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On the performance enhancement of thermo-compressor and steam turbine blade cascade in the presence of spontaneous nucleation

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ABSTRACT

In the present study, increasing the performance of thermo-compressors and steam turbines by volumetric cooling and inlet superheating is addressed. The efficacies of these two proposed methods are assessed using a numerical code developed based on Eulerian-Eulerian description of the two-phase fluid flow accounting for the spontaneous nucleation. The results show that maximum increase of 2.8% in entrainment ratio and 4.2% increase in isentropic efficiency are achieved for thermo-compressor and steam turbine blade cascade respectively. As the result, flow passage cooling and increasing the superheating level at the flow inlet could be considered as reliable techniques for wetness loss reduction in industrial apparatuses.

1. Introduction

Non-equilibrium condensation occurs in several industrial apparatuses including primary nozzles of thermal vapor compressors (TVCs) used for multiple-effect water desalination systems (MED) [1,2] and blade cascades of the last stage of steam turbines ubiquitously found in the steam and nuclear power generation plants [3,4]. When a stream of water vapor passes through a nozzle or a turbine blade cascade, it experiences a sharp decrease in the pressure and temperature. The saturation line will be eventually crossed provided that the sufficient temperature gradient prevails to nucleate small water droplets throughout the flow domain [4].

The generated high speed wet steam (consists of the nucleated water droplets distributed across the water vapor) continues to move along the flow passage and the nucleated droplets keep on with growing; therefore, a massive amount of latent heat due to nucleation and droplet growth releases and transfers to the vapor which results in a noticeable increase in vapor pressure called condensation shock. Condensation shock unfavorably affects the performance of thermo-compressors and steam turbines (for example a rule of thumb predicts 1% reduction in the turbine efficiency for each 1% increases in the wetness fraction) [5]. Thus, it is highly desirable to control the condensation shock prompted by non-equilibrium condensation in nozzles/blade cascades in order to suppress the new losses introduced by non-equilibrium condensation (also known as wetness loss) and subsequently enhance the performance of thermo-compressors and steam turbines. To achieve this goal, the first step was to explore the physics of spontaneous condensation via experimental and theoretical studies.

Early experimental studies of the non-equilibrium condensation were focused on the visualization of the aforementioned phase change phenomenon in nozzles and turbine cascades and accurately recording the pressure distribution across the condensing zone [6–8]. Recent advances in the theoretical modeling of wet steam flows with spontaneous condensation has made it possible for the computational fluid dynamics (CFD) to be utilized as an effective tool in examining the non-equilibrium condensation in various geometries.

To numerically tackle the nucleating two-phase flow problem, first attempts were mainly concerned with wet steam flows through converging-diverging nozzles. Gerber and Kermani [9] have developed a model for homogenous nucleation in high-speed flows based on a Eulerian-Eulerian description of two phase flow and classical nucleation theory. A good agreement between the numerical results and experimental data was reported

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for a Laval nozzle. The effect of turbulence modeling on non-equilibrium condensation steam through nozzle was investigated by Avetissian et al. [10,11] and Patel et al. [12]. They modified the well-known k-ε turbulence model in order to accurately predict the pressure and droplets radius distributions along the nozzle axis.

Sun et al. [13] compared various nucleation methods for the simulation of nitrogen spontaneous condensation flow in cryogenic nozzles. They showed that the nucleation theory which is based on classical nucleation theory and modified by Kantrowitz for non-isothermal effects shows a better prediction of pressure drop, location of condensation onset compared with experimental data. Noori Rahim Abadi et al. [14] proposed a two-fluid model for the simulation of supersonic flow of wet steam within high-pressure nozzles accounting for liquid/gas slip velocity. It was shown that the so-called two-fluid formulation is superior to the one-fluid formulation especially high-pressure nozzles. Halam and Hric [15] presented a new equation of state for two-phase mixture of water which saved 50% CPU time in comparison with widely used IAPWS-95 formulation when it is employed for nucleating flow computations.

As nucleating flow models became more mature, they were used to study more complex flows. Among these flows, two-phase flow through turbine blade cascade has gained a significant interest from researchers due to its practical prominence. Dykas et al. [16] were one the first who studied the problem and highlighted the importance of using real gas model in simulation of transonic wet steam flows in order to obtain reasonable estimation for thermodynamic loss. The effect of back pressure on the non-equilibrium condensation through a turbine cascade was studied numerically and experimentally by Yousif et al. [17]. It was reported that low back pressure cause high liquid mass fraction for a wide range of inlet conditions.

Dykas and Wroblewski [18] presented a two-fluid formulation for homogenous condensing flow accounting for gas flow turbulence and compressibility together with slip velocity at the gas/liquid interface neglecting the viscosity of water phase. Significant velocity slip is reported around the trailing edge of turbine blade. They further extended their work to capture the formation of coarse water droplets prompted by shock waves at the trailing edge of blades [19]. A 3D numerical simulation of wet steam flow through stationary and moving blades of a steam turbine was carried out by Yu et al. [20].

