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Research Paper

Boundary layer of non-equilibrium condensing steam flow in a supersonic nozzle

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HIGHLIGHTS

- Non-equilibrium condensation steam flow in a supersonic Nozzle.
- Dynamics of self-excited oscillation and asymmetric bifurcation modes.
- Velocity phase diagrams of oscillating modes.
- Mass fluxes for both core flow-field and boundary layer of condensing steam flow.

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ABSTRACT

The occurrence of non-equilibrium process of steam condensation has a significant effect on the efficiency of low pressure part steam turbine. To investigate the phenomenon of non-equilibrium condensation of supersonic nozzle including several self-excited oscillating modes, a full Navier-Stokes viscous laminar model for non-equilibrium condensing steam flow was established and validated by experiments and theory. The flow characteristics of pressure oscillation and velocity phase diagrams of different self-excited oscillating modes were analyzed. Finally, the distinct distributions of mass fluxes for both core flow field and viscous boundary layer of the condensing steam flow were discussed further. The results showed the relative variation of the displacement thickness of throat boundary layer is up to 55.73% which is significant.

1. Introduction

In high-capacity condensing turbines, the efficiency of low pressure part steam turbine operating in the wet steam region is substantially lower than that operating in the superheated steam region [1]. Thus, the occurrence of non-equilibrium process of steam condensation has a significant effect on the efficiency of the total system generating electricity or heat. The non-equilibrium condensation process also exists in supersonic steam ejector [2], supersonic swirling separator [3] and gaseous carrier flows [4]. The supersonic nozzle is widely used as a means of studying non-equilibrium process of steam condensation [5,6]. Moreover, the supersonic nozzle is also a traditional mass flow instrument with high accuracy, repeatability and reproducibility [7–9], the flow field and mass flow-rate of which are affected by the non-equilibrium condensation [10].

The non-equilibrium condensation was first discovered by Schmidt [11,12] in slender nozzle flows of moist air. The non-equilibrium condensation in converging-diverging nozzles can result in both steady and unsteady flows of operation depending on the inlet stagnation conditions [13]. Wegener [14] analyzed the unsteady compressible flow condensation with heat addition due to the condensation of water vapor by homogeneous nucleation. The theoretical analysis of choking in steady non-equilibrium wet steam flows was presented by Young [15]. And then, the one dimensional time-marching prediction of unsteady condensation phenomena due to supercritical heat addition and the two-dimensional calculation of self-excited oscillating flow were successively performed by Guha and Young [13] and White and Young [16].

With the in-depth research, the asymmetric flow patterns with moving oblique shock systems were found in supersonic wind tunnel and investigated by simple unsteady numerical model by Adam and Schnerr [17]. White [18,19] modified the numerical model of non-equilibrium condensation process mainly containing nucleation and droplet growth theory. On the basis of them, Simpson

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Nomenclature

A	area, m^2
C_d	discharge coefficient, –
C_*	critical flow function, –
C_{hom}	correction factor of mass flow-rate for homogeneous condensation, –
c	empirical factor in Eq. (14)
d	throat diameter of nozzle, mm
g	Gibbs free energy, J·kg^{-1}
H	total enthalpy, J·kg^{-1}
h	static enthalpy, J·kg^{-1}
h_{lg}	latent heat of liquid, J·kg^{-1}
J_d	nucleation rate, m^{-3}·s^{-1}
K	Boltzmann's constant. 1.38×10^{-23} J·K^{-1}
Kn	Knudsen number, –
m_m	mass of water molecule, 2.99×10^{-26} kg
$m\circ_d$	condensing mass flow-rate due to the growth of existing droplet, kg·s^{-1}
$m\circ_e$	condensing mass flow-rate due to the growth of developing droplet, kg·s^{-1}
$NBTF$	nucleation bulk tension factor, –
N_d	the droplet number density, kg^{-1}
p	pressure, Pa
q_m	mass flow-rate, kg·s^{-1}
R	gas constant, J·mol^{-1}·K^{-1}
R_m, R_v	specific gas constant, J·kg^{-1}·K^{-1}
r	droplet radius, m
r^*	critical radius, m
G	mass flow density, kg·m^{-3}·s^{-1}
T	temperature, K
t	time, s
T_s	saturation temperature, K
u	velocity, m·s^{-1}
x, y	Curvilinear coordinates
X, Y	Cartesian coordinates

