Investigation of pitch variation on wet steam flow parameters in a turbine blade cascade

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Abstract

The presence of the liquid phase in the last stage of the steam turbine leads to thermodynamic and mechanical losses. This paper presents an investigation of the pitch to chord variation to reduce the liquid phase at the exit of the cascade turbine blade in wet steam flow. In this regard, the genetic algorithm is utilized to find optimum pitch to chord. The wetness fraction (WF), droplet size (DS), number of droplets (ND) and erosion rate (ER) are the objectives of this study. The calculations were conducted by employing 2D compressible Reynolds-averaged Navier-Stokes (RANS) equations, and the Eulerian-Eulerian approach are employed for modeling condensing flow. The agreement obtained between the numerical and experimental results is satisfactory. The results show that a pitch to chord ratio of Pi/AC=0.76 is the suitable case. In this case compare to original case, the wetness fraction, droplet size, and erosion rate are reduced 3.59%, 1.94%, and 10.25% respectively.

Keywords: pitch variation, wetness fraction, droplet size, number of droplets, erosion rate

Introduction

Finding the optimal pitch to chord ratio of steam turbines has been a challenging task ever since because it has an essential effect on efficiency and losses. In addition, the last stages of the steam turbine are associated with condensation. This phenomenon leads to the attendance of a liquid phase which results in thermodynamic and mechanical losses. It should be noted if the wetness fraction is increased by one percent, the efficiency will decreases as well [1]. Therefore, the perception of the condensation phenomenon can be gratefully useful in the design process. A plethora of studies are conducted on the phenomenon of condensation. Dykas et al. [2] evaluated the non-equilibrium condensing steam flow of transonic in half arc nozzles and stator blades which are located in the last stage of the steam turbine. Dykas et al. [3] experimentally investigated the condensation of steam flows in a non-equilibrium state which is occurred in a linear rotor blades cascade. Walker et al. [4] reviewed the various techniques to measure the wetness content including the liquid film and moisture content. Joseph et al. [5] described a numerical approach to calculate the thermodynamic loss related to non-equilibrium condensation for the nozzle and turbine cascade. Wróblewski and Dykas [6] presented a model intended for the condensing steam flow through the de Laval nozzle to reconstruct the size of a water droplet. Cao et al. [7] indicated that parameters of flow field and location of vortex influenced, the droplet size, number of droplets, and condensation location of the steam turbine. The energy losses due to rotor blade profile and droplet size were studied by Sengupta and Bhattacharya [8]. Salmani et al. [9] proposed an innovative method to predict droplet radius and wetness fraction regarding roughness in the turbine blades. Their method was founded on Buckingham Pi-theorem and merely with the use of dry vapor data.

Researchers are interested in reducing the losses with shape optimization. Mahrooghi and Lakzian [10] illustrated that performance of Wells turbines can be substantially enhanced with the blade deformation. Trigg et al. [11] utilized GA to proposed a systematic approach to obtaining optimal blade profile with minimum losses. Keisari and Shams [12] utilized the genetic algorithm to optimized the shape of the wet-steam nozzle. Their results show that the size and number of droplets were improved by 5.61% and 10.7%, respectively. Yang et al. [13] investigated the impact of the trailing edge cutback on the performance of the blade. RahimAbadi et al. [14] used the genetic algorithm approach to shape the optimization of turbine blades. Maximum droplet radius and rate of droplet nucleation were the objectives of this optimization. The results demonstrate that their method improved 2.1% in turbine blade efficiency. Xu Han et al. [15] studied the effects of the non-axisymmetric end wall of the turbine blade cascade on steam parameters. Their results indicate that the non-axisymmetric end wall decreases the droplet size.

