Experiment Design for Windage Loss Model Development Applicable to S-CO_2 Turbomachinery

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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 being developed for the distributed power generation using nuclear energy. The S-CO_2 Brayton cycle has favorable performance such as competitive efficiency at moderate temperature range, high compactness and simple configuration [1]. This is because S-CO_2 has nonlinear property change without phase transition near the critical point (7.38 MPa, 31 ℃) [2]. However, this nonlinearity makes the control of this system difficult. Furthermore, 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 windage loss model for CO_2.

In this paper, existing windage loss models are reviewed to examine the applicability to the S-CO_2 and the problems of the existing models. In addition, measuring windage losses under various conditions is planned to be performed at the Autonomous Brayton Cycle loop (ABC loop) in KAIST. The experimental setup attached to ABC loop for the windage model development will be presented in the paper.

2. Windage loss Models for S-CO_2 Turbomachinery

2.1 S-CO_2 Brayton Cycle

S-CO_2 has nonlinear property changes near the critical point as shown in Fig. 1. It makes 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 because of low compressibility as shown in Fig. 2 and recuperation as shown in Fig. 3. Fig. 4 [4] shows efficiency of various power cycles.

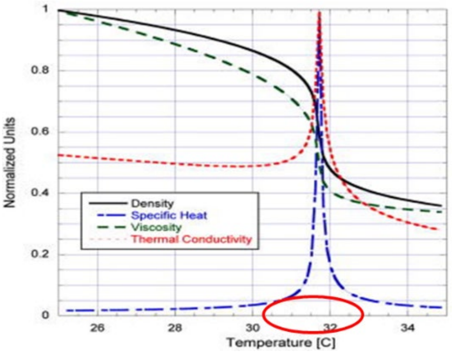


Fig. 1. Thermo-physical properties of CO_2 near critical point (7.4 MPa)

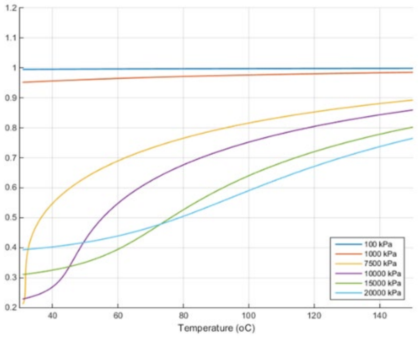


Fig. 2. Compressibility factor of CO_2

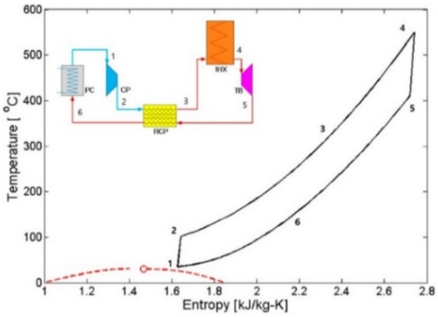


Fig. 3. T-S diagram of S-CO_2 simple recuperated Brayton cycle

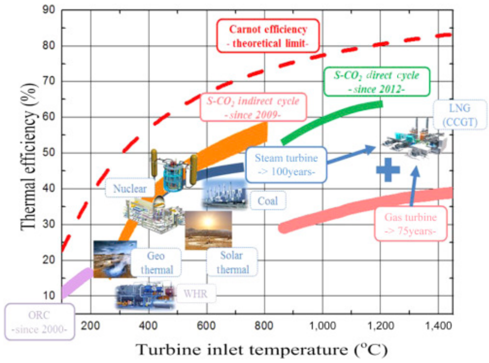


Fig. 4. Efficiency of various power cycles

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 characteristic of S-CO_2 affects the controllability of the system. In addition, the component should be able to handle the instability arising due to properties.

2.2 Windage loss in S-CO_2 Brayton Cycle

There are several losses associated with turbomachinery. The internal loss is in the main flow path as shown in Fig. 5 while the external losses in the minor flow paths in Fig. 6 [5]. The internal losses deteriorate the performance of compressor, and the external losses increase the required input work of the turbomachinery. From the previous experiments, it was revealed that the external losses in an S-CO$_2$ turbomachinery can be substantial [6].

