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An experimental study of partial admission losses with various blade tip clearances using a linear cascade

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ABSTRACT

Turbo-expanders have been used for energy conversion in many fields. They are sometimes operated in partial admission mode, depending on the stability of the energy source, such as solar energy or waste thermal energy, which can fluctuate depending on environmental or process condition. The ability to operate in partial admission can be advantageous because it allows continuous operation without interchanging components. However, this method also leads to lower turbo-expander efficiency. This experimental study was conducted to investigate losses at various partial admission rates. In addition, the effect of tip clearance was studied since it is another important parameter affecting turbo-expander performance. A linear cascade was fabricated with a nozzle that was set to 65° based on the axial direction. A blade row was designed to be movable along the pitchwise direction in order to investigate flow characteristics as a function of blade movement. Flow structures and pressure losses were measured for various partial admission rates and tip clearances. The experiment was conducted at a Reynolds number of 3×10^5 based on the chord. The experimental results showed that losses in the passages depended not only on partial admission rate but also location relative to the nozzle.

1. Introduction

Turbo-expanders are a core component in certain types of power generation systems, they have been used in many fields of application, including power plants, chemical process industries, transportation and so on. Recently, turbo-expanders have been used in the field of energy conversion to generate electricity from renewable energy sources, such as solar, waste thermal energy, ocean energy, geothermal energy and so on [1–4]. However, these renewable energy sources usually involve variable environmental conditions or working processes. As a result, the mass flow rate into turbo-expander can be varied because the available energy is fluctuated. Thus, turbo-expanders are often operated at partial admission. Operating the turbo-expander in partial admission mode is much better than stopping operation due to the reduced mass flow rate. In general, the adjustment of partial admission rate is performed by varying the spouting area at the nozzle [5].

The partial admission method started to control the output power of turbo-expanders in response to a required load. This technique has been popular because it does not require replacing any components or complex control devices. The partial admission rate is defined as the ratio of the spouting area of the nozzle to the full admission area on the rotor. Thus, the partial admission rate of 100% is equivalent to full admission. However, when a turbo-expander operates in partial admission, its efficiency typically deteriorates. For this reason, a large number of studies have been conducted over many years focusing on methods to improve turbo-expander's performance by appropriately adjusting its geometric parameters, such as reducing the axial gap between the nozzle and rotor [6], designing the passage channel to reduce non-uniform velocities [7], setting the optimal magnitude of the upper and lower overlap [8], adopting double stages [9], applying concaved blade shape [10] and so on.

When a turbo-expander is operated in partial admission, prediction of its performance is just as essential as improving its performance. Numerous studies have also been conducted that focus on methods of predicting performance. A prediction formula [11]

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Nomenclature

c	chord of blade [mm]
c_x	axial chord of blade [mm]
H	height of cascade [mm]
Ps	static pressure [Pa]
Pt	total pressure [Pa]
R	reference location
s	pitch [mm]
U	uncertainty
u	axial velocity [m/s]
x	axial flow direction
y	pitchwise direction
z	spanwise direction
Greek symbols	
ρ	density [kg/m^3]
ε	partial admission rate [%]
δ	tip clearance gap [mm]
σ	total pressure coefficient
ζ_s	vorticity [1/s]

was developed based on the Suter-Traupel's method and Stenning's method. Another prediction method [12] was developed with an assumption of incompressible flow. For a better prediction, the turbo-expander losses that occur in partial admission, such as scavenge loss, filling/emptying loss, and blade pumping loss, have been separated [13]. These losses were then used to develop a prediction model for an axial type turbo-expander [14]. As another method, a performance prediction was conducted using a relationship between partial admission losses and the influence of geometric parameters [15]. A performance prediction model was developed for a supersonic turbine operating in partial admission with the working fluid R113 [16]. A performance prediction for a single stage axial-type turbine was studied with various partial admission rates [17].

