



Influence of geometry on the efficiency of convergent–divergent nozzles applied to Tesla turbines



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ABSTRACT

Convergent–divergent (CD) nozzles were designed and manufactured to improve the injection efficiency of the working fluid in Tesla turbines. Ten nozzles have been designed using two different techniques: a one-dimensional approach and a two-dimensional approach with the method of characteristics. All nozzles had rectangular geometry at throat, while 3 had divergent section planar and 2 divergent section circular, considering each mass flow rate (55 and 70 kg h⁻¹). Nozzles were analyzed using air as the working fluid. A nozzle exit to throat area ratio (NAR) of 1.35 was used in all nozzles, while the nozzle pressure ratios (NPR) ranged between 2.15 and 3.25. At planar nozzles an $(x/H)_{\text{exit}}$ of 2.1 was more suitable for decreased of total pressure losses, while at circular nozzles the shock waves were canceled inside of divergent section.

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1. Introduction

Macroeconomic growth of a nation depends of its energetic infrastructure. Thus, the development of renewable energy is important against the increasing global energy consumption. Conventional turbines for the production of work using superheated steam as working fluid. Condensation of steam can cause damages the turbine blades, which limits their application with saturated steam. An alternative to micro-power generation (up to 250 kW) is to use Tesla machines, which are simpler than conventional turbines and allow operation in the presence of water droplets (condensation). The overall performance of Tesla turbines can be increased through the development of more efficient nozzles [31]. Tesla turbines have a simplified mechanical structure compared to conventional turbines, which represents lower manufacturing costs and maintenance. With the proper design of the nozzle, this type of turbine can achieve yields similar to those found in conventional turbines for micro-power generation.

1.1. Tesla turbine

Tesla turbines were designed by Nikola Tesla in 1910. Nikola Tesla produced three prototypes of the Tesla turbine in partnership with the American company Allis Chalmer Manufacturing Company, Milwaukee, USA. The largest turbine built was designed for

a thermal power of 500 kW. Turbine had 60 disks of 1.5 m in diameter and rotation of 3600 rpm. Saturated steam at 550 kPa was used as the working fluid. The main difficulty observed in the tests was the stretching radial of the disks [5]. Radial elongation seen in Tesla's experiments inhibited the development of these machines by many years. The advancement of metals technology renewed interest in the development of turbomachinery based on the principle proposed by Tesla. Basically, Tesla turbines (Fig. 1) consist of parallel metal discs assembled with a minimum spacing. The discs are coupled on a shaft, constituting the rotor element. The discs are covered with a cylindrical housing, which is called the stator of the turbine.

The discs have holes near the center to allow the exhaust of the working fluid. Working fluid is injected tangentially to the discs by a suitable nozzle. Nozzles used in a Tesla turbine generally has a rectangular geometry at throat, and has the function of uniformly distributing the working fluid between the turbine discs. Fig. 2 illustrates the typical positioning and shape of nozzles in a Tesla turbine.

Over the years, researchers have concentrated their efforts on the efficiency of the rotor and the flow regime between the turbine discs [15,7,14], and little attention was paid to other important elements of the turbine, especially the injector nozzle. The injector nozzle is cited as a major cause of low efficiencies of Tesla turbines [30,32,4,22,10,12]. Schmidt [32] conducted experiments to evaluate the performance of the Tesla turbine for power generation from biomass combustion. In the experiments was used a Tesla turbine made of 304L stainless steel with 45 discs of 0.3 m in diameter, with a spacing of 1.5 mm between the discs, a disc thickness of 1.5 mm, a nominal velocity of 10,000 rpm and an electrical power

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of 50 kW. The authors concluded that it is possible to use the exhaust gases from the combustion of biomass in Tesla turbines because no significant degradation in the turbine was observed in the experiments. Soot deposits were found in the rotor components, but no soot accumulation was found in the turbine housing. The overall yield (turbine + nozzle) was 11% with gases exhausted from the combustion of biomass and 13.7% using saturated steam as the working fluid. Guha [12] analyzed the performance of a convergent nozzle developed for Tesla turbines. The author suggested the use of a stagnation chamber upstream of the injector nozzle to minimize the effects of turbulence. The author reports that due to the small length of the injector nozzles, friction losses are very small. With the turbulence minimized upstream of nozzle, the flow downstream of nozzle becomes more uniform.

1.2. Convergent–divergent (CD) nozzles

Convergent–divergent (CD) nozzles are used to increase the kinetic energy of fluid in several applications. Occurrence of shock waves and the expansion of the fluid in the nozzle compromise its effectiveness and, consequently, the overall yield (turbine + nozzle) [40].

When a shock wave interacts with a boundary layer, diverse types of flow phenomena occur: flow separation, unsteadiness, complicated mixing, turbulence, shock induced boundary layer separation, and so on [35].

