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Numerical investigation of nitrogen spontaneous condensation flow in cryogenic nozzles using varying nucleation theories

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ABSTRACT

The thermodynamic irreversible loss by condensation can have an important influence on the flow characteristics and thermal efficiency in air or nitrogen cryogenic turbo-expander involving spontaneous condensation flow. However, the design of wet type turbo-expander for cryogenic liquid plants has been constrained due to the complexity of nucleation theory and the difficulty of data measurement in cryogenic environments. This paper presents numerical simulations for prediction of nitrogen spontaneous condensation flow in cryogenic nozzles. The non-equilibrium simulations were performed using three nucleation theories with the help of ANSYS CFX solver. The standard Redlich-Kwong gas state equation and Eulerian–Eulerian governing equations were used in simulations. Comparison with the equilibrium condensation model the non-equilibrium condensation model achieves a better prediction of the flow characteristics for spontaneous condensation flow in cryogenic environments. The nucleation theory which is based on classical nucleation theory (CNT) and improved by Kantrowitz for non-isothermal effects shows a better prediction of pressure drop, location of condensation onset and supercooling compared with experimental data. The influence of varying nucleation theories on the calculation of nucleation rate, the supercooling distribution and the liquid mass fraction distribution were also analyzed.

1. Introduction

Towards the temperature zone above 63.15 K, the triple point of nitrogen, air or nitrogen spontaneous condensation will take place in cryogenic turbo-expander due to a rapid expansion. The thermodynamic irreversible loss resulting from the spontaneous condensation can significantly affect the flow characteristics and thermal efficiency of turbo-expander. However, the complexity of condensation nucleation theory and the hard of measurement in cryogenic environments prevent the improvement of the design of wet type cryogenic turbo-expander. Since the classical nucleation theory was formulated in the early 20th century by Farkas [1], Becker and Döring [2], Volmer [3], Zeldovish [4] and Frenkel [5], numerical and experimental studies on nucleation performed in the past have primarily focused on water being the working fluid. Because of a lack of accurate knowledge on intermolecular potentials and uncertainties in some key physical properties, it is challenging to perform simulations of air or nitrogen nucleation. In 1952, Faro and Small et al. [6] studied the nucleation of nitrogen during condensation in the gas phase. Willmarth and Nagamatsu [7] measured the static pressure and light scattering to determine the location of nitrogen condensation onset in a supersonic nozzle. Wegener [8,9] also made a significant contribution to the nitrogen condensation with wind tunnels. Following these studies, many other researchers investigated the Wilson plot of nitrogen and calculated the nucleation rate using supersonic nozzles [10,11], shock tubes [12,13] or nucleation pulse chambers [14]. The expansion of nitrogen investigated in the above studies all ended up with temperatures below the triple point, implying that the condensate is likely in the form of solid particles. Dotson [15] carried out experiment at the NASA Langley's 0.3-m cryogenic wind tunnel and used conditions at temperatures above the triple point. However, condensation occurred outside the CAST-10 airfoil. Hence, the comparison between the simulations of internal flow with this set of test data was not explicit. Goodheart [16] used two numerical methods to model the nitrogen spontaneous condensation flow in supersonic nozzles, but did not validate the calculations due to a lack of corresponding experimental data.

The purpose of this paper is to supply a validated method and an appropriate nucleation theory to predict nitrogen spontaneous condensation flow in interior channel, which is basis theory for the design of wet type cryogenic turbo-expander.

