Experimental approach to measure windage loss in supercritical CO_2 condition

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1. Introduction

A concept of fully modularized fast reactor with a supercritical CO_2 (S-CO_2) cooled direct Brayton cycle, namely KAIST Micro Modular Reactor (MMR), for 10MWe power output is developed for the distributed power generation using the nuclear energy. The supercritical CO_2 (S-CO_2) Brayton cycle has high performance in power conversion. It has high efficiency at moderate temperature range, high compactness and simple configuration[1]. This is because S-CO_2 has nonlinear property change without phase change near the critical point(7.38MPa, 31℃)[2]. However, this nonlinearity makes the control of this system difficult. Furthermore, due to the high density of S-CO_2, the windage loss becomes significant in the rotating machinery [3]. Dramatic property change of CO_2 near critical point becomes a challenge to develop a good windage loss model for S-CO_2 conditions. In this paper, the windage loss model of the S-CO_2 turbomachinery is investigated. In addition, measuring windage loss will be performed at the Autonomous Brayton Cycle loop (ABC loop) constructed in KAIST. The loop is designed to investigate the S-CO_2 Brayton cycle's performance and develop design methods of the components.

2. Windage loss in S-CO_2 Brayton Cycle

2.1 S-CO_2 Brayton Cycle

S-CO_2 has nonlinear property changes near the critical point as shown in Fig 1. These characteristics make the S-CO_2 Brayton cycle to have advantages of both gas Brayton cycles and steam Rankine cycles. It has compact turbomachinery and simple configuration because of no phase change. In addition, it achieves reduced compression work and high efficiency. Fig 2 shows CO_2's low compressibility when it is in supercritical state. Fig 3 [4] shows efficiency of various power cycles.

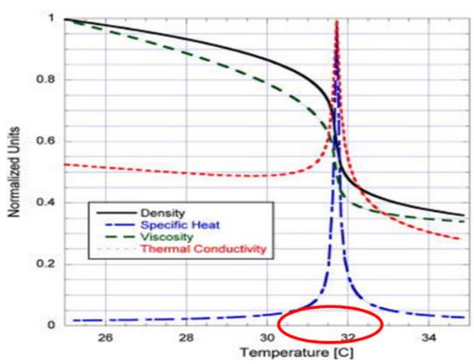

Fig 1. Nonlinear thermo-physical properties of CO_2 near critical point (7.4 MPa)

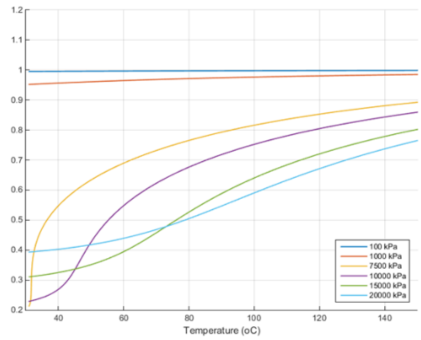

Fig 2. Compressibility factor of CO_2

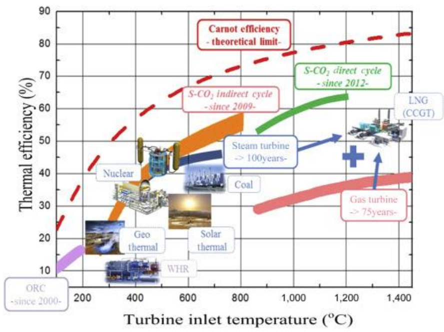

Fig 3. Efficiency of various power cycles

However, despite of these advantages, S-CO_2 Brayton cycle has technical challenges originating from dramatic property changes of CO_2 near the critical point. This characteristics of CO_2 affect the controllability of the system. In addition, the component should be able to handle the unexpected instability.

2.2 Windage loss in S-CO_2 Brayton Cycle

There are several losses while operating turbomachinery. The internal loss is caused in the main flow path while the external loss in the minor flow paths. The internal losses hinder the performance of compressor and the external losses increase input work of the turbomachinery. From the previous experiments, the external losses can be substantial [5].

