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Study on heterogeneous condensing flow characteristics in turbine cascade

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1. ABSTRACT

Particles in wet steam induce heterogeneous condensation. This study investigates how changes in particle concentration affect the flow characteristics of heterogeneous condensation. The results show that increasing particle concentration leads to higher thermodynamic losses and outlet humidity at the turbine blade. Notably, at a particle concentration of $1\times10^{16}m^{-3}$, thermodynamic losses decrease by 15%, and humidity by 6%, compared to homogeneous condensation.

2. INTRODUCTION

Due to the inevitable generation of wet steam in the last two stages of the low-pressure turbine of steam turbines, and the occurrence of heterogeneous condensation in impure steam, the safety and economic efficiency of steam turbines are affected. Therefore, the main purpose of this paper is to investigate the impact of heterogeneous condensation on wet steam losses and to identify appropriate methods to reduce the thermodynamic irreversible losses generated during the condensation phase transition process.

This paper uses Dykas blade cascade[1] as the research object to conduct calculations for both homogeneous condensation flow within the blade cascade channel and heterogeneous condensation flow under various particle concentrations. The specific computational methods are detailed in Table 1.

Table 1 Computational schemes for different heterogeneous condensation conditions

Name	P_{in}/kPa	T_{in}/K	P_{out}/kPa	T_{out}/K	$N_{in}(m^{-3})$	$R_{in}(m)$
N0R0	122	380	59	358.65	—	—
N16R1	122	380	59	358.65	1×10^{16}	1×10^{-9}
N17R1	122	380	59	358.65	1×10^{17}	1×10^{-9}
N18R1	122	380	59	358.65	1×10^{18}	1×10^{-9}

Through comparative analysis of the nucleation rate ratio, supercooling ratio, thermodynamic loss ratio, and humidity under different conditions of heterogeneous and homogeneous condensation flow, this paper clearly elucidates the inhibitory effect of heterogeneous condensation on droplet condensation. Furthermore, it identifies the influence patterns of particle concentration variation on heterogeneous condensation: increasing particle concentration effectively reduces the nucleation rate and diminishes the deviation of steam from equilibrium. However, with further concentration increase, the effectiveness of heterogeneous condensation in reducing thermodynamic losses gradually diminishes, leading to a significant increase in humidity, which is detrimental to improving the efficiency of steam turbines.

3. METHDOLOGY

Based on the Euler-Euler two-fluid model, this paper establishes the governing equations for the non-equilibrium condensation process of steam and utilizes User-Defined Scalars (UDS) to load mass, momentum,

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and energy source terms. Moreover, to accurately simulate the condensation phenomenon of wet steam, the ideal gas equation of state is replaced with the Virial equation of state in this study.

In studying heterogeneous condensation flow, it is assumed in this paper that impurity particles are spherical with smooth surfaces, and their chemical properties are considered inert. Building upon Fletcher's classic theory of heterogeneous coronal nucleation, this paper derives the nucleation rate J_{het} for insoluble heterogeneous condensation, with the calculation expression as follows[2]:

$$J_{\text{het}} = 4\pi R_{in}^2 N_{in} J_0 \exp\left(-\frac{\Delta G^*}{KT_{\text{g}}}\right) \tag{1}$$

$$\Delta G^* = -\frac{4\pi\rho_{\text{l}}}{3m} RT_{\text{G}} \ln S\left(r_{\text{c}}^3 - R_{\text{p}}^3\right) + 4\pi\sigma\left(r_{\text{c}}^2 - R_{\text{p}}^2\right) \tag{2}$$

Additionally, this study has adjusted the surface tension of liquid droplets based on the influence of water droplet surface curvature, with the specific calculation formula provided as follows[3]:

$$\sigma_0\left(T\right) = 1.07 \times 235.8\left(1 - \frac{T}{647.3}\right)^{1.256}\left[1 - 0.625\left(1 - \frac{T}{647.3}\right)\right] \tag{3}$$

In this paper, Gyarmathy droplet growth model optimized by Young[4] based on Langmui three-layer theoretical model and modified by low pressure is adopted:

$$\frac{dr}{dt} = \frac{\lambda_{\text{v}}(T_s - T)}{h_{vl}\rho_l r} \frac{1 - r^*/r}{\left(\frac{1}{1 + 1.5Kn} + 3.78(1 - \psi)\frac{Kn}{\Pr_v}\right)} \tag{4}$$

$$\psi = \frac{RT_s}{h_{vl}}\left[\vartheta - \frac{1}{2} - \left(\frac{\gamma + 1}{2\gamma}\right)\left(\frac{C_{\text{p}}T_s}{h_{vl}}\right)\left(\frac{2 - q_{\text{c}}}{2q_{\text{c}}}\right)\right] \tag{5}$$