In the case of thermal vapor compressors (TVCs), primary models were developed the simulation of MED-TVC systems with horizontal shell and tube evaporators [21–23]. Kouhikamali et al. [24,25] developed a 1D thermodynamic model to simulate MED-TVC units and validated its accuracy by industrial data taken from manufactured units in the south of Iran. Ameur et al. [26] proposed a mathematical model for the investigation of ejectors performance. The model was based on a thermodynamic approach in which conservation equations and properties of real refrigerants are being used. Their results agreed fairly well with experimental data. Sharifi et al. [27] successfully employed a mixture model for simulating the wet steam flow through a thermo-compressor and analyzed the effect of deviation of wet steam from ideal gas behavior on the fluid flow. Noori Rahim Abadi et al. [14] further refined the model to account for gas/liquid velocity slip and the volume of water droplet formed in the primary nozzle of a thermo-compressor.

Despite numerous theoretical studies (some of them cited earlier) on the non-equilibrium condensation, the use of two-phase flow modeling for the overall performance evaluation of steam turbines and thermo-compressors and ultimately devising new techniques for the corresponding wetness loss reduction are fairly limited. As an effective technique for loss reduction in wet steam flows across a steam ejector, Wang et al. [28,29] proposed "inflow superheating". Using a wet steam model (one fluid formulation neglecting the gas-liquid velocity slip) it was concluded that selecting a proper degree of superheat at the primary nozzle inlet of a steam ejector weakens the condensation shock and postpones its occurrence; meanwhile the flow condition at the nozzle outlet remains essentially the same and the mixing process between primary and secondary is improved. Moreover, over superheating could adversely affect the net energy consumption of the device. As an alternative method for loss reduction in the nucleating flow through nozzles, Mahpeykar et al. [30] showed that with removing a fraction of condensation latent heat through continuous cooling of the divergent section of a nozzle, condensation shock will gradually disappear. However, the cooling of nozzle results in higher wetness fraction throughout the divergent section in contrast to the size of nucleated water droplet which does not deviate significantly from the adiabatic flow condition.

To the best of our knowledge, no attempt has been made to evaluate the efficacy of superheating and volumetric cooling for the performance enhancement of thermo-compressors and turbine cascades experiencing non-equilibrium condensation. Therefore, in the present work, the use of inflow superheating and uniform cooling (within the divergent section of TVC's primary nozzle and at the surface of turbine blades) for alleviating condensation shock in thermo-compressors and turbine cascades is evaluated employing a two-fluid formulation and classical nucleation theory together with droplet growth model. The use of two-fluid formulation is essential for accurate modeling of high-pressure nucleating flow through primary nozzle of a TVC and the blade to blade flow passage of a steam turbine [14].

To do so, the manuscript is organized as follows: in Section 2, the governing equations for wet steam transonic flow with condensation and the details of the numerical method employed in this work are presented. Finally, the work is concluded by highlighting its major findings.

2. Governing equations

In this study, a two fluid model is adopted in which the continuity, momentum and energy conservation equations are solved for each phase separately. The governing equations for the gaseous phase are given by Ref. [31]:

$$\frac{\partial(\rho_v(1-\alpha))}{\partial t}+\frac{\partial\left(\rho_v(1-\alpha)u_{vj}\right)}{\partial x_j}=-(\Gamma_1+\Gamma_2) \tag{1a}$$

$$\frac{\partial(\rho_v(1-\alpha)u_{vi})}{\partial t}+\frac{\partial\left(\rho_v(1-\alpha)u_{vj}u_{vi}+(1-\alpha)p\delta_{ij}\right)}{\partial x_j}-\frac{\partial\left((1-\alpha)\tau_{ij}\right)}{\partial x_j}=-(\Gamma_1+\Gamma_2)u_{\mathrm{int}j}-F_{Di}-p\frac{\partial\alpha}{\partial x_i} \tag{1b}$$

$$\frac{\partial(\rho_v(1-\alpha)E_v)}{\partial t}+\frac{\partial\left(\rho_v(1-\alpha)u_{vj}H_v\right)}{\partial x_j}+\frac{\partial\left((1-\alpha)q_{vj}-(1-\alpha)u_{vj}\tau_{ij}\right)}{\partial x_j}=-(\Gamma_1+\Gamma_2)(H_{\mathrm{int}v}-h_{lv})-pu_{\mathrm{int}i}\frac{\partial\alpha}{\partial x_i}-u_{\mathrm{int}i}F_{Di} \tag{1c}$$

where u, ρ, α, Γ and p are velocity, density, liquid volume fraction, mass transfer rate (which will be introduced shortly) and pressure respectively. Additionally, E and H denote total energy and enthalpy