In the design of the steam turbine, the optimization of the ratio of pitch to chord for blades is one of the most essential concerns of researches. If the space between the blades is reduced, the viscous losses resulting from boundary layers are increased, and the power is reduced. If the space between blades is increased, the undesirable gradient becomes more probable. The undesirable gradient leads to the separation of flow and, hence, an increase in viscous losses. Zweifel [16] in an experimental study, proposed the optimal ratio of pitch to chord for dry steam turbine blades and showed the effect of pitch changes on the magnitude of losses. Dossena and D’Ippolito [17] investigated the effect of three incidence angles, six Mach number, and three-pitch to chord ratios, on the development of secondary flows of turbine cascades. Walker and Hesketh [18] optimized the low-reaction steam turbine blades by changing the pitch to chord ratio. Results show that if the blades are spaced well apart, the profile losses will decrease but, the secondary loss will increase. Segawa and Shikano [19] proposed an optimal reaction blade of a steam turbine that operates on a high-pressure condition. Pitch to chord ratio, a radius of leading-edge, turning angle and maximum blade loading location were the control factors of that study. Results denote that stage efficiency is increased by about 1.5% with an optimum blade. A highly loaded rotor cascade, which had an increase of pitch to chord ratio by 14% without deterioration of performance, has been developed by Segawa and Shikano [20]. To the best of our knowledge, no attempt was reported to optimize the ratio of pitch to chord in turbine blade cascade in wet steam flow. Therefore, in this study, the effects of variations of the pitch to chord ratio in turbine blade cascade in wet steam flow are studied. In this regard, the Eulerian–Eulerian model are utilized to simulate the two-phase viscous wet-steam flow. In addition, a multi-objective method is used for the optimization process. For this purpose, wetness fraction (WF), droplet size (DS), number of droplets (ND) and erosion rate (ER) all measured at the exit, are introduced as a criterion for proposing the optimal cases. Moreover, Figure 1 shows the schematic of the present study.

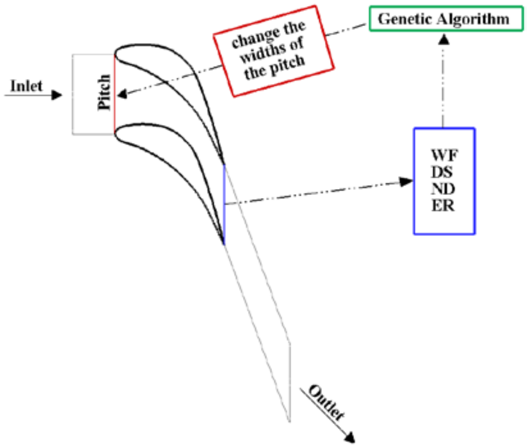


Figure 1: Schematic illustration of the turbine blade, flow passage, optimization loop based on the change the widths of the pitch, and objective function at the end of the passage.

Introducing Geometry and Boundary Conditions

The boundary conditions are expressed in Table 1. Pressure type is considered for inlet and outlet boundary, and blades' sides are fixed and followed by no-slip conditions. The periodic boundary conditions are also utilized at the inlet and outlet of the passage. Figure 2 illustrates the geometry and boundary conditions.

Table 1: Boundary conditions of turbine cascade blade [21].

Po in	172 kPa
To in =Ts (Po in)-8	380.66 K
Po out =0.48 Po in	82.56 kPa

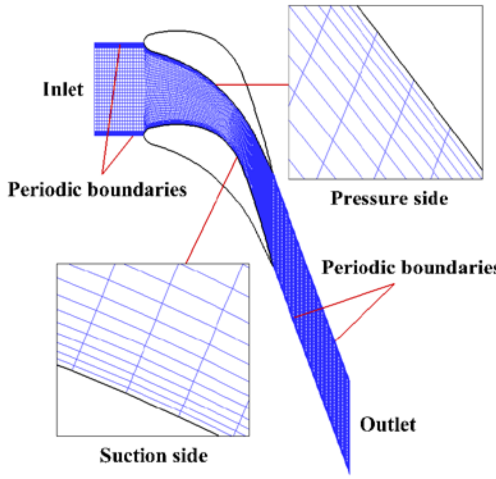


Figure 2: Computational grid and the boundary conditions of the cascade turbine blade.

Governing Equations

The Eulerian-Eulerian approach is employed to model the condensing steam flow. The two-phase flow is simulated utilizing the two-dimensional viscous compressible Navier-Stokes equations and energy equation, combined with nucleation and the droplet growth equations.