The windage loss (shaft friction loss) is one of the external losses which is generated by secondary flow. The secondary flow is a rotational flow induced by the rotating shaft's surface. The viscous skin friction acts as torque on the shaft and therefore additional power is needed to overcome this resistance. This loss is not only a function of the turbomachinery geometry but also the fluid's property. The main variables are the shaft length, clearance between the shaft and the wall (stator), density and viscosity of the fluid.

As presented in reference [3], in an S-CO_2 system, the windage loss is a major cause of power loss so the minimization of the loss is necessary to commercialize the S-CO_2 system. However, in the case of S-CO_2 turbomachinery, there are only studies of total external losses. Therefore, the windage loss models are reviewed in this study. Windage loss models were developed in the previous studies [6, 7]. Those models are shown in the equations below.

Mack's model

$$C_f = \begin{cases} \dfrac{1.8}{Rec_r^{1/4}} \dfrac{(1+c_r)^2}{(1+c_r)^2-1}, & Ta \leq 41.3\ (laminar\ flow) \\ \dfrac{K}{Ta^{1/5}}, & Ta > 400\ (fully\ turbulent\ flow) \end{cases}$$

Modified Mack's model

$$C_f = \begin{cases} \dfrac{4}{Re} \dfrac{(1+c_r)^2}{(1+c_r)^2-1}, & Ta \leq Ta_{crit} \\ \dfrac{K}{Ta^{1/5}}, & Ta > Ta_{crit} \end{cases}$$

Vrancik's model

$$C_f = \begin{cases} \dfrac{2}{Re}, & (laminar\ flow) \\ \dfrac{1}{\sqrt{C_f}} = B + 1.768 \ln\left(Re\sqrt{C_f}\right) & (turbulent\ flow) \end{cases}$$

These models are used to calculate the windage loss from the experimental shaft trajectory data as shown in Figs. 4 to 6. The viscosity and density around the shaft are calculated from the previous study [8]. For the early stage of the research, the calculation is simplified by assuming that properties are uniform in axial direction. The time step is 0.0001 sec. The clearance is 200 μm and the axial length is 200 mm. inlet conditions of each test is shown in Fig. 7.

