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Research Paper

Numerical studies on the off-design performance of a cryogenic two-phase turbo-expander

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HIGHLIGHTS

- The gas expansions in a cryogenic turbo-expander at 420 off-design conditions are simulated.
- The effect of non-equilibrium condensation on the turbine outlet parameter is analyzed.
- The comparison of performance maps in superheated and two-phase conditions are conducted.
- New 3-D turbo-expander performance maps of reaction and efficiency are given.

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ABSTRACT

The two-phase turbo-expanders are in more popular as their advantage of more provided cooling capacity in cryogenic applications. However, it makes the preliminary or alternative design and off-design prediction for this type turbine to remain an unworked area, due to a lack of better understanding for machine performance under two-phase conditions. This paper numerically studies the machine off-design performance based on a cryogenic turbo-expander, which is a key equipment to supply main cooling capacity for an air separation plant. The investigative off-design conditions including 420 numerical cases cover both superheated region and two-phase region. The simulations of gas expansion involving two-phase flow in nozzle and impeller are performed on non-equilibrium condensation model of ANSYS CFX. According to the state of gas expansion end point, the numerical results could be categorized as three types, i.e. superheated, supercooled and spontaneous condensation expansions. The effect of non-equilibrium thermodynamic process on the outlet parameters also is revealed via comparison with results from ideal equilibrium condensation model. Moreover, the turbo-expander performance maps under superheated and two-phase conditions, including mass flow rate, degree of reaction and total-to-static efficiency, are compared and analyzed. Finally, taking liquid mass fraction as a fundamental parameter as well as velocity ratio, new 3-D performance maps of reaction and efficiency are developed. The research achievements could be applicable to turbine design and performance prediction at two-phase conditions.

1. Introduction

The expansion turbine or turbo-expander is one type of the radial-inflow turbines which are now widely used in a wide variety of applications. As early as in 1898 Lord Rayleigh has proposed the concept that the turbo-expander replaces the piston expander for producing cold in air liquefaction. At present, the turbo-expanders have been widely used as the main refrigeration generator in air separation or cryogenic liquefaction plants. The performances of turbo-expander, such as efficiency and reliability, are closely of relevance to the overall economic efficiency of the cryogenic plants. In the preliminary design of complete turbine, many design specifications require well-selected and matched. It is rather ineffective that the designer must specify all of the design parameters. A better method used is to build a new turbine from a reasonable or empirical set of existing values. Thus, it is meaningful to know the performance of the turbine under arbitrarily given specifications so that alternative and improved designs can be compared and assessed. The off-design performance calculations are also helpful in the prediction of a plant under varying operating conditions.

In 1960s, the great application prospect of the radial-inflow turbines used in Brayton cycles for space power systems drives NASA to carry out many investigations. A FORTRAN computer program was developed by NASA for predicting the off-design performance of radial-inflow turbines [1]. The program supplies a convenient way to obtain off-

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Nomenclature

A/m^2	flow area
C/m s^{-1}	absolute velocity
J/m^{-3} s^{-1}	nucleation rate
M/-	Mach number
N/rpm(rev min^{-1})	rotated speed
P/MPa	pressure
Q_m/kg s^{-1}	mass flow rate
R	degree of reaction or gas constant
T/K	temperature
U/m s^{-1}	circular speed
a/m s^{-1}	sound velocity
d/m	impeller tip diameter
h/J kg^{-1}	static enthalpy
h_0/J kg^{-1}	total enthalpy
Δh/J kg^{-1}	enthalpy drop
r/m	liquid droplet radius
u, v, w/m s^{-1}	velocity component
v_s/-	velocity ratio
x	x-coordinate or quality
y	y-coordinate or liquid mass fraction
y_{ih}/-	liquid mass fraction by isenthalpy transformation
z/-	z-coordinate

Greek letters

α/-	volume fraction
β/-	relative velocity angle
γ/-	heat capacity ratio
ρ/kg m^{-3}	density
ξ/-	loss coefficient
η/-	isentropic efficiency

Subscript

0	total or stagnation state
1	Nozzle outlet
2	impeller inlet
3	impeller outlet
c	critical state
in	nozzle inlet
g	gas
l	liquid
Neq	non-equilibrium
Eq	equilibrium
$equvi$	equivalent parameter
sat	saturated state
rel	relative

design performance without making actual tests. Aiming at the aerodynamic design of turbines and compressors, Glassman [2] summarizes some NASA Lewis computer codes, which also could realize the calculations of design and off-design performance.

