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Numerical second law analysis around a turbine guide vane using a two-equation turbulence model and comparison with experiments

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ABSTRACT

The present investigation considers determination of entropy production from the flow field around a turbine guide vane, and the numerical simulation of this flow field by means of Computational Fluid Dynamics (CFD). These CFD simulations are based upon RANS, the Reynolds Averaged Navier-Stokes equations, and are carried out using ANSYS CFX-14.0 and the Shear Stress Transport (SST) turbulence model. The flows around the vane from an experimental investigation are simulated for three vane Mach number distributions, each of which is characterized by a different vane trailing edge Mach number. To obtain entropy production from the numerical flow field, two approaches based on second law analysis are utilized: a *conventional* and a *differential* one. The *conventional approach* describes global entropy production between two thermodynamic states by calculating it from the total pressure loss inherent to irreversible processes. The *differential approach* makes use of the entropy transport equation and yields local entropy production rates directly from local flow field variables predicted by CFD. Global entropy production is then determined by integrating local exergy destruction rates along pathlines, with respect to time. Global exergy destruction results for the wake of the guide vane, obtained using the pathline integration approach, are compared with results from the conventional method analysis and from experimental measurements. The comparison of both numerical approaches with the experiments thereby also serves the purpose to validate them. The most important differences between both numerical methods and the experiments are an under-prediction of maximum exergy destruction near the center of the wake, and an under-prediction of the width of the exergy destruction profile by the pathline integration approach. These differences are believed to be because: (1) the numerical model does not correctly account or include all diffusive effects, which are present within the experimental arrangement, and (2) the sensitivity of the pathline-integration approach to the accurate prediction of the course of pathlines through the flow field.

1. Introduction

One of the most important challenges in designing turbomachinery components is the minimization of any and all types of losses which result in lost energy and reduced performance. As a result, considerable research has been directed toward loss minimization for optimization of aerodynamic designs, and increased overall operating efficiency. One means to characterize associated losses is by means of anergy, which represents the residual energy that cannot be converted into useful work. Anergy is then also related to entropy production. For certain flow situations, entropy production is then the same as exergy destruction, where exergy describes the amount of energy that can be extracted from a thermodynamic system as useful work. All irreversible processes thus convert exergy into anergy, and hence, cause a loss of available work. Note that the consideration of such losses is the advantage of second law methods compared to first law methods, which can only account for energy balances but cannot describe loss mechanisms.

In order to minimize exergy destruction, minimize irreversibilities, and convert fluid energy efficiently, it is essential to design turbomachinery components with minimal second law losses associated with aerodynamics. The most common of these aerodynamics losses are generally a result of expansions, compressions,

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Nomenclature

Latin

C	True chord (m)
C_{ax}	Axial chord (m)
C_μ	Model constant (–)
c_p	Specific heat capacity ($JK^{-1}kg^{-1}$)
Ec_τ	Friction Eckert number (–)
$F_{scaling}$	Factor viscous scaling (–)
h	Channel height (m)
K	Turbulence kinetic energy (m^2s^{-2})
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
Ma	Mach number (–)
P	Locations on pathline
p	Static pressure (Pa)
R	Ideal gas constant ($JK^{-1}kg^{-1}$)
Re_τ	Friction Reynolds number (–)
s	Specific entropy ($JK^{-1}kg^{-1}$)
T	Static temperature (K)
T_τ	Friction temperature (K)
T_W	Wall temperature (K)
Tu	Turbulence intensity (–)
t	Time (s)
u_1, u_2, u_3	Velocity components (ms^{-1})
u_τ	Friction velocity (ms^{-1})
V	Velocity magnitude (ms^{-1})
w_{loss}	Global exergy destruction (Jkg^{-1})
x, y, z	Spatial directions (m)

Greek

γ	Flow turning angle (°)
θ	Dimensionless temperature (–)
ν	Kinem. viscosity (m^2s^{-1})
ρ	Density (kgm^{-3})
σ_{ij}	Viscous stress tensor (m^2s^{-2})
τ_W	Wall shear stress ($kgms^{-2}$)
ω	Dissipation rate (s^{-1})

Subscripts/Superscripts

Diss	Dissipation
Heat	Heat conduction
ex	Vane passage exit
turb	Turbulent
t	Total value
$+$	Dimensionless wall coordinates
0	Ambient value
$\overline{\quad}$	Mean value
$'$	Fluctuating value

Acronyms

CFD	Computational Fluid Dynamics
EXP	Experimental Results
GCI	Grid Convergence Index
PS	Pressure Side
RANS	Reynolds-averaged Navier-Stokes
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
SS	Suction Side

boundary layer development, wake development, viscous dissipation, shear, and flow friction, acting individually or in combination with each other. In the present study, such losses are analyzed through determination of entropy production and exergy destruction, both from a rate perspective and from a global or integrated perspective. Furthermore, it is also a goal of this study to validate these two methods by comparing them to experimental data.

Only a few other recent investigations consider the usefulness of the second law of thermodynamics for such analysis of aerodynamic flow losses. One reason for this usefulness is that the assessment of loss in terms of the entropy generation rate is not dependant on whether it is examined from the perspective of a stationary or rotating blade row. As a result, this approach enables direct comparison between measurements from cascades and rotating facilities for the case of isentropic processes [1]. Also valuable are estimations of lost work potential because they provide direct representations of energy losses from exergy destruction. Several recent studies address entropy generation as related to cascade efficiency and overall turbomachinery design [2,3]. Other recent studies address entropy production in shear layers and boundary layers [1,4–6], including aerodynamic entropy generation from boundary layers with augmented freestream turbulence levels [1]. Entropy generation minimization is also used for thermodynamic optimization of fluid flow systems, and as such, is applied to systems ranging from simple heat exchangers to gas turbine engines [3,5,6].

In the past decades, the increasing use of Computational Fluid Dynamics (CFD), led to the development of various models and methods to determine entropy production from numerical flow field data. Naterer and Camberos [7] present a detailed overview of studies dealing with entropy and second law thermodynamics in CFD simulations. Adeyinka and Naterer [8], for example, determine entropy production for convective heat transfer flows, and Sciubba [9] deals with the calculation of entropy from CFD for improving turbomachinery designs. Moore and Moore [10] were the first ones developing a numerical model for entropy production in turbulence. Later on, Adeyinka and Naterer [11] present an approach of modeling turbulent entropy production by applying Reynolds averaging to the second law of thermodynamics for turbulent flow. This model, however, requires instantaneous values of temperature and velocity and can hence only be used with Direct Numerical Simulation (DNS). In contrast, Kock and Herwig present a method to determine entropy production from RANS-based turbulent numerical flow fields, which allows for the determination of entropy production for industrial applications [4,12].

The present investigation considers the determination of entropy production from the flow field around a turbine guide vane [13], and the numerical simulation of this flow field by means of CFD — Computational Fluid Dynamics. These CFD simulations are based upon RANS, the Reynolds Averaged Navier-Stokes equations, and are carried out using ANSYS CFX-14.0 and the Shear Stress Transport (SST) turbulence model. The flow field is selected to match that within the turbine vane experiments described by Ligrani and Jin [13] and by Zhang and Ligrani [14]. Flows around the vane from this experimental investigation are simulated for three vane Mach number distributions, each of which is characterized by a different vane trailing edge Mach number. Of particular interest is the determination of entropy production from the numerical flow field, using a conventional and a differential second law analysis approach. Here, the conventional approach determines global entropy production between two thermodynamic states by