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Effect of inlet wetness on transonic wet-steam and moist-air flows in turbomachinery

Satoru Yamamoto *, Shota Moriguchi, Hironori Miyazawa, Takashi Furusawa

Dept. of Computer and Mathematical Sciences, Tohoku University, 6-6-01 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8579, Japan

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ABSTRACT

This study investigates the effect of inlet wetness on transonic wet-steam and moist-air flows through turbine and compressor cascade channels. We first simulated the transonic wet-steam flows through a Bakhtar's turbine cascade channel under wind-tunnel conditions with inlet wetness. We then predicted the effects of inlet wetness on the moist-air flows expected through an aircraft engine and an industrial gas turbine. For this purpose, we simulated the transonic moist-air flows through a transonic compressor cascade channel while changing the inlet wetness conditions. In both wet-stream and moist-air flows, the inlet wetness was quite sensitive to the growth and evaporation rates of the water droplets, and greatly influenced the shock location. Our results for moist-air flows suggest that the temperature beyond the shock is effectively decreased by a large number density of smaller water droplets.

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1. Introduction

Injection of water droplets is a common technique for improving the performance of a compressor [1,2]. As the water droplets stream with air through the compressor passages, they completely or partially evaporate under the pressure increase. The phase change to vapor absorbs latent heat from the surroundings, decreasing the temperature of the compressor. In another approach, water droplets are injected into the steam flow through long-rotor-blade rows in a low-pressure steam turbine. This technique is expected to suppress the oscillation of the rotor blades under low-flow conditions [3,4].

Water vapor in steam flows or air flows conditionally condenses into small water droplets. Condensation of wet-steam flows in a steam turbine may be governed by homogeneous nucleation and nonequilibrium condensation. Water droplets rapidly begin nucleating under supercooled conditions, where the temperature and pressure decrease to far below their saturated values [5–8]. The latent heat released during the vapor-to-liquid phase change of water increases the temperature of the turbine.

Condensation is also conditionally observed over aircraft cruising through very humid air [9]. The condensation may be dominated by heterogeneous nucleation onto small particulates, such as soot or aerosols in the atmosphere. Heterogeneous nucleation begins when the saturated temperature and pressure fall just below their saturated values. The latent heat may be released more slowly in nucleation than in nonequilibrium condensation. Because the water droplets at the inlet of the turbine and compressor may act as particulates, the inlet wetness strongly affects the condensation in steam and air flows. Water droplets are meta-stable when their size is equivalent to the critical size that maximizes their free energy [10]. At larger and smaller sizes than the critical size, water droplets tend to further grow or shrink, respectively. The free energy of a water droplet is governed by the temperature and pressure both inside and outside the droplet. A water droplet evaporates more rapidly as its size is reduced from the critical size. The evaporation rate of water droplets may be primarily responsible for decreasing the temperature of moist-air and wet-steam flows through compressors and turbine blade rows, because the vaporization process absorbs heat. However, the effect of inlet wetness on the condensation and evaporation of water droplets in compressors and turbines has never been investigated from a free-energy perspective. Water droplets can continue growing even in already wetted flows. The growth deeply depends on the

* Corresponding author.
E-mail address: yamamoto@caero.mech.tohoku.ac.jp (S. Yamamoto).

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Nomenclature

e	total internal energy per unit volume
I_c	homogeneous nucleation rate
J	Jacobian of transformation
k	turbulent kinetic energy
k_B	Boltzmann constant
n	number density of water droplets
p	static pressure
R	specific gas constant
r	radius of a water droplet
r^*	critical radius of a water droplet
s_k	source term for equation of turbulent kinetic energy
s_ω	source term for equation of dissipation ratio of turbulent kinetic energy
T	static temperature
t	physical time
u_i	physical velocities (i = 1, 2)
x_i	Cartesian coordinates (i = 1, 2)
x_0	reference length
β	condensate mass fraction
δ_{ij}	Kronecker's delta (i, j = 1, 2)
ξ_i	general curvilinear coordinates (i = 1, 2)
ρ	total density
ρ_v	density of water vapor
ρ_l	density of water liquid
κ	thermal conductivity coefficient
τ_{ij}	viscous stress tensors (i, j = 1,2)
σ	surface tension
σ_{ki}	dissipation term for equation of turbulent kinetic energy
$\sigma_{\omega i}$	dissipation term for equation of dissipation ratio of turbulent kinetic energy
Γ_c	mass generation rate
ω	dissipation ratio of turbulent kinetic energy

droplet velocity, which changes the surrounding temperature and pressure. Especially in the supersonic state, the temperature and pressure are significantly affected by the resultant shocks. Therefore, resolving the growth rate of water droplets in supersonic flows with shocks is also crucial for accurately predicting transonic wet-steam and moist-air flows.

