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Non-equilibrium condensation process of water vapor in moist air expansion through a sonic nozzle

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ABSTRACT

Non-equilibrium vapor condensation phenomenon through a sonic nozzle is very complicated and closely related to the flow measurement of the sonic nozzle. The gas–liquid two-phase flow Eulerian models for homogeneous and heterogeneous nucleation of moist gas in transonic nozzle flow were built to investigate the effect of vapor condensation on the mass flow rate of the sonic nozzle. Grid independence was achieved by using a solution-adaptive refinement. The CFD models were carefully validated by published experimental data and analytical results. It was shown that the flow rate of the sonic nozzle is affected by both homogeneous and heterogeneous nucleation. In comparison with the experimental data, the effects of vapor condensation on the mass flow rate of the sonic nozzle were obtained. Besides, experiments on periodic, unsteady condensation flow in the sonic nozzle were also reported. This unsteady flow will also affect the flow rate of the sonic nozzle. The results of experiments accorded well with simulations and semi-empirical formula. All the results can be used to further analyze the effect of unsteady flow induced by vapor condensation on the flow rate of the sonic nozzle.

1. Introduction

Sonic nozzles are used in the precise flow measurement as flow meter and transfer standard, because the mass flow rate of a sonic nozzle is not influenced by its downstream disturbance [1–3]. The working fluid of the sonic nozzle is either atmospheric or compressed air for the flow measurement. The water vapor in moist air will reach saturation and enter into supersaturation along with the drop of temperature of the expanding gas through the sonic nozzle [4,5], which easily gives rise to gas–liquid two-phase flow caused by the non-equilibrium vapor condensation phenomenon [6]. Therefore, it is necessary to clarify the effect of vapor condensation on the flow field and flow rate of the sonic nozzle.

In the field of sonic nozzle, Aschenbrenner first discussed this issue and put forward that the traveling time of the fluid from reaching the saturation state till passing the throat is in the order of 10^{-4}–10^{-2} s which is not sufficient to allow the generation of droplets or crystals of ice [7]. However, the time lag of the nucleation process is in the order of 10^{-9} s [8–10]. Thus, there is enough time to generate large amounts of droplets. Additionally, if the inlet relative humidity is large enough or the gas contains soluble impurities served as condensing core, the condensation even appears at the subsonic section before the nozzle throat [11].

For decades, many humidity correction factors without considering the effect of vapor condensation were obtained by Lim [3], Aschenbrenner [7], Stewart [12], Li and Mickan [13], Britton [14] and Li [15], respectively. However, there is no unified standard to date because of considerable errors among the correction equations. Recently, some high-precision humidity tests were reported by Lim [3] and Chahine [16], respectively. They found that the experimental data are less than the theoretical correction results. This phenomenon is more likely to be caused by vapor condensation. Although condensation will generally occur behind the nozzle throat, the supercritical latent heat addition of vapor condensation will lead to thermal choking and the mass flow rate of the sonic nozzle might be affected [17]. Besides, the flow might be unsteady during the adding of supercritical latent heat to flow, which can also prove that the flow field and mass flow rate will be affected by vapor condensation [17]. Previously, unsteady flow oscillations caused by supercritical heat addition while vapor condensation occurs near the throat of converging–diverging nozzles had been observed by Wegener [18], Barschdorff [19] and Skillings [20].

In the current study, the gas–liquid two-phase flow Eulerian models implemented in CFD solver suited for moist air nucleating flow were built. Grid independence was achieved by using a solution-adaptive refinement. The CFD models were validated by experimental data and algebraic formula. Compared with the experimental data, the effects of vapor condensation on mass flow rate of the sonic nozzle were obtained. In addition, the pressure

