Stator Blade Design of an Axial Turbine using Non-Ideal Gases with Low Real-Flow Effects

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Abstract

The rising requirements for efficient energy recovery systems have led to an increasingly greater research of ORC systems. The reduction of CO2 emissions, the restricted use of fossil fuels and the enhancement of sustainable energy sources are the most important advantages of this technology. These systems function with the use of organic gases, like it can be understood from their name. The main characteristic of these gases is their large density, which means that their thermodynamic parameters vary in a different way compared to an ideal gas. Taking into account that the turbine constitutes the most important part of an ORC system, and in combination with the requirement of supersonic flow within the turbine, it is obvious that its design is a complex subject. This paper aims to investigate both the existence of a correlation between the working fluid and the geometry of the stator in an ORC system that functions with low real-flow effects gases, and the creation of a computational tool, which depending on the working fluid, will produce the preliminary geometry of a two-dimensional blade. In order to design the stator, an innovative method was used based on supersonic nozzles. For the design of the supersonic nozzles, the method of characteristics was chosen. The geometry that occurred, was checked with the use of an algorithm that solves the Euler equation system numerically. The most important advantages of the procedure described above are its simplicity as well as the precision of the provided results.

1. Indtroduction

The tendency to solve environmental issues and the ever-growing demand for electrical energy has led to the search for low-grade heat sources such as industrial waste and solar energy [1]. The Organic Rankine Cycle (ORC) is one of the most effective technical approaches for the conversion of renewable energy into electricity [2]. The ORC outweighs the steam cycles because of the ORC's high thermodynamic performance, specifically in the case of conversion of low temperature energy sources. Additionally, their low cost, high reliability and small size, have increased their demand

From the second law of thermodynamics, we gather that the lower the temperatures of heat sources, the lower the thermodynamic efficiency coefficient. Therefore, the use of the so called ORC fluids is necessary. These are dense fluids, with high molecular complexity, low boiling point and are affected by real-gas effects. Dense gases are defined as the vapors which are, in thermodynamic conditions, near the saturation curves. They are characterized by complex molecules and medium to large molecular weights. When the thermodynamic conditions are such that the pressure and density are low, any gaseous substance that is in the thin gas region can be described by the equation of state for ideal gases:

P=ρRT------(1)

However, in many applications of turbomachinery, like the ORC systems, the thermodynamic conditions of the working fluid are near the critical point and the real gas effect, resulting from the nonlinear molecular interactions, are not negligible. In this case, the above equation is modified with the introduction of a compressibility factor Z=p/ρRT, which is always less than 1 for real gases and calculates the divergence from the behavior of ideal gas for which Z=1 [3]. For a fluid, the compressibility factor can be calculated as a function of reduced thermodynamic properties (i.e. their normalization in relation to the properties of the critical point). The above is true for relatively simple molecular models. The dynamics of dense gases can be described through the fundamental derivative, as it is shown below

$$\Gamma = \frac{c^4}{2u^3}\left(\frac{\partial^2 u}{\partial p^2}\right)_s = 1 + \frac{\rho}{c}\left(\frac{\partial c}{\partial \rho}\right)_s \qquad \text{----------2}$$

In this paper, gases whose fundamental derivative Γ is close to 1 are studied. These gases are affected by the phenomena that occur from real flows and are called low real-flow effect gases. Investigating the thermodynamical curves and based on preexisting experimental data [5], there is a plateau in which the values of fundamental derivative, the specific heat ratio and the compressibility factor are constant for a particular temperature range. The aim of this investigation is therefore, to development of a fully adaptive computational tool which gives the opportunity to any user to design a Stator Blade of an ORC turbine depending on the working fluid. Until now, there is not any robust computational tool for Stator Blade of an ORC turbine

Supersonic Nozzle Design The most widespread technique in order to design the divergent part of supersonic nozzles, assuming two-dimensional flow, is MOC. As shown in Figure 1, there are two characteristic lines which run through every grid point. The slope of these lines is defined by the next equation [6]:

$$\left(\frac{dy}{dx}\right)_{char} = \tan(\theta \pm \mu) \qquad \text{----(3)}$$

It should be noticed that the sign + or − denotes a left-running or a right-running characteristic line, respectively. In the case of a dense gas, to which the influence of real-gas effects is quite low, is permitted to use the above equations in order to create a divergent nozzle. That means that the investigated gas has constant value of specific heat ratio in the operating conditions.

