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Experimental and numerical studies on self-excited periodic oscillation of vapor condensation in a sonic nozzle

Hongbing Ding, Chao Wang *, Chao Chen

Tianjin Key Laboratory of Process Measurement and Control, School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, China

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ABSTRACT

The unsteady nozzle flow induced by vapor condensation has many different self-excited periodic oscillation modes and affects flow field and mass flow-rate of sonic nozzle. A detailed discussion of thermal choking and oscillation frequencies of this unsteady flow was carried out. To investigate these different oscillation modes, an experimental sensor for measuring inlet humidity/temperature, and monitoring pressure oscillation was built. A numerical model for condensation process in sonic nozzle was established and validated by experimental data of moist nitrogen reported by Wyslouzil and Lamanna. The output of measurement sensor for nozzle flow of moist air agreed with the results of this numerical model. At last, four different oscillation modes caused by vapor condensation were explored. The rules of frequencies and amplitudes of pressure signals for these oscillation modes were discussed in detail. All results can promote the study on the effect of vapor condensation on accurate metering of sonic nozzle.

1. Introduction

In many industrial processes, sonic nozzles are used in the accurate flow measurement as a flow meter and transfer standard, since the mass flow-rate of the sonic nozzle is not affected by its downstream flow disturbance [1,2]. Generally, the working fluid of the sonic nozzle is either atmospheric or compressed air or some other gas. It is well known that all of them are not usually dry, and the water vapor in moist gas will reach saturation and enter into supersaturation along with the drop of temperature the expanding gas through a sonic nozzle [3–5], which easily appears the non-equilibrium condensation phenomena [6]. Therefore, it is necessary to discuss and determine the effect of vapor condensation on the flow field and mass flow-rate of the sonic nozzle. For the condensation phenomena in a sonic nozzle, Aschenbrenner firstly researched and thought that the condensation does not affect the moist air flow-rate of a sonic nozzle [7]. The humidity correction factor without vapor condensation was obtained by Lim [8], Aschenbrenner [9], Britton [10], Stewart [11], Li [12] and Mickan [13], respectively. However, there exist considerable errors among these correction equations. It has not formed uniform standard as well.

However, two independent high-accuracy humidity experiments by Lim [8] in 2011 and Chahine [14] in 2013 showed that all experimental data were less than the ones obtained with correction equations. The most likely reason is that the mass flow-rate will be reduced by the complex diverse condensation phenomenon. Li and Mickan [15] study the effect of vapor condensation at the downstream pipeline of the nozzle on flow-rate. However, the condensation phenomenon in nozzle has not been studied yet.

Although the vapor condensation generally occurs behind the throat of nozzle, according to the theory of thermal choking [16,17], the flow might be unsteady which has different modes of self-excited periodic oscillations [18–20] and the mass flow-rate of moist gas will be affected by the supercritical latent heat addition in sonic nozzle. Therefore, the condensation effect on flow-rate of sonic nozzle should be discussed in detail. In this paper, the different oscillation modes of this unsteady flow were studied by experiments and simulations. The rules of frequencies and amplitudes of pressure signal for different oscillation modes were discussed in detail.

2. Problem statement

2.1. Moist gas flow-rate in the sonic nozzle without vapor condensation

Under the critical flow, the ideal mass flow-rate q_{mi} [2] is calculated by

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* Corresponding author. Tel.: +86 022 27402023.
E-mail address: wangchao@tju.edu.cn (C. Wang).

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Nomenclature

A_t	area at the nozzle throat (m^2)
a_{cr}	critical velocity of sound ($m\ s^{-1}$)
C^*	critical flow function (–)
C_d	discharge coefficient (–)
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
d	throat diameter of nozzle (m)
E	energy ($J\ kg^{-1}$)
f	frequency (Hz)
h_{lg}	latent heat of water ($J\ kg^{-1}$)
J	nucleation rate ($kg^{-1}\ s^{-1}$)
k	Boltzmann's constant 1.38×10^{-23} ($J\ K^{-1}$)
M	Mach number (–)
m_m	mass of water molecule (2.99×10^{-26} kg)
m_p	the mass of single droplet (kg)
m_v	liquid mass changing rate (s^{-1})
n_p	the droplet number density (kg^{-1})
p	pressure (Pa)
Q_{cr}	dimensionless critical heat addition (–)
q_{cr}	critical heat addition (J)
q_m	mass flow rate ($kg\ s^{-1}$)
R	radius of the wall curvature (m)
R_v	specific gas constant ($J\ kg^{-1}\ K^{-1}$)
r	droplet radius (m)
S	supersaturation (–)
T	temperature (K)
u	uncertainty
v	velocity ($m\ s^{-1}$)
x, y	Cartesian coordinates
w_0	specific humidity (–)
Y	wetness fraction (–)