Conservation Equations

Conservation equations of mass, momentum, and energy for viscous compressible condensing steam flow in two-dimensional cartesian coordinates can be written as follows [22]:

$$\frac{\partial W}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=\frac{\partial R}{\partial x}+\frac{\partial S}{\partial y} \tag{1}$$

In the above-mentioned equations, W shows the independent variable vector, F and G indicate non-viscous terms, S and R denote viscous terms as shown:

$$W=\begin{bmatrix}\rho\\ \rho C_x\\ \rho C_y\\ \rho e_0\end{bmatrix},\quad F=\begin{bmatrix}\rho C_x P\\ P+\rho {C_x}^2\\ \rho C_x C_y\\ \rho C_x h_0\end{bmatrix},\quad G=\begin{bmatrix}\rho C_y\\ \rho C_y C_x\\ P+\rho {C_y}^2\\ \rho C_y h_0\end{bmatrix} \tag{2}$$

$$S=\begin{bmatrix}0\\ \tau_{xy}\\ \sigma_y\\ \sigma_y C_y+\tau_{xy}C_x+k\frac{\partial T}{\partial y}\end{bmatrix},\quad R=\begin{bmatrix}0\\ \sigma_x\\ \tau_{yx}\\ \sigma_x C_x+\tau_{yx}C_y+K_t\frac{\partial T}{\partial x}\end{bmatrix}$$

It is worth mentioning that two-phase density is based on the liquid phase and vapor phase and is calculated as follows; which β is the liquid mass fraction

$$\rho=\frac{\rho_v}{1-\beta} \tag{3}$$

It should be noted that the conservation equations are calculated with respect to the properties of the two-phase mixture as [23]:

$$\phi_{lv}=\phi_l\beta+(1-\beta)\phi_v \tag{4}$$

here ϕ indicates properties such as entropy, enthalpy, thermal conductivity, and specific heat. In addition, liquid mass-fraction, β, and the number of droplets per unit volume, η, were solved as follow [24]:

$$\frac{\partial\rho\beta}{\partial t}+\frac{\partial}{\partial x_i}(\rho C_i\beta)=\Gamma \tag{5}$$

$$\frac{\partial\rho\eta}{\partial t}+\frac{\partial}{\partial x_i}(\rho C_i\eta)=\rho I \tag{6}$$

where Γ represents mass generation per unit volume, I denotes the rate of droplet nucleation and ρ indicates the two-phase density.

Nucleation and Droplet Growth Equation

Condensation of steam flow leads to phase change phenomenon which involves nucleation and droplet growth processes. To form droplets, if the molecular clusters overcome the free critical energy obstacles, spontaneous condensation occurs. The variation of the Gibbs free energy can be written as [24]:

$$\Delta G=-m_r RT_v Ln\, S+4\pi r^2\sigma \tag{7}$$

where S shows the supersaturation ratio and it is defined as [25]:

$$S=\left(\frac{P}{P_s(T_v)}\right) \tag{8}$$

where P represents vapor pressure and $P_s(T_v)$ indicates saturation pressure at vapor temperature. According to thermodynamic equilibrium, there is a critical radius, r^*, that must be achieved to form a stable core from supercooled vapor. In addition, the variation of critical Gibb's free energy is defined as ΔG^*. In this regard, by derivatizing equation (13), the ΔG^* and r^* are calculated as [26]:

$$\Delta G^*=\frac{4}{3}\pi {r^*}^2\sigma \tag{9}$$

$$r^*=\frac{2\sigma}{\rho_l RT_v Ln\, S} \tag{10}$$

The classical theory of homogeneous condensation expresses the formation rate of the liquid droplet embryos from a supersaturated steam as follow [27]:

$$I_{classic}=q_c\frac{\rho_v^2}{\rho_l}\sqrt{\frac{2\sigma}{\pi M_m^3}}\cdot exp\left(-\frac{4\pi {r^*}^2\sigma}{3K_b T_v}\right) \tag{11}$$

where q_c indicates the coefficient of condensation, which is assumed to be one, K_b represents the Boltzmann constant, M_m shows the molecular mass and σ expresses liquid surface tension. A plethora of corrections have been conducted to the classical nucleation theory. Among them, Kantrowitz corrections have good enough accuracy for non-isothermal effects [22]:

$$I=\frac{1}{(1+\theta)}I_{classic} \tag{12}$$

where θ illustrates the factor of non-isothermal correction and it is defined as follow:

$$\theta=\frac{2(\gamma-1)}{(\gamma+1)}\left(\frac{h_{lv}}{RT}\right)\left(\frac{h_{lv}}{RT}-0.5\right) \tag{13}$$

where γ denotes the specific heat ratio and h_{lv} presents enthalpy of evaporation.