A review of the previous studies on performance prediction for partial admission found that the developed prediction models accurately estimated the turbo-expander's performance when it operated at a high partial admission rate. However, there were some discrepancies between the predicted results and the experimental results when turbo-expanders operated at a low partial admission rate. In particular, when a turbo-expander is operated using a fluctuating thermal energy source, the expander may be operated at a very low partial admission rate. Therefore, it is important to accurately predict the performance of a turbo-expander operating in low partial admission, since the results of this prediction can determine the correct direction of design considering the trade-offs between many design parameters.

In this study, the losses in the passages between blades were investigated with various partial admission rates in order to obtain basic information to develop a better prediction model for a turbo-expander operating at a low partial admission rate. This kind of information could not be found from literature survey. Even though experimental studies performed using a blade row [18–20] to investigate the performance of a partially admitted turbo-expander, those experimental results showed only force variation on the blade. In this experiment, in order to measure the losses in the passage of a turbo-expander operating at a partial admission rate, a blade row with a square-type nozzle was employed. The blade row was designed to be moveable along the pitchwise direction. Flow structure and pressure were measured both up and downstream of the blade row in a steady state. By adjusting the blade row movement, the experiment was conducted with various partial admission rates. In addition, the effect of tip clearance, which is the gap between the blade tip and the casing, was investigated since that is an important parameter affecting the performance of the turbo-expander.

2. Experimental facility

2.1. Cascade apparatus

Fig. 1 shows the configuration of a linear cascade apparatus, consisting of a nozzle and turbine blades. Each blade was marked serially as B_1, B_2 and so on, according to its location. The nozzle was manufactured like a straight duct whose cross-section was a square of 200 mm × 200 mm. Air was spouted toward the blade row through this nozzle from an open-type wind tunnel operated at a rated power of 30 kW. The experiment was conducted at a Reynolds number of 3×10^5 based on the blade chord. Nineteen blades were used in the cascade to simulate a turbo-expander operating in partial admission. Therefore, seven blades could be applied to both sides to appropriately establish a stagnation region, corresponding to the region outside of the admission region, as shown in Fig. 2. This kind of stagnation region is naturally generated when a turbo-expander operates in partial admission.

Fig. 2 shows the configuration of the cascade on a horizontal plane with a coordinate, the blade profile, admission region, nozzle and so on. The origin of the coordinate was set to a point where a line connecting the leading edges of the blades was crossed by a line extended from the right wall of the nozzle on the lower plate. In the coordinate, the y- and z-direction were set to the pitchwise and spanwise directions, respectively. The blade row was moved along the pitchwise direction. The nozzle was installed with an inclination angle of 65° from the x-direction which was equivalent to the axial direction.

The blades used in the cascade had the blade profile of those in a turbo-expander that is used for energy conversion. The blade row was set to a stagger angle of 10.52° and a solidity (c/s) of 1.38, like the original turbo-expander. The blade was enlarged only to reduce the experimental uncertainty. Its chord was 195 mm and the height of the cascade was set to 200 mm. This height is equivalent to the height between the hub and the casing on a turbo-expander. The hub and casing were replaced with a lower and upper plate in the cascade, respectively. In order to adjust tip clearance, which is a gap between the blade tip and the upper plate, without changing the height of the cascade (H), slots were machined in the lower plate so that the blades could move through the slots, as shown in Fig. 3. The blades were installed on the second lower plate underneath the lower plate. Hence, the blades in the cascade were precisely installed with equal pitch due to the slots machined in the lower plate. In addition, the tip clearance was also precisely adjusted using the second lower plate.

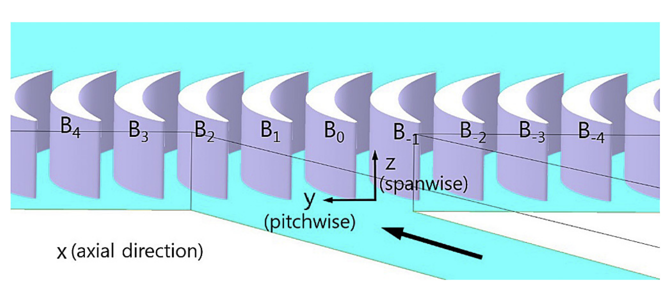

Fig. 1. Configuration of the linear cascade apparatus.