Greek

Δp	amplitude (peak of pressure signal)
η_m	mixture molecular weight ($kg\ mol^{-1}$)
η_v	vapor molecular weight ($kg\ mol^{-1}$)
Θ	parameter in Eq. (3)
κ	isentropic exponent (–)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	viscosity (Pa s)
π	reduced pressure, p/p_c (–)
ρ	density ($kg\ m^{-3}$)
σ	liquid surface tension ($N\ m^{-1}$)
τ	reduced temperature, T/T_c (–)
τ_χ	condensation time (s)
υ	volume of single liquid molecule (m^3)
Φ_0	inlet relative humidity (–)
ω	the condensation mass fraction (–)

Subscripts

0	stagnation condition at inlet
i	isentropic flow
L	liquid
t	throat
v	vapor
s	saturation condition
w	water including vapor and liquid
$*$	evaluation at $M = 1$

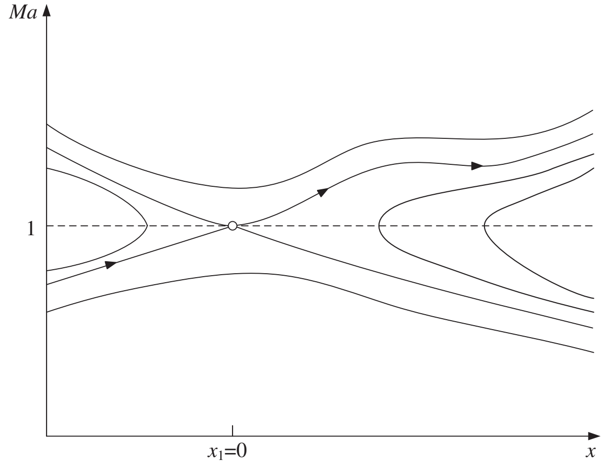

Fig. 1. M–x phase plane with only one singularity at $x_1 = 0$ (the classical saddle point at the throat without heat addition).

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

where A_t is the cross-sectional area at nozzle throat which is equal to $\pi d^2/4$. If the vapor condensation is ignored, the humid air flow-rate, as an example, can be calculated by Ref. [2]

$$q_{m,h} = q_{mi} \cdot C_d \cdot (1 + X_{CO_2}(0.25 + 0.04732\pi) + \Phi_0 \cdot A \cdot B) \tag{2}$$

where $A = 0.127828\tau^3 - 0.789422\tau^2 + 1.63166\tau - 1.12818$ $B = -0.000288749\pi^2 - 0.00191022\pi + 0.00569536 - 0.0719995/\pi$, X_{CO_2} is mole fraction of CO_2 in the air (if not known, use 0.0004). p_c = 3.786 MPa, T_c = 132.5306 K.

2.2. Thermal choking in the sonic nozzle with condensation phenomena

Thermal choking is introduced to analyze the effect of vapor condensation. The supercritical heat addition will lead to thermal choking of the flow [16]. A dimensionless expression for the critical heat addition Q_{cr} in quasi-one-dimensional nozzle flows with vapor condensation is given by Delale [21,22]:

$$Q_{cr} = \frac{q_{cr}}{c_p T_0} = \frac{\omega_{cr} h_{lg}}{c_p T_0} = \frac{\left[(p + \rho v^2)/(\rho v)\right]^2}{4 T_0 \Theta(g)} - 1 \tag{3}$$

where $v_1 = \rho v A$ and

$$\Theta(g) = \frac{(1 + \Gamma)}{2\Gamma}(1 - \omega\eta_m/\eta_v) \tag{4}$$

where

$$\Gamma = \frac{\kappa}{1 + (\kappa - 1)\omega\eta_m/\eta_v} \tag{5}$$

and ω is the condensation mass fraction (i.e. $\omega = m_L/m$). m_L is mass flow-rate of condensation liquid. If the flow is isentropic along the constant area duct till the point of condensation onset, Eq. (3) reduces to

$$Q_{cr} = \frac{\left(1 - M^2\right)^2}{2(1 + \kappa)M^2\left[1 + 1/2(\kappa - 1)M^2\right]} \tag{6}$$

where $0 < Q_{cr} < 1.0417$ for $1 < M < \infty$. The classification of singularities at the $M = 1$ of differential system for the quasi-one-dimensional