognized [3,6] as a major source of loss in a conventional Tesla turbine.)

The Tesla disc turbine is simple to manufacture and is less expensive. It is capable of generating power for a variety of working media like Newtonian fluids, non-Newtonian fluids, mixed fluids and particle-laden two-phase flows (many aspects of two-phase flow may be found in Refs. [7–11]). The turbine has a self-cleaning nature due the centrifugal force field. This makes it possible to operate the turbine in case of non-conventional fuels like biomass which produce solid particles. It also suggests that this bladeless turbine may be well suited to generate power in geothermal power stations [12].

* Corresponding author. Tel.: +91 3222281768; fax: +91 3222282278.
E-mail addresses: a.guha@mech.iitkgp.ernet.in, guha.a@rediffmail.com (A. Guha).

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Nomenclature

$a_{C,\theta}$	θ-component of Coriolis acceleration
$a_{C,r}$	r-component of Coriolis acceleration
$a_{CF,r}$	r-component of centrifugal acceleration
$a_{F,\theta}$	θ-component of viscous acceleration
$a_{F,r}$	r-component of viscous acceleration
a_H	$\equiv \frac{V_r V_\theta}{r}$
$a_{I,r}$	r-component of inertial acceleration
b	Gap between the two discs
k	Isentropic coefficient of fluid
p	Pressure
P	Modified pressure $= p - \rho g_z z$
p'	Non dimensional pressure $= \frac{p-p_2}{\rho\Omega^2 r_2^2}$
r	Radial coordinate
R	Radius ratio $= \frac{r}{r_2}$
U	Absolute velocity of fluid
V	Relative velocity of fluid
$\dot{W}_{th}$	Theoretical ideal power output
$\dot{W}_{loss}$	Overall loss in Tesla turbine
$\dot{W}_{act}$	Theoretical power output with loss
z	Axial coordinate
γ	Tangential speed ratio $= \frac{\overline{U}_{\theta 2}}{\Omega r_2}$
$\Delta\tilde{\bar{V}}_\theta$	$\equiv \frac{(\bar{V}_\theta - \bar{V}_{\theta 2})}{\Omega r_2}$
Δp_{ic}	Pressure drop between inlet and central exit of the rotor
ζ	Non dimensional average relative tangential velocity $= \frac{\overline{V}_\theta(r)}{\overline{V}_{\theta 2}}$
ζ_m	Modified ζ
θ	Azimuthal direction in cylindrical coordinate system
μ	Viscosity of the working fluid
ν	Kinematic viscosity of working fluid (here the fluid is air)
ξ	Non dimensional average relative radial velocity $= \frac{\overline{V}_r(r)}{\overline{V}_{r2}}$
ρ	Density of the working fluid
τ_w	Wall shear stress on one side of a single disc
ϕ_2	$\equiv \frac{\overline{V}_{r2}}{\Omega r_2}$
Ω	Rotational speed of the disc
Ω_{steady}	Steady state rotational speed of the disc
$\Im$	Torque on one side of a single disc
$\Im_{tot}$	Total torque

Subscripts

r	Component along the r direction
z	Component along the z direction
θ	Component along the θ direction
1	Central exit of the rotor
2	At rotor inlet

Overbar

$\overline{(\,)}$	z-averaged (z varies from 0 to b) flow variables

In this paper a theory is described that gives the three-dimensional fields of velocity and pressure in the Tesla disc turbine. The presented theory also gives the torque and power output which have been verified by comparing the theoretical predictions with recent experimental measurements [13]. (All experimental results and numerical illustrations of the theory given in this paper are for air as the working fluid.) By a systematic order of magnitude analysis, the dominant terms have been retained in the governing conservation equations. This has made it possible to formulate analytical solutions and to develop clear physical interpretation for each term in the equations. Thus the roles of each of the centrifugal, Coriolis, inertial and viscous forces in generating torque and power and in establishing the pressure field have been comprehensively investigated and explained here. This physical exposition of the rotating flow in a Tesla disc turbine has been achieved for the first time in the present paper.

1.1. Previous work on Tesla disc turbines and related issues

Rice [6] in his article "Tesla turbomachinery" had described the advances of research (up to 1991) in the field of the Tesla turbine. There are two old approaches which are worth mentioning: the truncated series substitution methodology [14] and the bulk parameter analysis [15,16,3]. The problem of using truncated series substitution methodology is its lower accuracy; the bulk parameter approach is not useful because of the inadequacy of the friction factor concept [6]. A simple but very effective method for measuring the net power output and overall loss (the bearing and other losses), called the "angular acceleration method", has been developed and fully described by Hoya and Guha [4]. This proved to be a successful method for overcoming many difficulties associated with the determination of very low torque at very high angular speed. The reference gives detailed measurements and operational experience for Tesla disc turbines. It has previously been recognized that the performance of the nozzle and the inlet is a limiting factor for the overall efficiency of such turbines. Rice [6] wrote: "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. [...] As a result, only modest machine efficiencies have been demonstrated". Through a systematic study of the major sources of loss, Guha and Smiley [5] developed a new design of nozzle-inlet assembly that reduces the loss tremendously and substantially improves the uniformity of the velocity profile in the jet. The analysis and design [5] therefore addresses and solves a major issue in the design of Tesla disc turbines that seems to have seriously affected their development for over 50 years.

Several studies have been conducted in the past two decades on various aspects of Tesla disc turbines.[1] Couto et al. [17] presented a simple calculation procedure for estimating the number of discs required inside the Tesla turbine to accomplish a prescribed job. Their calculation is based on the estimation of boundary layer thickness of the rotating fluid on the rotating disc. They assumed that for laminar flow $\delta \approx 5\sqrt{\nu(r_2 - r_1)/U_\theta}$ (δ is the boundary layer thickness) though using the absolute tangential velocity for calculation of the boundary layer thickness for a relative rotational reference frame may not be appropriate. Furthermore their calculation had no experimental or numerical verification. Valente [18] claimed that a Tesla turbine can be used successfully in gas liquefaction plants for pressure reduction of hydrocarbon gases. According to them gas liquefaction can be done nearly isothermally by the use of a Tesla turbine. Deam et al. [19]

[1] One of the reviewers has drawn our attention to some performance curves of Tesla disc turbines that are available on the Web: numerical results of Tahil are available at http://www.stanford.edu/~hydrobay/lookat/tt.html#ref1b, and experimental results of Lezsovits on a Tesla turbine working on biomass fuel are available at http://mycite.omikk.bme.hu/doc/40405.pdf. Details of the numerical or experimental procedure are however not given and these results have not been formally published.