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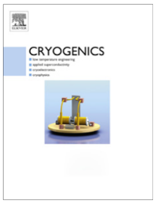

Numerical study on the spontaneous condensation flow in an air cryogenic turbo-expander using equilibrium and non-equilibrium models

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ABSTRACT

The difficulty of data measurement in cryogenic environments and the complicated mechanism of nucleation process have restricted the design of wet type turbo-expander for cryogenic liquid plants. In this paper, equilibrium and non-equilibrium models are used to model the spontaneous condensation flow in a cryogenic turbo-expander along the main stream passage including nozzle, impeller and diffuser. The comparison shows a distinct difference of the predicted wetness fraction distribution along the streamline between the equilibrium model and the non-equilibrium model. In non-equilibrium model, the distributions of supercooling and nucleation rate along the length of turbo-expander are given for the analysis of flow characteristics. The comparison of outlet wetness fraction with the experimental data is also provided for verification and discussion. Both the effects of the rotation on nucleation and the effects of the nucleation on flow along suction side of the impeller are investigated.

1. Introduction

One of the main components of most air separation or cryogenic liquefaction plants is the expansion turbine or turbo-expander. Turbo-expander is the main cold generator in low pressure air separation cycle. Hence, the development of air separation technology is closely related with the evolution of cryogenic turbo-expander. In the turbo-expander, expansion generally takes place within the gas-phase region. The design and fluid mechanism of the gas expansion turbine has been understood comprehensively [1–3]. When gas expansion involves two-phase flow, it will bring about a larger enthalpy drop and more cooling capacity, which reduces the energy consumption of the air separation cycle. Due to this advantage the wet type cryogenic turbo-expander has attracted great interest over many years. Unfortunately, the condensation in wet type turbo-expander is a rather complicated physical process. For example, when flowing through a Laval nozzle, the saturation pressure decreases more quickly than the gas pressure due to a rapid expansion. The saturation point is passed and a supersaturated state can be achieved as illustrated in Fig. 1. With further expansion the gas molecules overcome the free energy barrier and condense onto nuclei (this point is called "Wilson point"). Such process of spontaneous condensation is also called homogeneous nucleation because of no foreign nuclei. At the beginning of condensation, a high supercooling leads to a maximum value of nucleation rate, i.e. the formation of sufficient nuclei within a short moment. It is known as "rapid condensation zone" as shown in Fig. 2. In this stage the nucleation is the predominant factor for the dramatical increase of wetness fraction. As a result of gradual decreases in supercooling and nucleation rate the droplet formation will come to an end. However, the droplet growth continues forcing the gas back to equilibrium state which mainly accounts for the wetness increase. This is called as "wet equilibrium zone".

The spontaneous condensation is accompanied with thermodynamic irreversible losses and consequently reduces the turbo-expander efficiency. In addition, the impact of droplets on the blade causes erosion and wear, which reduces the service life and even influences the operating reliability. Global understanding of spontaneous condensation and homogeneous nucleation is basis of design of high-efficiency wet type turbine. In wet steam turbine field, as early as in 1912 Baumann [4] has proposed an empirical formula for the prediction of wetness loss. Gyarmathy [5] gave an overall summary of the wetness loss and corresponding calculation methods for wet steam turbine. Miller and Schofield [6] illustrated the influence of wetness fraction on the wetness loss based on a low-pressure (LP) steam turbine. Meanwhile, since the classical nucleation theory (CNT) has been established in early 20th century [7–10], many researchers keep working on the improvement

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Nomenclature

Main symbols

D	diameter (m)
h	enthalpy (J/kg)
J	nucleation rate ($\text{m}^{-3}\ \text{s}^{-1}$)
L	latent heat (J/kg)
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})
p	pressure (MPa)
p_0	stagnation pressure (MPa)
p_c	critical pressure (MPa)
q	condensation coefficient
R_g	gas constant ($\text{J kg}^{-1}\ \text{K}^{-1}$)
R	droplet radius (m)
R^*	critical radius of a droplet (m)
S_m	mass source term
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_i	velocity component (m s^{-1})
U	blade velocity (m s^{-1})
v	velocity in the y-direction (m s^{-1})
v_molar	molar volume ($\text{m}^3\ \text{mol}^{-1}$)
x_i	coordinate component
y	wetness fraction