To understand the effect of inlet wetness on the transonic wet-steam and moist-air flows in turbines and compressors, we investigated several flow problems. We first simulated wet-steam flows assuming homogeneous nucleation through a Moses–Stein nozzle [11] and the cascaded channel of a Bakhtar's turbine [12] under wind-tunnel conditions, and compared the results with those of experiments. Second, we simulated and compared the wet-steam flows at the wet and dry inlet of a Bakhtar's turbine. Third, our numerical method was applied to the simulation of moist-air flows through a transonic cascade channel [13], changing the inlet-flow conditions to those of an aircraft engine or an industrial gas turbine. Finally, we investigated the effect of inlet wetness on the transonic wet-steam and moist-air flows in the turbine and compressor cascade channels.

2. Governing equations and numerical methods

The fundamental equations for simulating wet-steam and moist-air flows are based on the compressible Navier–Stokes equations and a nonequilibrium condensation model. Turbulent flows are simulated by the shear-stress transport turbulence model [14]. The equations are written in general curvilinear coordinates as

$$Q_t + L(Q) = \frac{\partial Q}{\partial t} + \frac{\partial F_i}{\partial \xi_i} + \frac{\partial F_{vi}}{\partial \xi_i} + S = 0, \tag{1}$$

where Q is a vector composed of nine unknown variables, defined by $Q = \begin{bmatrix} \rho & \rho u_1 & \rho u_2 & e & \rho_v & \rho\beta & \rho n & \rho k & \rho\omega \end{bmatrix}^T$. The fluxes F_i, F_{vi} and S are derived as $F_i = J(\partial\xi_i/\partial x_j)\boldsymbol{f}_j$, $F_{vi} = J(\partial\xi_i/\partial x_j)\boldsymbol{f}_{vj}$, and $S = Js$, where $J = \partial(x_1 x_2)/\partial(\xi_1\xi_2)$, and $\boldsymbol{f}_i$, $\boldsymbol{f}_{vi}$, and $\boldsymbol{s}$ are the vectors of inviscid flux, viscous flux, and source terms, respectively. These three vectors are expressed in Cartesian coordinates as follows:

$$\boldsymbol{f}_i = \begin{bmatrix} \rho u_i \\ \rho u_1 u_i + \delta_{i1} p \\ \rho u_2 u_i + \delta_{i2} p \\ (e+p)u_i \\ \rho_v u_i \\ \rho\beta u_i \\ \rho n u_i \\ \rho k u_i \\ \rho\omega u_i \end{bmatrix}, \quad \boldsymbol{f}_{vi} = -\begin{bmatrix} 0 \\ \tau_{1i} \\ \tau_{2i} \\ \tau_{ki}u_k + \kappa\partial T/\partial x_i \\ 0 \\ 0 \\ 0 \\ \sigma_{ki} \\ \sigma_{\omega i} \end{bmatrix}, \quad \boldsymbol{s} = -\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\Gamma_c \\ \Gamma_c \\ I_c \\ s_k \\ s_\omega \end{bmatrix}.$$

The fundamental equations comprise the conservative equations for total density, momenta, total energy, density of water vapor, density of water droplets, number density of water droplets, turbulent kinetic energy, and dissipation ratio of turbulent kinetic energy. We suppose that water droplets are sufficiently small and that flow is homogeneous without velocity slip between the working gas and water droplets.

We apply the equation of state for an ideal gas with condensate mass fraction β. For sufficiently small β, this equation can be approximated as [15]

$$p = (1-\beta)\rho RT. \tag{2}$$

The speed of sound is then derived as

$$c^2 = \frac{C_{pm}}{C_{pm} - (1-\beta)R}\frac{p}{\rho}, \tag{3}$$

where the isobaric specific heat C_{pm} is the linear combination of the specific heats of the gas and liquid phases, weighted through β.

The governing equations were solved by a high-order, high-resolution finite-difference method based on the fourth-order compact MUSCL TVD (Compact MUSCL) scheme [16]. Roe's approximate Riemann solver [17] was applied for space difference of convection terms. The viscosity term was calculated by a second-order central-difference scheme, and time integration was performed by LU-SGS scheme [18].

3. Condensation model

Assuming spherical water droplets with radius r and applying

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