Γ shows the rate of mass generation per unit volume as follow [24]:

$$\Gamma=\frac{4}{3}\pi\rho_l I {r^*}^3+4\pi\rho_l\eta\bar{r}^2\frac{\partial\bar{r}}{\partial t} \tag{14}$$

where $\bar{r}$ indicates the average droplet radius and $\frac{\partial\bar{r}}{\partial t}$ denotes the rate of the droplet growth:

$$\frac{\partial\bar{r}}{\partial t}=\frac{P}{h_{lv}\rho_l\sqrt{2\pi rT}}\left(\frac{\gamma+1}{2\gamma}\right)C_p(T_l-T_v) \tag{15}$$

Numerical Method

In this study, the effects of variation of the pitch to chord ratio in turbine blade cascade in wet steam flow have been investigated. In this regard, all of the presented numerical calculations are performed with compressible and steady-state two-dimensional Reynolds-averaged Navier-Stokes (RANS) equations. Furthermore, the finite volume integration method is utilized to discretize the conservation equations of the vapor and liquid phases. Besides, the solution method is based on a density-based couple solver with the Eulerian–Eulerian approach. Moreover, the upwind scheme is used to discretize the space. The criteria of convergence are below 10^{-6} for all dependent variables.

Grid Independence Study

To obtain the optimal mesh size, a grid independence study is performed. Figure 3 indicates the pressure distribution on the suction side through the original blade. The grid with 10848 nodes is obtained as the suitable grid size. In addition, the grid independence for other cases is conducted and tabulated in Table 1.

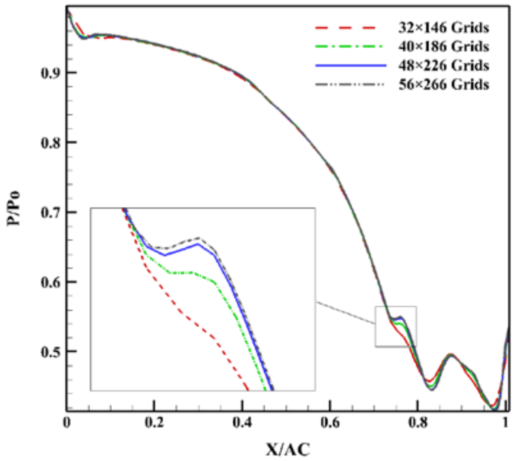


Figure 3: Comparison of the static pressure distribution on the suction side for different grids size of the original case.

Table 1. Grid independence for other cases

case	Pitch/Axial chord	Grid size
Case 1	0.6	9040
Case 2	0.64	9944
Case 3	0.68	10396
Case 4	0.76	11300
Case 5	0.88	12204

Validation

Validation is conducted to confirm the numerical method used in the present study. It is worth mentioning that, Bakhtar et al. [28] in the experimental study, measured the pressure distributions on surfaces and average droplet radius at the end of this blade, respectively. Figure 4 and Figure 5 indicates a comparison of the average droplet radius and pressure distribution with experimental data, respectively [47]. The numerical wet steam results show a good consistency for the pressure distribution and average droplet radius.