4. RESULTS

In Fig. 1, the computed results of heterogeneous condensation flow under varying particle concentration conditions are depicted. It is evident from the figure that, in comparison to homogeneous condensation, several parameters of heterogeneous condensation are diminished. As the particle concentration increases, both the nucleation rate and the degree of supercooling in the flow field decrease progressively. Nevertheless, the thermodynamic losses incurred during the condensation process escalate. This phenomenon arises because the heightened particle concentration engenders a larger population of droplets with impurity particles as nuclei, thereby resulting in thermodynamic losses surpassing the reduction attributed to the inhibitory effect.

The humidity distribution in Fig. 2 reveals that in heterogeneous condensation flow, humidity generation precedes that in homogeneous condensation flow. Furthermore, only in heterogeneous condensation flow with a particle concentration of $1\times10^{16}\text{m}^{-3}$ does the humidity at the outlet of the flow field decrease below that of homogeneous condensation flow. This phenomenon arises because external impurity particles can inhibit the spontaneous formation of condensation nuclei by vapor molecules, yet the number of droplets with particles as nuclei is on the rise. Thus, only when the particle concentration is relatively low, is the combined humidity from homogeneous and heterogeneous condensation reduced. For example, the humidity in Fig. 2(b) decreases by 6% compared to Fig. 2(a). However, as depicted in Fig. 2(c) and (d), the humidity within the flow field increases with rising particle concentration, as also evidenced by the analysis of thermodynamic loss variations in Fig.1.

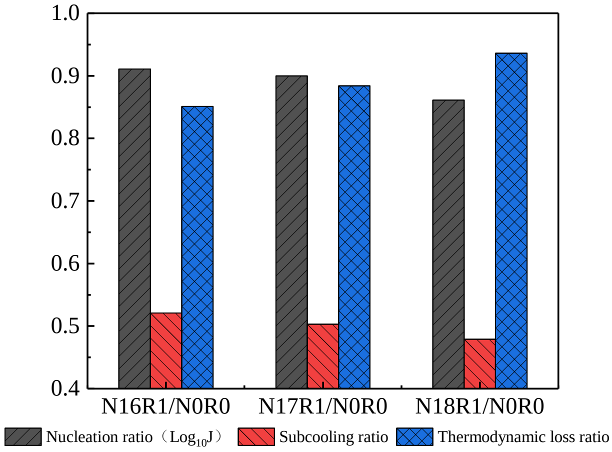
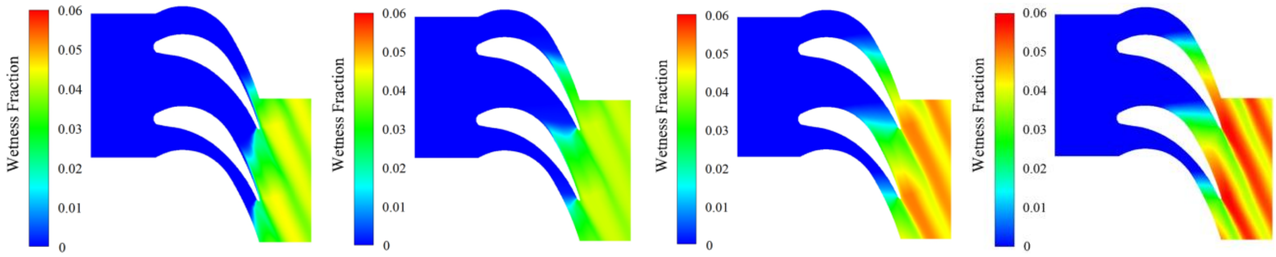


Fig. 1 Comparison of heterogeneous coagulation parameters at different concentrations



(a) N0R0 (b) N16R1 (c) N17R1 (d) N18R1

Fig. 2 Moisture distribution in heterogeneous condensation flow field at different concentrations

5. CONCLUSIONS

The heterogeneous condensing flow in cascade channels is numerically calculated in this paper. The results show that the impurity particles in the steam significantly affect the condensation flow of wet steam:

(1) With the increase of particle concentration, the nucleation rate in the flow field continues to decrease, the thermodynamic loss increases slightly, but it is still lower than the homogeneous condensation flow condition, and the humidity also increases.

(2) When the particle concentration is 1×10^{16}m^{-3} and the particle size is 1×10^{-9}m, the inhibition effect on homogeneous condensation is the best. Compared with homogeneous condensation, the thermodynamic loss of condensation at this time is reduced by 15%, and the humidity is reduced by 6%.

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