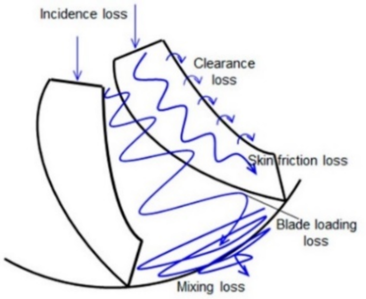
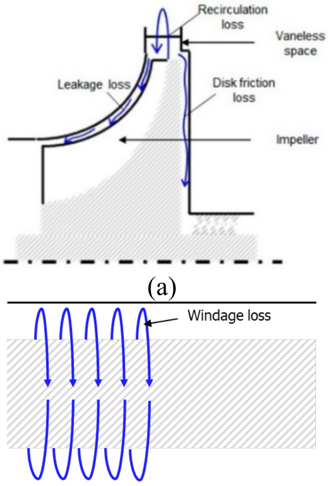


Fig. 5. Internal loss mechanism



(a)

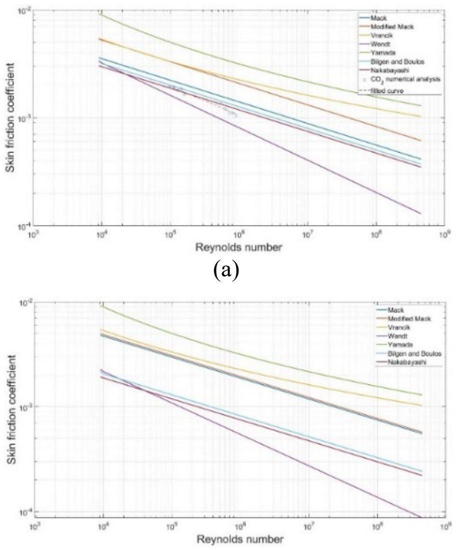
(b)

Fig. 6. External loss mechanism; (a) impeller [5] & (b) shaft

The windage loss is one of the external losses generated by the secondary flow rotating around the shaft. This flow causes viscous skin friction that acts as torque on the shaft. Therefore, additional power is needed to overcome this resistance. This loss is a function of the turbomachinery geometry and the fluid's property as shown in equation (1). The main variables are the shaft length, clearance between the shaft and the wall (stator), density and viscosity of the fluid.

$$P_{windage\,loss} = \omega T_f = \omega \int r_i \tau_f(r_i)\, dA = C_f \pi \rho \omega^3 r_i^4 l \qquad (1)$$

As presented in reference [3], in an S-CO$_2$ system, the windage loss is a major cause of power loss. In Sandia National Lab, scavenging pump is used to reduce the cavity pressure [7] due to this reason. Minimization of additional equipment is necessary to commercialize the S-CO$_2$ system. Therefore, windage loss models to accurately predict C_f in equation (1) are reviewed. Since there are only numerical studies in the case of S-CO$_2$ [8], the reviewed experimental models [9~14] are from air, water, oil experiments. These experimental models and numerical studies with S-CO$_2$ are compared as shown in Fig. 7.

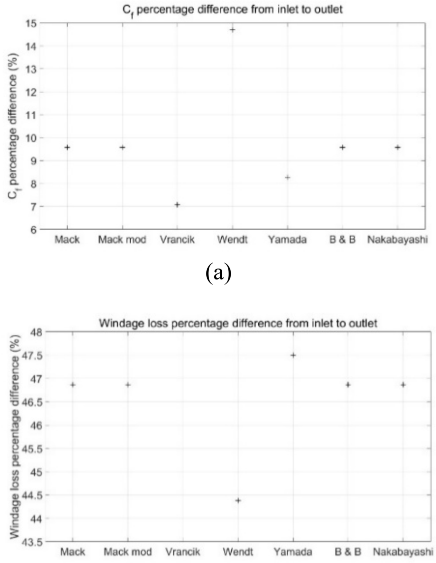


(a)

(b)

Fig. 7. Windage loss model comparison; (a) geometries with numerical study [14] and (b) with KAIST S-CO$_2$ rotor test rig

The comparison (a) shows Nakabayashi model and Bilgen & Boulos model have close prediction values of C_f. However, this changes in comparison (b). Therefore, existing models cannot explain the numerical analysis and test results for all conditions satisfyingly.