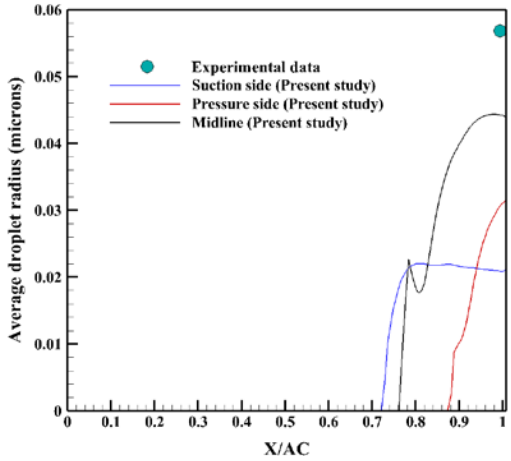


Figure 4: Comparison of the numerical results of wet steam flow through turbine cascade blades for the average droplet radius on the suction side, pressure side, and mid passage with experimental data.

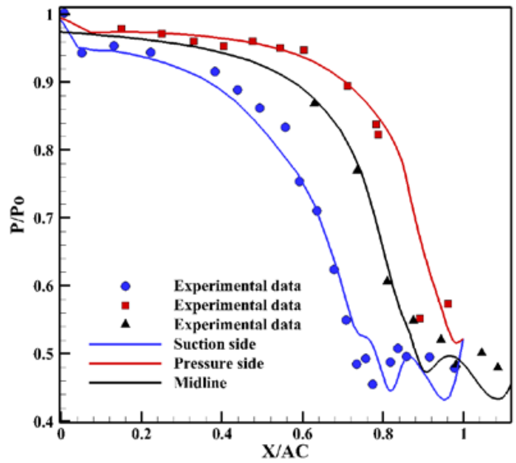


Figure 5: Comparison of the numerical results of wet steam flow through turbine cascade blades for the pressure distributions on the suction side, pressure side, and mid passage with experimental data.

Results and Discussion

In order to design turbine cascades, finding the optimal pitch to chord ratio for the blades is one of the most important challenges for designers. In this paper, to study the effects of variation in pitch to chord rate on the condensation process, the pitch is changed and five other cases are designed. As already shown in Figure 6, the results of pitch variation on wetness fraction (WF), droplet size (DS), number of droplets (ND) and erosion rate (ER) are provided; it is noteworthy that to make the objective of the problem dimensionless, objectives are divided by the original case.

$$\mathrm{WFR} = \frac{\mathrm{WF}}{\mathrm{WF}_{\mathrm{Original}}} \qquad (16)$$

$$\mathrm{DSR} = \frac{\mathrm{DS}}{\mathrm{DS}_{\mathrm{Original}}} \qquad (17)$$

$$\mathrm{NDR} = \frac{\mathrm{ND}}{\mathrm{ND}_{\mathrm{Original}}} \qquad (18)$$

$$\mathrm{ERR} = \frac{\mathrm{ER}}{\mathrm{ER}_{\mathrm{Original}}} \qquad (19)$$

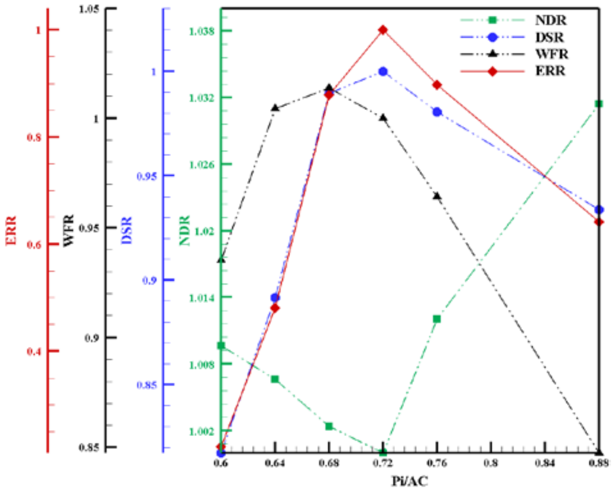


Figure 6: Effect of pitch variation on the non-dimensional parameters at the end of the passage.