Greek symbols

α_g	volume fraction of gas phase
α_l	volume fraction of liquid phase
η	Kantrowitz's factor
λ_g	thermal conductivity ($\text{W m}^{-1}\ \text{K}^{-1}$)
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
τ	shear stress (N m^{-2})
μ	dynamic viscosity (Pa s)

Subscripts

0	stagnation state
1	impeller inlet
c	critical state
E	energy
g	gas phase
l	liquid phase
m	mass
m	mixture
tot	total state
sat	saturation state
sc	supercooling level

of CNT, such as Courtney [11], Dufour and Defay [12], and Girshick and Chiu [13]. Whereby, the nucleation theory mostly used today is suggested by Kantrowitz who considered the non-isothermal effects [14] into CNT. In cryogenic field, an empirical formula is adopted by Obata et al. [15] to study the influence of wetness on the wet type turbine performance based on a large helium refrigeration system. Faro et al. [16] studied the nucleation of nitrogen during condensation in the gas phase. Willmarth and Nagamatsu [17] measured the static pressure and light scattering to determine the location of nitrogen condensation onset in a supersonic nozzle. Wegener et al. [18–20] also carried out many theoretical and experimental studies on the nitrogen nucleation in wind tunnel or nozzle. Sun et al. [21] studied the nitrogen spontaneous condensation flow in cryogenic nozzles with three nucleation theories. The high rotate speed and strict sealing requirements in cryogenic environment make it difficult for the observation and measurement of the spontaneous condensation in turbo-expander. Fortunately, advances in computer and computational fluid dynamics (CFD) technology supplies us a feasible and visualized method to achieve representation of this phenomenon in cryogenic turbo-expander.

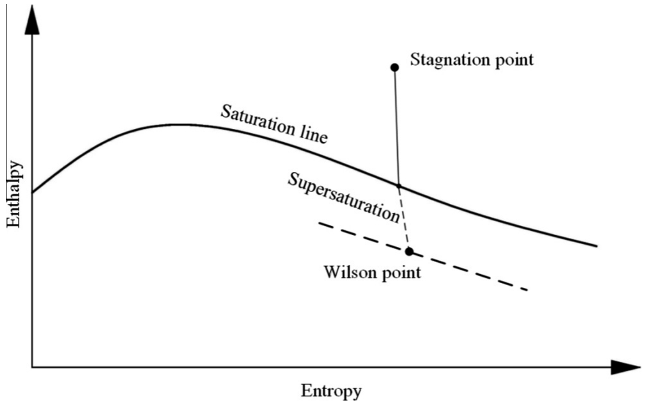

Fig. 1. Representation of spontaneous condensation in h–s diagram.

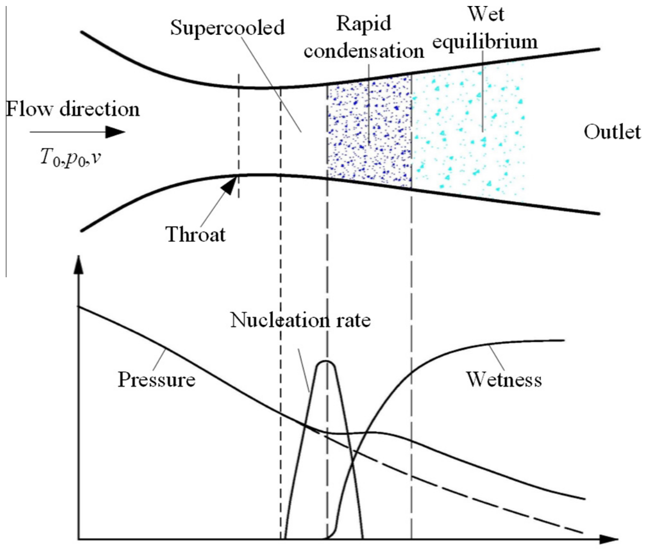

Fig. 2. Schematic diagram of the spontaneous condensation in a Laval nozzle.