Greek

α	volume fraction, –
β	similarity coefficient, –
γ	isentropic exponent/reduced Gibbs free energy, –
ΔG_1	bulk Gibbs free energy change, J·kg^{-1}
Δp	amplitude of pressure oscillation, Pa
ΔT	sub-cooling, $T_s(p)$-T_c, K
δ_1	displacement thickness of the boundary layer, m
δ_{ij}	Kronecker delta function
η	Kantrowitz correction, –
λ	thermal conductivity, W·m^{-1}·K^{-1}
λ_1	velocity factor, –
μ	dynamic viscosity, Pa·s
π_1	reduced pressure, p/p^*
ρ	density, kg·m^{-3}
σ	liquid surface tension, N·m^{-1}
Γ_t	effective thermal conductivity, W·m^{-1}·K^{-1}
τ	period of oscillation, s
τ_1	inverse reduced temperature, T^*/T
$\tau_{i,j}$	deviatoric stress tensor, Pa

Super-, Subscripts

0	at stagnation condition
c, d	continuous and dispersed phases
hom	homogeneous nucleation
i, j	tensor notation
s	saturation
t	nozzle throat
$*$	frozen flow

[20] explored the bifurcation and asymmetric oscillation for the unsteady flow of condensing steam in the nozzle of Moore et al. [21] by unsteady numerical investigation. And then, Dykas [22] examined the numerical Modeling of steam condensing flow in low and high-pressure nozzles. The asymmetric modes in different nozzle geometries and with different inlet conditions for pure steam flow were discussed by Yu [23]. It should be mentioned that Gerber [24], Yousif [25], Halama [26], Indrupskiy [27] and Chang [28] put forward two or three-dimensional condensation models to improve the calculation accuracy.

In recent years, the effect of condensation on boundary layer of the supersonic nozzle has been increasingly emphasized. Setoguchi [29] discussed the effect of condensation on the displacement thickness of boundary layer on the curved surface by theoretical and numerical method. Matsuo [30] numerically researched the interaction phenomena of the boundary layer in the case of high relative humidity with strong condensation shock wave. Subsequently, Shimamoto [31], Zavershinsky [32], Ankudinov [33] and Ding [34,35] put forward theoretical or numerical method to investigate the effect of condensation on boundary layer.

In present work, A Navier–Stokes viscous laminar model of non-equilibrium condensation steam flow implemented in CFD solver in supersonic nozzle was built and validated by experiments and theory. The flow characteristics of symmetric oscillation and asymmetric bifurcation were investigated and the velocity phase diagrams were firstly applied to the analysis of the self-excited oscillation. Some new results about the characteristics of the core flow region and the displace thickness of the boundary layer in condensation flow were clarified.

2. Physical model

A full Navier-Stokes viscous laminar model for non-equilibrium condensation flow in a supersonic nozzle was established to govern the continuous phase and the dispersed phase. The laminar model is feasible to be used in the numerical model through the validation of discharge coefficient of laminar flow [34]. The continuous phase is the vapor steam, and the dispersed phase is the droplet totally formed by non-equilibrium condensation.

2.1. Modeling of continuous vapor phase

For the continuous vapor phase, the mass conservation and momentum conservation equations in tensor form can be written as follows:

$$\frac{\partial \rho_c \alpha_c}{\partial t} + \frac{\partial}{\partial x_i}(\rho_c u_i \alpha_c) = -(m\circ_e + m\circ_d) \tag{1}$$

$$\frac{\partial \rho_c \alpha_c u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho_c u_i u_j \alpha_c) = \frac{\partial}{\partial x_j}\left(\alpha_c \mu \frac{\partial u_i}{\partial x_j} + \mu \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\mu \delta_{ij} \frac{\partial u_j}{\partial x_j}\right) - \alpha_c \frac{\partial p}{\partial x_i} - (m\circ_e + m\circ_d)u_i \tag{2}$$