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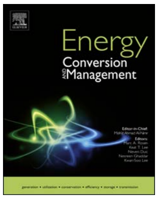

Effect evaluation of a novel dehumidification structure based on the modified model

Guojie Zhang, Liang Wang, Sen Zhang, Yimin Li, Zhongning Zhou*

School of Electrical and Power Engineering, China University of Mining & Technology, Xuzhou 221116, China

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ABSTRACT

In the course of energy conversion, steam turbine is one of the most important equipment, but the wet steam at the low-pressure stage will cause losses. The losses caused by condensing flow not only reduce the efficiency of steam turbine but also influence reliability. This paper firstly numerically investigated the Dykas cascade using the modified model, and compared with the experimental data. The results showed that the modified model had an enormous advantage in predicting the condensing flow. Besides, the advantage was obvious in calculating the pressure distribution of the blade and shock angle emerged in the blade trailing edge. Secondly, a novel dehumidification structure was proposed and the effect was calculated and discussed. The result showed that the novel structure had a positive effect on reducing the nucleation zone and the liquid mass fraction. Besides, the influence of different passage diameters was investigated, the conclusion can be drawn: both the liquid mass fraction of the outlet and the nucleation zone decrease with the increment of the passage diameter. Finally, an improved dehumidification structure which can be easily manufactured was presented and the structure with different φ was calculated. The results showed that when $\varphi = 0$, the dehumidification efficiency was remarkable, and the structure can be easily manufactured. However, the decrement of the liquid mass fraction was inconspicuous with the further increment of φ.

1. Introduction

As one of the most important equipment for energy conversion, steam turbine plays an irreplaceable role in industry and improving the national economic strength and the living standard of people. However, during the operation of the steam turbine, non-equilibrium condensing flow always takes place in low-pressure (LP) stage, which will lead to the formation of lots of fine droplets. A great deal of fine droplets following the high-velocity steam not only reduce the efficiency of steam turbine, but also erosion of the blades. Besides, the condensing flow has a direct impact upon losses, both thermodynamic and aerodynamic.

Because heat and mass transfer between the liquid and vapor phase will take place during the condensation process, the steam mixed up with lots of droplets formed by the condensation cannot be considered as single fluid [1], the two-phase model is more suitable to describe the condensing flow and estimate the losses [2]. However, the formation of tiny droplet is so quick that it is difficult to measure using experimental methods.

For the last several decades, theoretical, experimental and numerical studies on the condensing flow have been employed to investigate the characteristics of the condensation process. Some researchers [3–6] experimentally investigated one-dimension supersonic Laval nozzles, and similar investigations were also carried out by Yellott et al. [7–9]. Numerical studied concentrating on Laval nozzles were completed by White [10]. Bakhtar and Zidi experimentally presented the nucleation process of three different expansion rates in two-dimensional nozzle, and achieved the pressure distribution and droplet sizes data of the nozzle centerline [11], after then the improvement of condensation theory attracted their attention [12]. Besides, Bakhtar [13–20] comprehensively investigated the numerical and experimental studies concentrating on the performance of a cascade of turbine rotor tip section blading in condensing flow, including blade surface pressure distributions, wake traverses, droplet measurements, prescribed droplet sizes, theoretical treatment and so on. A numerical model based on the Euler-Lagrangian method was developed by Gerber et al. [21]. Furthermore, the Moore low-pressure jet nozzle was validated and illuminated by employing the model and the numerical results were in good agreement with the experimental data. Under high pressure and transonic conditions, the numerical method of non-equilibrium condensation based on the Euler-Euler method was studied by Gerber and Kermnai [22] and their calculated results had little error compare to the experimental results. The transonic condensing flow in the linear blade

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* Corresponding author.
E-mail address: zhouzhongning2018@126.com (Z. Zhou).

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Nomenclature

u	velocity component (m s^{-1})
H	total enthalpy (J kg^{-1})
h	static enthalpy ((J kg^{-1}))
S_m	mass source term (kg m^{-3} s^{-1})
S_u	momentum source term (kg m^{-2} s^{-2})
S_h	energy source term (W m^{-3})
N	droplet number per unit volume (m^{-3})
J_d	nucleation rate (m^{-3}s^{-1})
V	volume
r	droplet radius (m)
r_*	droplet critical radius (m)
S	super saturation ratio
p	pressure (N m^{-2})
T	temperature (K)
h_{vl}	latent heat (J kg^{-2})
Kn	Kundsen number ($\bar{l}/2r$)
$\bar{l}$	mean free path of vapor molecules (m)
k	Boltzmann constant (1.3807 × 10^{-23}JK^{-1})
M_m	the individual water molecular mass (kg)
Y^+	non-dimensional distance from the wall
m^*	mass production rate (kg s^{-1})
C_p	specific heat at constant pressure (J kg^{-1} K^{-1})
q_c	condensation coefficient
NDS	novel dehumidification structure
IDS	improved dehumidification structure
ΔT	supercooling degree (K)
t	time (s)
Pr_v	Prandtl number
R	gas constant (J kg^{-1}K^{-1})
u^*	the friction velocity (m s^{-1})