For lower nozzle pressure ratio (NPR-ratio of inlet to outlet pressure), a normal shock appears in the divergent section of the nozzle. As the NPR is increased, the flow separates due to adverse pressure gradients and the shock bifurcates in the form of a lambda shape, which consists of an incident shock, reflected shock, and Mach stem (Fig. 3). The point of co-incidence of these shocks is known as triple point. The incident shock turns the flow away from the wall whereas the reflected shock tries to turn back the flow to the original direction. The flow behind the Mach stem is subsonic because of the normal shock. However, the flow behind the reflected shock is still supersonic [34].

When the static pressure is increased, an adverse pressure gradient can cause the boundary layer to detach from the nozzle wall surface. This increase in static pressure, which contributes to increased potential energy of gas, thereby decreases the flow kinetic energy. At higher NPRs, the flow separates asymmetrically, where one lambda foot is larger than the other. Asymmetric flow

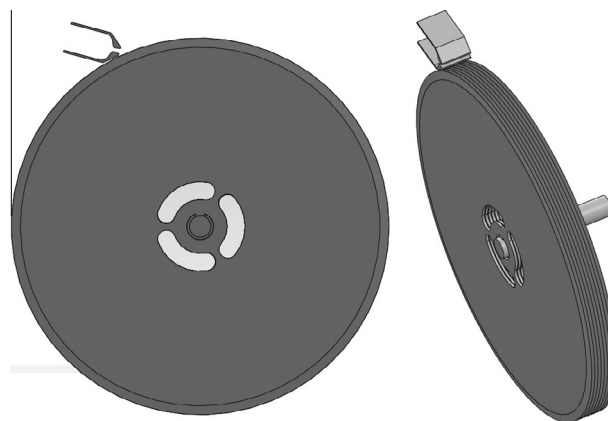


Fig. 2. Positioning of the nozzle in a Tesla turbine.

separation was predicted by Xiao et al. [36,37] for NPR between 1.5 and 2.4, depending upon the initial flow field. For higher NPRs ($\text{NPR} \geq 2$), Hunter [16] analyzed that the separation is not a result of a stronger shock-wave/boundary-layer interaction, but it comes through the natural tendency of an overexpanded flow.

Supersonic flow separation in a CD nozzle results in instability of the plume exiting the nozzle [26]. The phenomenon of supersonic nozzle flow separation is deemed responsible for the instability. Papamochou and Johnson [26] suggests that the instability mechanism is due to an interaction between the expansion fan reflected from the smaller lambda foot with the shear layer of the larger separation zone. The proposed mechanism is shown in Fig. 4.

The instability causes the exhaust gas to lose the build up fluid kinetic energy, hence decelerate flow speed, and decreasing the overall thrust [8].

Considering a supersonic gas jet issuing from an orifice into still air, there are various different interactions which can occur depending of NPR. In the case of overexpanded supersonic jets the pressure at the exit plane is lower than the ambient pressure into which the jet is issuing, while if the exit plane pressure is higher than the ambient pressure there is an underexpanded flow. As the NPR increases the flow becomes overexpanded, uniform (design condition) and finally underexpanded.

Several studies have been carried out on the flow in rectangular supersonic CD nozzles. A two dimensional CD nozzle with rectan-

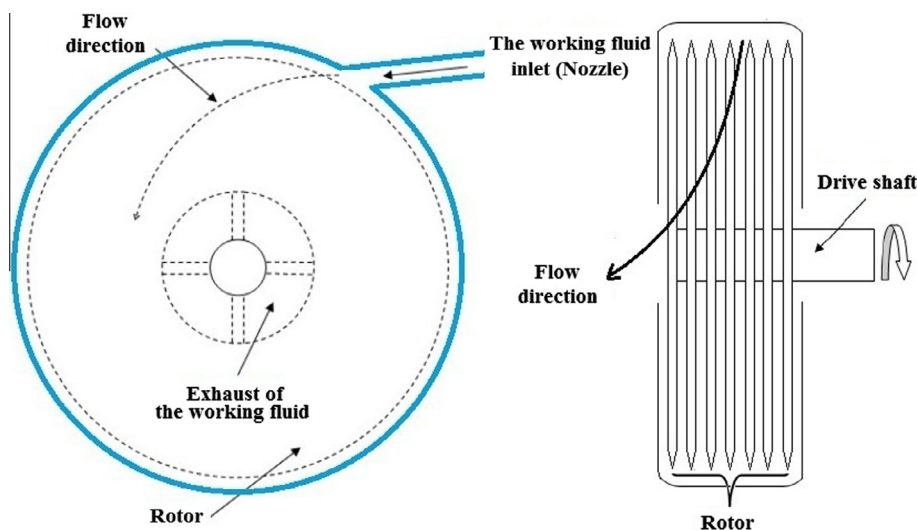


Fig. 1. Schematic drawing of a Tesla turbine.

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