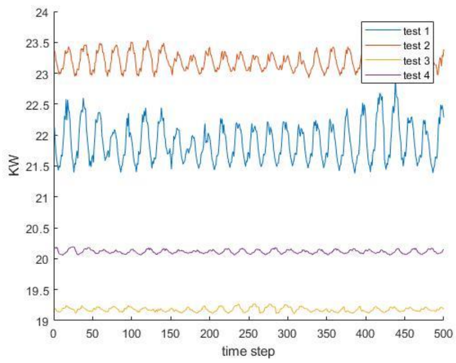

Fig 4. Windage loss with Mack's model

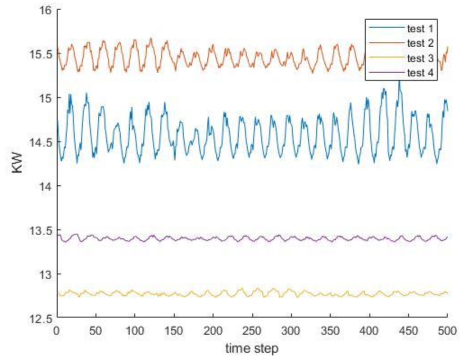

Fig 5. Windage loss with Mack's modified model

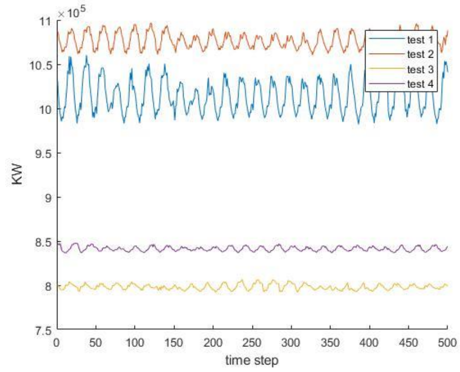

Fig 6. Windage loss with Vrancik's model

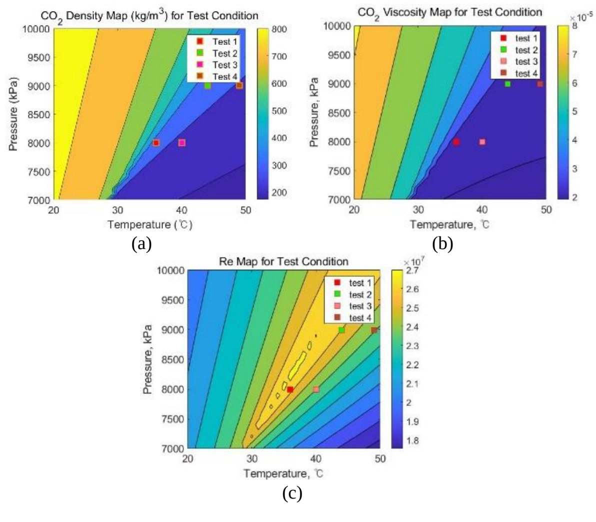

Fig 7. Description of the test condition; (a) Density, (b) Viscosity (kg m^{-1} s^{-1}), (c) Reynolds number

3. Design of Windage Loss Experiments

3.1 ABC loop

The ABC loop has key components of the S-CO_2 Brayton cycle: turbine, compressor, recuperator, pre-cooler, and heater as shown in Fig. 8. This system is designed to withstand more than 100 bar and 100 ℃ to test above the critical point of CO_2.

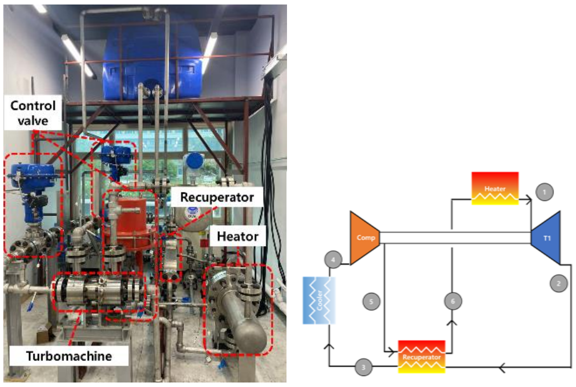

Fig 8. ABC loop and layout

3.2 External Loss Study with AMB Test Rig

The external losses can be calculated as below [5].

$$W_{loss,ext} = W_{input} - H_{CO2} - Q_{water} - Q_{leak}$$

W_{input} can be obtained from power analyzer and other terms are from the sensor data. $W_{loss,ext}$ consists of the following losses.

$$W_{loss,ext} = W_{disk} + W_{windage} + W_{bearing}$$

Therefore, modeling the windage and other losses is required to separately investigate the term. For this, the AMB test rig in Fig. 9 is planned to be used. It is noted that the impeller is removed to omit disk loss in the external loss.

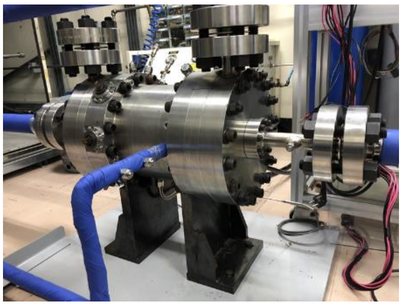
Fig 9. AMB test rig

3. Summary and Conclusions

In this paper, the windage loss models are reviewed and analyzed. As for the further works, the ABC loop in KAIST, which simulates the S-CO_2 power conversion system in an experimental scale, is planned to be used to investigate CO_2 properties effect on the windage loss. With this system, the windage loss test will be conducted for the windage loss model development.

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