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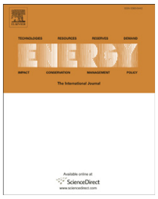

Investigating the entropy generation in condensing steam flow in turbine blades with volumetric heating

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ABSTRACT

In the last stages of steam turbines, the existence of the liquid phase results in wetness losses. This study intends to analyze the effect of volumetric heating on condensing steam flow in the stationary cascade of turbine blades and the losses associated with wetness. Numerical simulation of a turbulent flow of wet steam in the cascade of turbine blades was conducted based on two phase Eulerian-Eulerian description and SST k - ω turbulence model. Numerical solution results show a consistency with experimental data in the adiabatic cases. An agreement was also shown between the numerical solution and analytical solution results in the presence of heat transfer. The numerical results proposed that by applying volumetric heating to the convergent section, the wetness fraction in the cascade of turbine blades can be reduced which prevent corrosion losses. As volumetric heating is increased to $2.0 \times 10^5 \left(\frac{\mathrm{kW}}{\mathrm{m}^2}\right)$, the entropy generation is ascending; while as the liquid phase disappears and the entropy generated from the liquid is eliminated at $3.55 \times 10^5 \left(\frac{\mathrm{kW}}{\mathrm{m}^2}\right)$, the entropy generation shows a descending trend which ascends again by increasing volumetric heating. Hence, applying an appropriate volumetric heating can prevent the corrosion associated with the liquid phase and control total entropy generation.

1. Introduction

During the course of steam expansion in turbine blades, the vapor first supercools and then nucleate to form a two phase mixture. The liquid phase in the steam flow causes thermodynamic, aerodynamic and mechanical losses, affecting the last stages of the turbine which thereby reduces turbine efficiency. The efficiency drop is approximately considered 1% for each percent of wetness fraction. Since more than 80% of world electricity is generated in fossil fuel and nuclear plants, the existence of wetness in the low pressure stages of the steam turbine results in massive energy loss in the world. Therefore, further research is expected to lead to an improved design.

In recent decades, numerous studies have been conducted to understand the nucleation and droplet growth in nozzles and steam turbines. In this regard, Moore et al. [1] performed an experimental study on condensing flows in nozzles. The study provided more accurate information about the homogeneous nucleation process. These experimental data corroborate either nucleation theories or numerical solutions of condensing flows in nozzles and steam turbines. In addition, Bakhtar et al. [2] showed that although the classical nucleation theory provides accurate qualitative data to predict the process of nucleation in a steam nozzle, it offers relatively lower predictability information. Therefore, to develop the classical nucleation theory, various corrections have been made to the classical nucleation equation, including Courtney [3] and Kantrowitz [4] corrections providing fairly accurate results in a wide range of pressures.

There are currently different growth models proposed by various authors. In this context, the Hertz – Knudsen model [5,6] is based on the kinetic theory of gases. In this model, the growth rate of droplets is proportional to the difference in the collision rate of the molecules with the surface of droplets, and the rate of evaporation from the droplet surface. Also, a model for droplet growth with the basis of heat transfer conditions surrounding the droplet was proposed by Young [7], which was used by many researchers.

Bakhtar and Zidi [8,9] to experimentally and numerically investigate the effect of condensing flows in steam turbines. Yousif et al. [10] was also aimed to numerically analyze the homogeneous

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Nomenclature

A	area (m^2)
C_p	specific heat of liquid, (J/kg K)
C_v	vapor isochoric specific heat, (J/kg K)
E	total energy, (J)
G	bulk Gibbs free energy change, (J/kg)
h	static enthalpy, (J/kg)
I	nucleation rate, (1/m^{3}s)
K_b	Boltzmann's constant
K_t	thermal conductivity, (W/m K)
m_r	liquid mass, (kg)
M_m	molecular mass, (kg/mol)
P	Pressure, (Pa)
q_c	condensation coefficient
Q	Volumetric heating rate, (kW/m^2)
r	droplet radius, (m)
$\bar{r}$	average radius, (m)
R	gas constant, (J/kg K)
S	Entropy, (J/kg K)
t	Time, (s)
T	Temperature, (K)
$u,\ v$	velocity components, (m/s)
w	wetness fraction
x	cartesian direction, (m)