Greek symbols

ρ	density (kg m^{-3})
α	volume fraction
τ	shear stress (Pa)
σ	surface tension (N m^{-1})
λ	thermal conductivity (W m^{-1}K^{-1})
φ	the angle between the passage centerline and negative direction of X (°)
γ	ratio of specific
μ	kinetic viscosity (Pa s)
ν	dynamic viscosity (m^2s^{-1})
τ_w	the wall shear stress (Pa)
δ_{ij}	Kronecker delta function

Subscript

l	liquid phase
v	vapor phase
d	droplet
sat	saturation
0	stagnation condition
out	outlet
i,j	cartesian tensor notation

cascade and nozzle were deeply studied by Dykas and Wrólewski [23–26] in experiment and numerical simulation and the losses under different condensing flow states were discussed. More than that, they also investigated liquid phase evaporation and droplet size distribution in condensing steam flow [27–29]. Yang [30] investigated the supersonic condensation flow characteristics and found the condensation does not appear immediately with saturation state of steam. The modified model has been developed by Zhang [31] to predict the condensing flow, the conclusion that the modified model can more accurate to predict the Wilson point and blade surface pressure has been drawn. Besides, some researchers [32–34] have comprehensively investigated the condensing flow in refrigeration system using experimental and numerical method.

As early as in 1912, Baumann investigated the losses caused by condensing flow, the conclusion that 1% wetness emerging in steam turbine may lead a 1% decrease in the efficiency of the stage was drawn [35]. The predicted results adopting the Baumann rule were in line with the operating experience of a steam turbine in general. However, in a multi-stage turbine, the losses predicted by the rule do not coincide with the experimental results [36,37]. The reason is that the rule does not take the size and number of the droplet formed into account in condensation process. Omidvar [38] and Mohseni [39] investigated the entropy generation in two-phase flow. Li [40] has presented a new approach to quantitatively evaluate the wetness losses in steam turbines and the approach was more accurate than Baumann rule. Kermani [41] investigated the general formula to evaluate the thermodynamic and aerodynamic losses in condensing flow and used a new two-phase CFD model to validate the correctness.

Although the research about the condensing flow and losses estimation has been abundantly investigated, a satisfactory solution that can suppress the formation of condensing flow is not provided. As the condensing flow has a major influence on the efficiency and reliability of the steam turbine, the design of dehumidification structure is of great urgency. With the nucleation theory developing, the numerical simulation method is gradually applied to investigate the condensing flow process [42]. Therefore, using the numerical method to evaluate the dehumidification efficiency of the dehumidification structure makes sense.

It is still not comprehensively addressed the characteristics of condensation in steam turbines, because of the rapid nucleation and condensation process in condensing flow. In this paper, the main aim is that a novel dehumidification structure is proposed, and the dehumidification efficiency is discussed. The novel structure optimization is conducted on that basis. Firstly, the Dykas linear cascade including abundant experiment data is employed to validate the reliability and accuracy of the numerical method, and the distribution of nucleation rate and liquid mass fraction is presented and analyzed. Secondly, a novel dehumidification structures is proposed, and the nucleation rate and droplet growth rate of the path centerline are discussed; the dehumidification efficiency of the novel structure with different passage diameters is discussed. At last, an improved structure which can be easily manufactured based on the novel structure is presented and the dehumidification efficiency is discussed in detail.

2. Mathematical models of condensation process

2.1. Modeling of continuous vapor phase

During the rapid expansion of steam, a condensation process will rapidly occur when the state path crossed the vapor saturation line. The expansion process leads to the superheat steam first subcool and then nucleate, at last, a two-phase mixture of saturated vapor and tiny droplets will be formed. Because the droplet is very fine, so the following assumptions are made: 1. The velocity slip between the droplet and vapor is disregarded [43]. 2. The interactions between droplets are omitted. 3. The volume of the condensed droplets is negligible since the droplet sizes are very small in general. Therefore, from the above assumptions, the control equations of mass, momentum and energy for the vapor phase in condensing flow are shown in (1)–(3).