(a)

(b)

Fig. 8. Windage comparison; (a) $C_{f,inlet}$ & $C_{f,outlet}$ and (b) $P_{windage,inlet}$ & $P_{windage,outlet}$

The defects of existing windage loss models can be attributed to the rapid property changes of S-CO$_2$, which is not present in other fluids. Since heat is generated from windage loss, inlet and outlet conditions of secondary flow are quite different (inlet: 80 bar & 36 ℃, outlet: 79.5 bar & 70 ℃). This causes large changes in density ρ and thus C_f. This changes are analyzed with comparison (a) $C_{f,inlet}$ & $C_{f,outlet}$ and (b) $P_{windage,inlet}$ & $P_{windage,outlet}$ in Fig. 8.

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. 9. This system is designed to withstand more than 100 bar and 100 ℃ to test above the critical point of CO_2.

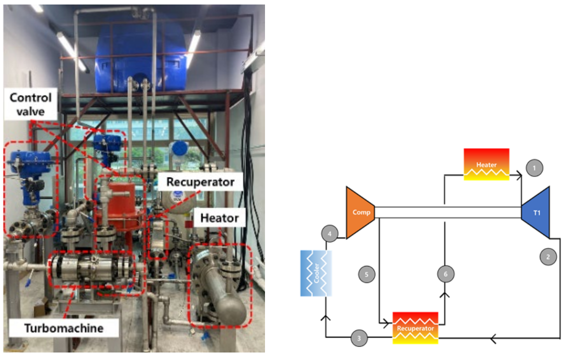


Fig. 9. ABC loop and layout

3.2 External Loss Study with AMB Test Rig

From the experiments, external loss can be obtained as shown in equations (2) and (3) [6].

$$W_{loss,ext} = W_{input} - H_{CO2} - Q_{water} - Q_{leak} \qquad (2)$$
$$W_{loss,ext} = W_{disk} + W_{windage} + W_{bearing} \qquad (3)$$

In equation (2), W_{input} can be obtained from power analyzer and other terms are from the sensor data. $W_{loss,ext}$ consists of the following losses in equation (3) so windage and other losses have to be separated. For this, the test rig shown in Fig. 10 is planned to be used. It is noted that there is no impeller or thrust disk in this test section. In addition, active magnetic bearing (AMB) has negligible friction. W_{disk} and $W_{bearing}$ are examined to be negligible from the Daily & Nece model and Schlichting model as shown in equations (4) and (5).

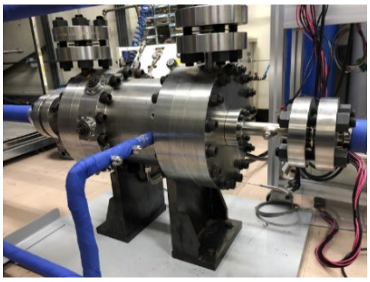


Fig. 10. S-CO_2 rotor test rig

$$W_{disk} = C_m * \frac{1}{2}\rho\omega^2 r_i^5 = 0.5\,W \qquad (4)$$
$$W_{bearing} = 0.0156 * \rho^{0.8}\omega^{2.8}r_o^{-0.4}(r_o^5 - r_i^5)/\mu^{-0.2} = 10.9\,W \qquad (5)$$

C_f will be obtained from wide pressure range. This is expected to contribute to selecting optimum cavity pressure for minimizing the scavenging pump size and the windage loss. Also, C_f will be obtained with close condition and open condition to study the axial flow effect. Finally, correction term will be developed for C_f from $C_{f,inlet}$ condition.

4. Summary and Conclusions

In this paper, the experimental and numerical windage loss models are evaluated. Based on this comparison, experiments for developing proper S-CO_2 windage loss model are designed. As for the further works, the ABC loop in KAIST, which simulates the S-CO_2 power conversion system in a lab 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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