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Nomenclature

A	area, m^2
C_d	discharge coefficient, dimensionless
c_{cr}	critical velocity of sound, m/s
c_p	specific heat capacity, J kg^{-1} K^{-1}
d	throat diameter of nozzle, mm
E	energy, J kg^{-1}
f_p	expansion rate coefficient, dimensionless
h	specific enthalpy, J kg^{-1}
h_{fg}	latent heat of water, J kg^{-1}
J	nucleation rate, kg^{-1} s^{-1}
k	turbulence kinetic energy, J kg^{-1}
k_p	expansion rate, s^{-1}
M	Mach number, dimensionless
m_m	mass of water molecule, 2.99 × 10^{-26} kg
N	the droplet number density, kg^{-1}
Pr	Prandtl number, dimensionless
p	pressure, Pa
Q_{cr}	dimensionless critical heat addition, dimensionless
q_{cr}	critical heat addition, J
q_m	mass flow rate, kg · $^{-1}$
R	radius of the wall curvature, m
R_v	specific gas constant, J kg^{-1} K^{-1}
r	droplet radius, m
S	supersaturation, dimensionless
s	specific entropy, J kg^{-1} K^{-1}
T	temperature, K
T_{cr}	critical temperature, 647.3 K
T_R	T/T_{cr}, reduced temperature of water, dimensionless
T_s	saturation temperature, K
u	velocity, m/s
w_L	mass fraction of liquid, dimensionless
w_0	specific humidity, dimensionless
Y	wetness fraction, dimensionless

Greek

γ	isentropic exponent, dimensionless
ΔT	subcooling, K
ε	turbulence dissipation, m^2 s^{-3}
κ	Boltzmann's constant, 1.38 × 10^{-23} J K^{-1}
Λ	thermal conductivity, W m^{-1} K^{-1}
λ	dimensionless velocity, dimensionless
μ	viscosity, Pa s
ρ	density, kg m^{-3}
σ	liquid surface tension, N m^{-1}
τ_c	the condensation time, s
υ	volume of single liquid molecule, m^3
Φ_0	inlet relative humidity, dimensionless

Subscripts

0	at stagnation condition
a	non-condensable gas/carrier gas
c	critical condition
i	isentropic flow
L	liquid
t	throat
v	vapor
W	Wilson point
w	water including vapor and liquid

oscillation frequencies of unsteady flow with different inlet relative humidities Φ_0 and specific humidity w_0 (namely, the mass fraction of the vapor in moist air) were also obtained accurately by a measurement sensor. All the experimental data agreed well with the theoretical and numerical results.

2. Condensation flow in sonic nozzle with latent heat release

2.1. Moist air flow rate without vapor condensation

Generally, the discharge coefficient C_d of the sonic nozzle is defined by $C_d = q_m/q_{mi}$, where q_m is the actual mass flow rate. The ideal mass flow rate q_{mi} is calculated by the following equation [1]:

$$q_{mi} = \frac{A_t C_* p_0}{\sqrt{R_v T_0}} \tag{1}$$

where C_* is the critical flow function and $A_t = \pi d^{2}/4$ is the cross-sectional area at the nozzle throat. The mass flow rate of moist air can be calculated by Eq. (2) in which the effect of vapor condensation is not taken into account [2]

$$q_{m,h} = q_{mi} C_d (1 + X_{co_2}(0.25 + 0.04732\pi) + \Phi AB) \tag{2}$$

2.2. Nucleation process and thermal choking

The Mollier diagram for homogeneous nucleation process of condensation flow is shown in Fig. 1. The initial superheated state of vapor can be specified by the stagnation condition p_0 and T_0. When the gas contains no external nucleus, the condensation does not occur at saturation point. The gas will become over-saturated and then lots of condensation nucleuses will appear when the gas reaches somewhere around the Wilson point. Because the time lag of the nucleation process and length-delay are very short, the area change during the condensation can be ignored and this process can be regarded as Rayleigh flow [9,10,17].

In Rayleigh flow, the supercritical latent heat addition will lead to thermal choking of the flow, which is a function of Mach number M, and isentropic exponent γ [17]. A dimensionless expression for

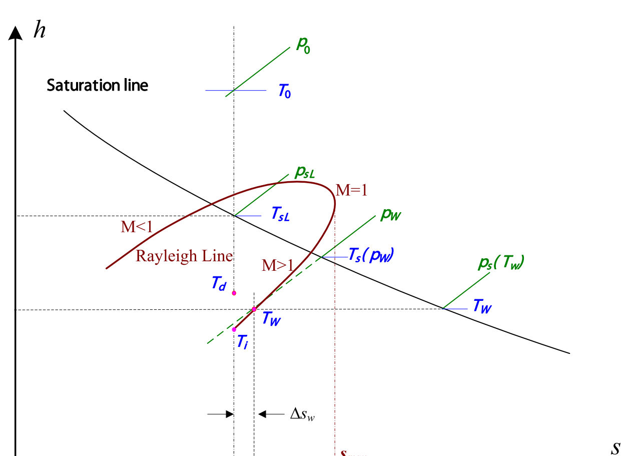

Fig. 1. The Mollier diagram for homogeneous nucleating in a vapor.