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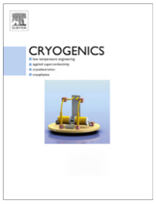

The measurement of thermodynamic performance in cryogenic two-phase turbo-expander

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ABSTRACT

Liquid fraction measurement in cryogenic two-phase flow is a complex issue, especially for an industrial cryogenic system. In this paper, a simple thermal method is proposed for measuring the liquid fraction in cryogenic two-phase turbo-expander by an electric heating unit in experimental study. The liquid fraction of the cryogenic two-phase flow is determined through the heat balance built at the outlet of the turbo-expander (inlet of heating unit) and the outlet of the heating unit. Liquid fractions from 1.16% to 5.02% are obtained from five two-phase expansion cases. Under the same turbo-expander inlet pressure and rotating speed, five superheated expansion cases are tested to evaluate the wetness loss in two-phase expansion. The results show that the proposed method is successful in measuring the liquid fraction of cryogenic two-phase expansion for turbo-expander in an industrial air separation plant. The experimental isentropic efficiency ratio and the tested Baumann factor decrease with the increasing mean wetness. Based on prediction of Baumann rule, the cryogenic turbo-expander with low liquid fraction in two-phase expansion cases suffers from more severe wetness loss than that with the higher liquid fraction.

1. Introduction

Turbo-expander is well known as one of the most significant devices to generate cooling capacity through isentropic expansion in high rotating speed. It is characterized by very high speed, light weight and high efficiency and is widely used in almost every modern air separation plants. More cooling capacity and higher liquefied fraction can be provided to the host cryogenic system when a turbo-expander operates into two-phase region, which could lead to the improvement of system efficiency through lower the system power consumption. Increasingly more designers have strived to utilize two-phase expansion turbo-expander in cryogenic system. In 1990, a miniature wet turbo-expander for a helium liquefier has been developed by Sixsmith et al. [1]. In the same year, a performance tests on a cryogenic turbo-expander operated in two-phase region for a large scale helium cryogenic system are conducted by Kato [2].

Liquid fraction (wetness) measurement is crucial in performance analysis of a two-phase expansion turbine. Therefore, as rapid gaseous flow experiences phase transition into two-phase region, determination of flow thermodynamic state becomes a focused point of vital concernment. In superheated region, the pressure and temperature of working flow are independent parameters of each other, i.e. the thermodynamic state parameters such as specific enthalpy, specific entropy of gaseous fluid are determined by both pressure and temperature. However, in two-phase region, the pressure and temperature are one-to-one correspondence and no longer independent parameters of each other. The working flow thermodynamic state such as specific enthalpy, specific entropy and mass liquid fraction cannot be determined from its pressure and temperature. Therefore, one more independent parameter besides pressure or temperature is needed for liquid fraction determination of two-phase flow.

Since heating method is successfully applied in operating turbine by Moore in British Central Electric Research Laboratory (CERL) in 1976, condensation method, throttling method etc. were developed for wetness measurement [3]. For cryogenic radial-inflow turbo-expander, Ardashev and Plachendovskii [4] conducted the research on cryogenic turbo-expander operated in two-phase regime, liquid fraction in the outlet of turbo-expander reached 8–14% measured by an electric heater in 1984, but the liquid fraction measurement equipment and principle was not described particularly. Optical method is another option for wetness measurement. Based on the Mie scattering from liquid droplets, diameter and distribution droplets can be measured, which has been proved by many successful experiments. In 2009, Cai and Niu [5] experimentally studied the properties of the wet steam

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Nomenclature

T	temperature (K)
p	pressure (MPa)
h	Enthalpy (J kg^{-1})
s	entropy (J kg^{-1} K^{-1})
U	voltage (V)
I	electric current (A)
D	diameter (mm)
P	electric power (W)
Q	heat (J kg^{-1})
m	mass flow rate (kg s^{-1})
y	liquid fraction
η	isentropic efficiency
σ	error

Subscripts

in	turbo-expander inlet
out	turbo-expander outlet
he	electric heater outlet
t	two-phase expansion test
s	superheated expansion test
h	heating dissipation test

flow in the low pressure 300 MW direct air-cooling steam turbine by using an optical-pneumatic probe. In 2014, Schatz and Eberle [6] researched both steam quality and the droplet size spectrum which measured by using a miniature combined optical/pneumatic probe in last stages of low pressure steam turbines.