Baines and Whitfield [3] present a procedure for analyzing the complete performance of radial-inflow turbines based on one-dimensional gas dynamics. They derived a one-dimensional expression representing the fundamental gas dynamics for the complete turbine components as shown in Eq. (1). Ghosh et al. [4] developed a 1-D theoretical model to investigate the complete performance maps of a cryogenic turbo-expander. The influence of varying pressure ratio and speed on mass flow and efficiency were determined from design and off-design calculations. Aungier [5] pointed out that a general performance map for all similar turbines could be established through proper definition of several fundamental equivalent performance parameters. The six non-dimensional groups are $\left\{\frac{Q_m}{A\rho_c a_c},\frac{Nd}{a_c},\frac{\Delta h_0}{a_c^2},\frac{\Delta h_{0,s}}{a_c^2},\frac{C}{a_c},\nu_s,\eta\right\}$, which cover the four fundamental units: mass, length, time and temperature. A generalized relationships chart provides the recommended values of velocity ratio and estimates of expected efficiency as a function of specific speed. The significance is to guide the designer in selecting the design parameters or improving the performance via comparisons.

$$\frac{Q_m\sqrt{\gamma R T_{0x,rel}}}{\gamma A_y P_{0x,rel}} = \cos\beta_y M_{y,rel}\left(1+\frac{\gamma-1}{2}M_{y,rel}^2\right)^{-\frac{1}{2}\frac{\gamma+1}{\gamma-1}} \times\left(1-\frac{\gamma-1}{2}\xi_{xy}M_{y,rel}^2\right)^{\frac{\gamma}{\gamma-1}}\times\left(1-\frac{\gamma-1}{2\gamma R T_{0x,rel}}(U_x^2-U_y^2)\right)^{\frac{1}{2}\frac{\gamma+1}{\gamma-1}} \quad (1)$$

In recent years, the great success of the Organic Rankine Cycles (ORC) applied in the low-grade energy utilization makes more and more researchers concern the radial-inflow turbine issues. The heat sources of ORC generally contain industrial waste heat, solar energy, ocean energy, biomass energy and so on, of which the temperature, pressure and mass flow are always easy to fluctuate. Therefore, turbine performance under off-design conditions appears especially important and must be taken into account in the cycle design and optimization. For an R143a radial-inflow ORC turbine in sensible geothermal conditions, Emilie et al. [6] numerically investigated the turbine performances under the off-design operating conditions. Dong et al. [7] carried out the preliminary 1D analysis and 3D simulations of the first stage of a two-stage radial-inflow turbine at nominal and off-design conditions, which is applied in a supercritical ORC. Zheng et al. [8] employed mathematic method and CFD method for analyzing the ORC turbine performance under design and off-design points.

With the development of high-efficiency cryogenic plants, the interest on two-phase turbo-expander is also continuously growing. The achievement of two-phase flow state at the turbo-expander outlet will supply more cooling capacity for the whole plants. Unfortunately, the phase-change expansion is a non-equilibrium spontaneous condensation process. It not only leads to additional efficiency loss, but also raises a rough issue for the turbine aerodynamic design and thermodynamic performance prediction. Very few literatures focusing on the cryogenic two-phase turbo-expander are published. Sixsmith [9] at Creare Inc. developed a small two-phase turbo-expander in helium liquefier, which could supply 444 W cooling capability for the particle accelerator of Fermi National laboratory. The Naka Fusion Centre [10,11] in Japan designed and manufactured a two-phase helium turbo-expander with a desired efficiency 70% and impeller diameter 59 mm. Obata et al. [12] proposed a theoretical method to investigate the wetness effect on the helium turbine performance. Niu et al. [13] experimentally studied the turbine thermodynamic performance under two-phase conditions in an air separation test rig. Sun et al. [14,15] provided the analysis of spontaneous condensation flow through the whole turbine channel with the aid of CFD software, and also presented the quantitative analysis of wetness loss. Chen et al. [16] mainly investigated the influence of rotor blade profile on the gas phase-change expansion and subsequently on the turbo-expander performance.

Most literatures on the cryogenic two-phase turbo-expander are still stuck in the understanding of spontaneous condensation fundamental flow theory or few experimental points test. A comprehensive guide theory on the design and performance prediction of this type turbo-expander is fairly lacking. In this paper, the off-design performance of a cryogenic two-phase turbo-expander are predicted and analyzed based on the validated numerical model [14]. The off-design conditions containing 420 numerical cases are determined by the variations of inlet temperature, inlet pressure and rotated speed. The results will reveal the laws of turbine performance maps under two-phase conditions.