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Nomenclature

Main symbols

A	cross-sectional area (m^2)
A^*	throat area in a nozzle (m^2)
c_p	specific heat capacity at constant pressure ($J\,kg^{-1}\,K^{-1}$)
ΔG^*	Gibbs free energy change at the critical radius (J)
h_{tot}	total enthalpy ($J\,kg^{-1}$)
J	nucleation rate, the number of droplets formed per unit volume per unit time ($m^{-3}\,s^{-1}$)
L	latent heat ($J\,kg^{-1}$)
k_B	Boltzmann constant ($J\,K^{-1}$)
Kn	Knudsen number
m^*	mass of a droplet at the critical radius (kg)
m_1	mass of a molecule (kg)
N_l	Droplet number per unit volume (m^{-3})
$\dot{P}$	expansion rate (s^{-1})
p	pressure (MPa)
p_0	stagnation pressure (MPa)
p_c	critical pressure (MPa)
Q_l	Heat transfer rate per unit area between the liquid and gas phases (J)
q	condensation coefficient
R_g	gas constant ($J\,kg^{-1}\,K^{-1}$)
R_l	Droplet radius (m)
R_l^*	critical radius of a droplet (m)
S	supersaturation ratio
S_m	mass source term
S_u	momentum source term in *x*-direction
S_v	momentum source term in *y*-direction
S_E	energy source term
T	temperature (K)
T_g	gas temperature (K)
T_l	liquid (droplet) temperature (K)
T_0	stagnation temperature (K)
T_c	critical temperature (K)
T_{sat}	saturation temperature (K)
T_{sc}	supercooling (K)
t	time (s^{-1})
u	velocity in the *x*-direction ($m\,s^{-1}$)
v	velocity in the *y*-direction ($m\,s^{-1}$)
v_m	molar volume ($m^3\,mol^{-1}$)
x	*x*-direction
y	*y*-direction

Greek symbols

α_g	volume fraction of gas phase
α_l	volume fraction of liquid phase
κ	isentropic exponent
η	Kantrowitz's factor
λ_g	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
ρ_g	gas density ($kg\,m^{-3}$)
ρ_l	liquid density ($kg\,m^{-3}$)
γ	ratio of specific heat capacity
σ	the bulk surface tension ($N\,m^{-1}$)
ω	acentric factor
μ_{eff}	effective dynamic viscosity (Pa s)

Subscripts

0	stagnation state
1	a single molecule
CNT	classical nucleation theory
CNT, C	classical nucleation theory improved by Courtney
CNT, K	classical nucleation theory improved by Kantrowitz
c	critical state
E	energy
g	gas phase
l	liquid phase
m	mass
m	mole
mix	the mixture of gas and liquid
t	throat
tot	total state
sat	saturation state
wp	Wilson point

2. Experimental technique

2.1. Experimental setup

In the experiment carried out by Ji (XJTU) [17], nitrogen (N_2) expansion was achieved in supersonic nozzles and the Wilson plot above the triple point was also presented. The N_2 condensation experiment was conducted in an experimental setup shown in Fig. 1. The liquid N_2 is obtained from an air separation tower and then evaporates to low-temperature N_2 gas in the Air–N_2 heat exchanger. The throttle valve 2 and bypass valve 3 are used to control the quantity of N_2 gas into the Air–N_2 heat exchanger and the

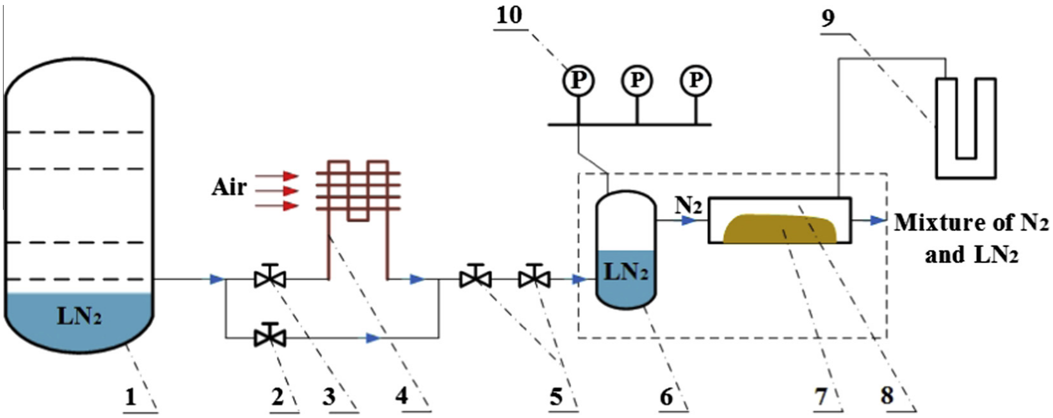

Fig. 1. A schematic diagram of the cryogenic supersonic nozzle apparatus: 1. Air separation tower, 2. Throttle valve, 3 Bypath valve, 4. Air–N_2 heat exchanger, 5. Throttle valves, 6. Dewar, 7. Blade of nozzle, 8. Flow passage, 9. U-shaped manometer, and 10. Standard pressure gauge.