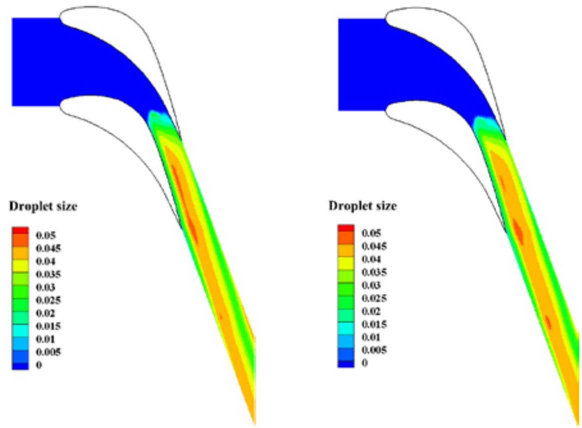
Genetic Algorithm optimization

The purpose of this study is to reduce wetness fraction, droplet size, number of droplet and erosion rate. Therefore, a genetic algorithm is utilized to optimize the pitch ratio. After optimization, the genetic algorithm proposed case 4. In this case pitch to chord ratio is equal to 0.76. In Table 2, the parameter changes in this study relative to the original state are provided.

Table 2. Optimized values of the objective functions

Objective function	Percentage of changes
WFR	Improved 3.59%
DSR	Improved 1.94%
ERR	Improved 10.25%
NDR	Degraded 1.20%

Figure 7 shows the droplet size for original and optimal case. It can be inferred from the Figures 7 that with an increase of one millimeter in blade pitch, droplets size in the blade outlet is smaller than the original case.

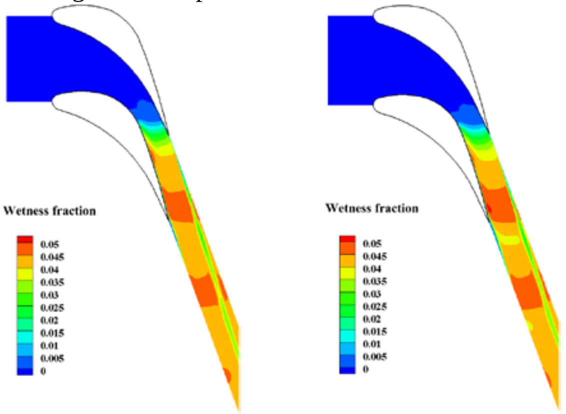


(a) (b)

Figure 7: Effects of the pitch variation on droplet size for; (a) original case, (b) optimal case.

Figure 8 indicates the wetness fraction for original and optimal case. According to Figure 7, by increasing blade pitch by one millimeter, droplet size is reduced.

Therefore, it is expected that wetness is reduced by increasing the blade pitch.



(a) (b)

Figure 8: Effects of the pitch variation on wetness fraction for; (a) original case, (b) optimal case.

Conclusions

In this paper, the effects of pitch variation on the condensing steam flow parameters are investigated in the stationary cascade of turbine blades. To control the losses of the presence of the liquid phase, the genetic algorithm is utilized to optimize the ratio of pitch to axial chord. Wetness fraction (WF), droplet size (DS), number of droplet (ND) and erosion rate (ER) at the outlet are objective functions. The results illustrate that wetness, droplet size and erosion rate at the nozzle blade of the steam turbine can be improved by increasing the pitch by one millimeter. In the optimal case compared to the original case, the wetness fraction, droplet size, and erosion rate are decreased 3.59%, 1.94%, and 10.25% respectively.

Nomenclature

AC	axial chord
C	velocity magnitude
C_x, C_y, C_z	velocity components
DS	droplet size
DSR	droplet size ratio
e_0	total energy
ER	erosion rate
ERR	Erosion rate ratio
G	Gibbs free energy
h_0	total enthalpy
I	droplet nucleation rate
K_b	Boltzmann's constant
K_t	thermal conductivity
m_r	liquid mass
M_m	molecular mass
ND	number of droplets
NDR	number of droplets ratio
P	pressure
Pi	pitch
q_c	condensation coefficient
R	gas constant
r	droplet radius
S	supersaturation ratio
T	temperature
t	time
WF	wetness fraction
WFR	wetness fraction ratio
X	axial length of the blade
Greek letters	
β	liquid mass fraction
Γ	mass generation rate
η	number of droplets per volume
ρ	density
τ	viscous stress tensor
σ	liquid surface tension
Subscript	
l	liquid
lv	liquid-vapor
s	saturation
v	vapor
Superscript	
*	critical

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