Considering the problem of nozzle configuration, a divergent nozzle is designed to expand a gas from sonic speed to a given supersonic Mach number at the exit Me. Using the Method of Minimum Length Nozzle, an attempt is made to create a robust tool avoiding any process of determining the expansion length. Figure 2 shows all the necessary parameters, which have to be calculated in order to produce the geometry shown below. Indicatively, the maximum angle θ*, for a known Me, is defined by

2.Numerical Solution of Euler Equations

Under the approach of the preliminary design of the stator blade, the flow is considered ideal (no friction exist). This approach is made because the solution of Navier-Stokes equations is computationally more difficult and the process of the solution requires much more time [9]. In addition, the Euler equations can cover many of the basic mechanisms of fluids. Therefore, in order to validate the produced geometry and have a better picture of how the flow parameters change, it is necessary to create an algorithm which applies the method [10]. The two-dimensional Euler equations, which are solved in the grid points [11], can be written in conservative form as:

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}=0$$

Where,

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ e\end{bmatrix},\quad E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (e+p)u\end{bmatrix},\quad F=\begin{bmatrix}\rho u\\ \rho uv\\ \rho v^2+p\\ (e+p)v\end{bmatrix}$$

3.Stator Blade Design

With the approach of the preliminary design of a two-dimensional blade (stator) for ORC, the design of the vane described below is not the optimal design and optimization of the blade geometry is not analysed as part of this paper. The generated blades profile provide an initial geometry, through which some basic principles of flow and the compatibility of the MOC can be explored. The design methodology is shown in figure 3: The supersonic blade vanes, are obtained by the post-processed nozzle geometry, which is generated using MOC [12]. Knowing the main turbine geometrical characteristics, such as the axial chord ch and the stager angle ω (figure 3), the blade vane is designed in the following way: the suction side (d-e') is obtained by rotating the MOC nozzle geometry by angle ω in clockwise direction. The leading edge (d-b) is designed as a circular arc with radius R, an angle ϕ controls the angular extension of the pressure side part of leading edge (c-b). Then, given ch, the point e is defined by the slope of the last two points of the MOC nozzle as a straight line. The pressure side (b-a) is designed as a third order polynomial verifying the constraints given by the end-point coordinates (a)-(b). The aft part (a-f) is determined by rotating the other side of MOC nozzle geometry by an angle θ in clockwise direction and set it in point f. Finally, a radius r is selected to determine the thickness (f)-(e) in order to obtain the trailing edge.

.Results Analysis and Discussion

Both the MOC algorithm and CFD [13], [14] code previously described are applied in order to quantify the variability of the nozzle shape geometries and performances under variable operating conditions. Three types of gases (CO2, isobutane and R134a) have been selected. The gases were selected based on the following characteristics; the selection criteria were high molecular weight and compressibility factor equal to one for the point of operation. Furthermore, a crucial parameter that was taken under consideration, was the decreasing Gas Constant number in order to investigate the variation of the blade shape. On the following table, gas properties are determined [15]. Total pressure is needed due to the procedure of the Numerical solution of Euler equations

Conclusions

In this paper, the dense dynamics of low real-gas effects of ORC axial turbines were investigated. A modern method for designing stator blades for ORC turbines is discussed. The determination of the stator vane performance of an axial ORC turbine is applied using a numerical computational method in order to solve the equations of Euler

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