Greek symbols

ρ	density, (kg/m^3)
η	number of liquid droplets per unit volume, (1/m^3)
μ	dynamic viscosity, (Pa s)
τ	viscous stress tensor, (Pa)
θ	non-isothermal correction coefficient
σ	liquid surface tension, (N/m)
Γ	mass generation rate, (kg/m^3 s)
β	liquid phase mass fraction

Subscript

l	liquid
v	vapor
mix	mixture
lv	liquid-vapor
s	saturation
g	gas

Superscript

$*$	critical condition

unstable condensation in the transonic steam of a low pressure turbine throat. Moreover, Dykas et al. [11] performed a similar study on condensing steam flow in the nozzle and between the turbine cascades. Multiphase model based on the Eulerian-Eulerian method for transonic turbulent steam flow was used by Gerber and Kermani [12]to study wetness distribution in a Laval nozzle and around the rotor tip of a steam turbine. In addition, Wróblewski and Dykas [13] investigated the parameters of condensing flow in a Laval Nozzle by using a double-fluid model. In another numerical study, Nikkhahi et al. [14] analyzed the effect of pressure change on the two-phase steam flow around the rotor tip of a two-dimensional turbine. Their results showed that the highest condensation occurs on the suction side which decreases as the downstream pressure drops. An analytical study made by Amiri et al. [15] determined the simultaneous effect of inlet static pressure and volumetric heating on the supersonic two-phase flow in a one dimensional convergent divergent nozzle. Mahpeykar et al. [16] analyzed the effect of local cooling on controlling the unfavorable effects of condensing shock in the wet steam flow in a one-dimensional convergent divergent nozzle in a theoretical study. Furthermore, Amiri and Kermani [17] and colleagues used an unstable thermodynamic model by employing an Eulerian-Eulerian method for studying the effect of supercooling degree on the aerodynamics of steam flow around the rotor tip of a steam turbine. The effects of surface cooling and inlet superheat degree on wet steam flow parameters were also studied in a numerical analysis by employing the Eulerian-Eulerian method by Ahmadpour et al. [18].

Engineering systems should minimize the irreversibilities associated with heat transfer and viscous shear stresses in order to offer better performance. Therefore, entropy generation needs to be considered a criterion for measuring the irreversibilities in designing the engineering systems. Several lines of studies have been recently introduced approaches to reduce thermodynamic losses and entropy generation in quenching processes [19], wells turbines [20–22], reservoir storage [23], cooling systems in nuclear reactors [24], convergent divergent nozzles and steam turbines. Kermani and Gerber [25] used a novel two-phase CFD model to analyze the aerodynamic and thermodynamic losses in a condensing steam flow in a convergent-divergent nozzle. Mahpeykar et al. [26] proposed the reduction of thermodynamic losses by spraying water droplets in a one dimensional supersonic convergence-divergence nozzle. Teymourtash et al. [27] analyzed condensing steam flow in a one dimensional Laval nozzle by using a thermodynamic model and highlighted the effects of increasing the divergence angle and injection of water droplets into the nozzle on entropy generation. Mahpeykar et al. [28] analytically investigated the condensing steam flow parameters and entropy generation by applying volumetric heating to the convergent section of a one-dimensional convergent-divergent nozzle. Mahpeykar et al. [29] also studied the effect of the simultaneous application of friction and volumetric heating and entropy generation in a one-dimensional convergent-divergent nozzle in a similar manner. Alongside, Lakzian and Masjedi [30] investigated the effect of slip between vapor and liquid phases in the condensing steam flow in a one dimensional supersonic nozzle. Their results indicated that considering the slip between the phases, leads to higher entropy generation and exergy losses. Additionally, Lakzian and Shaabani [31], by studying condensing flow in a one dimensional nozzle, showed that by considering the coalescence of formed droplets, entropy generation and exergy losses decrease compared to the state where coalescence is not taken into account. In order to reduce the thermodynamic and aerodynamic losses associated with homogeneous nucleation, Rahimabadi et al. [32] studied the optimization of the shape of a three-dimensional nozzle and two dimensional turbine blade. They were able to reduce the thermodynamic and aerodynamic losses due to spontaneous condensation, taking into account the nucleation rate and maximum droplet radius as the most appropriate factors for optimization.

To the best of our knowledge, no previous effort has been done to analyze whether applying volumetric heating to the convergent section of the stationary cascade of steam turbine blades could affect entropy generation. Therefore, in the current study, an Eulerian-Eulerian model by using a finite volume numerical method and the SST $k-\omega$ turbulence model for simulating the