The occurrence of super-saturation and spontaneous condensation in a rapid gas flow expanding into two-phase region has been researched for many years. Since the classical nucleation theory (CNT) was formulated in the early 20th century by Volmer and Weber et al., experimental studies of nucleation have primarily focused on water. In cryogenic field, following the study on nitrogen condensation in a hypersonic wind tunnel that conducted by Faro in 1952 [7], numerous successful experiments on the limits of super-saturation (Wilson Line) and nucleation rate with phase transition of argon and nitrogen by using supersonic nozzle [8], shock tube [9,10] and nucleation pulse chamber [11,12] were carried out.

As spontaneous condensation takes place in the flow path in a turbo-expander, liquid phase presence could lead to two main problems. The first problem is mechanical erosion caused by the long-term high velocity impact of liquid particles on turbo-expander blades. The impeller blades can be roughened, pitted or even mutilated. So, it is normal to set an acceptable wetness limit in both wet steam turbines and cryogenic turbo-expander design. Secondly, it was found that the isentropic efficiency of steam turbines or turbo-expander operated in two-phase region was considerably lower than that in superheated region. In wet steam turbine, Baumann rule was established as early as 1910 for evaluating the wetness loss in wet steam turbine, which indicated that 1% of mean wetness was likely to cause about 1% reduction of dry isentropic efficiency [13]. Corresponding to the original Baumann factor $\alpha_B = 1$, a considerable variation of tested Baumann factor (0.4–2.0) was observed based on a large number of experiments in reaction and impulse type turbines [14]. However, this conveniently applicable theory can provide little fundamental knowledge of wetness loss origin. For a better understanding of condensing flow in steam turbine, Gyarmathy [15] illustrated the detailed relaxation process, specifically, spontaneous condensation takes place if the rapid steam expands to a certain level of sub-cooling, and the latent heat is released from droplets to sub-cooling vapor and brings the steam back to equilibrium condition. In 1972, Miller and Schofield [16] published the tested Baumann factors for different mean wetness conditions in a wet steam turbine through experimental tests. They found that the tested Baumann factors at low average wetness region are larger than value of order 1 that expected by Baumann, which indicates that super-saturation effect produces a significant part of total loss in wet expansion. In order to assess the wetness loss more accurately, the wetness losses in steam turbine are divided into three main categories, namely the thermodynamic loss, the mass flow loss and the mechanical loss, according to the evaluation principle of wetness loss first developed by Gyarmathy and classification of wetness losses introduced by Moore, Guo [17], Laali [18] and Kawagishi [19].

In mathematical analysis for radial-inflow turbo-expander performance in wetness condition, Aungier [20] represented an empirical treatment for liquid phase by assuming the liquid droplets are ineffective in transferring work because it cannot follow the vapor phase streamlines. Another theoretical method is proposed by Obata to research the wetness effect on two-phase turbo-expander performance based on a large helium refrigeration system [21].

As reference to ASME PTC6-2004 for steam turbine, wetness can be determined from pressure and enthalpy, and heat balance is an applicable method to measure the wetness. In wet turbo-machinery performance tests, heating method is always firstly applied in wetness measurement. Moreover, in these cryogenic gas expansion and spontaneous condensation experiments [8–12], there are no external disturbances such as secondary flow or corner flow as well as boundary layer which will occur in turbo-expanders. So, taken the complicated cryogenic condition into consideration, the advantages of simple measuring principle and high reliability of heating method is preferred to other methods in cryogenic turbo-expander performance tests. In this article, a simple thermal method based on heat balance method is proposed for measuring the liquid fraction in cryogenic two-phase turbo-expander. An experimental test part is designed and integrated into the pipeline after the two-phase turbo-expander in an industrial air separation plant. With an electric heating unit, the two-phase flow out of the turbo-expander is heated into superheated state. And then based on thermal equilibrium relationship and take the heat loss along the test part into account, the liquid fraction of the cryogenic two-phase flow can be determined through the enthalpy and pressure at the outlet of the turbo-expander and the outlet of the heating unit. Liquid fraction from 1.16% to 5.02% is obtained from five two-phase expansion test cases 1*t*–5*t* (arranged according to the increasing liquid fraction). In order to evaluate the wetness loss, five superheated expansion processes, 1*s*–5*s*, are tested under identical turbo-expander inlet pressure and identical rotating speed corresponding to test cases 1*t*–5*t*, respectively. Compared with Baumann rule which indicated that 1% growth in liquid fraction leads to 1% efficiency reduction for the two-phase expansion process in a steam turbine, the isentropic efficiency ratio and tested Baumann factors in comparative tests indicates that cryogenic turbo-expander with low liquid fraction in two-phase expansion tests suffers from wetness loss more severely than that the two-phase expansion with the higher liquid fraction.