Refinement of Windage Loss Model in S-CO_2 Turbomachinery under Inventory Test Condition

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1. Introduction

The Supercritical CO_2 (S-CO_2) power cycle has emerged as a prominent candidate for power conversion system due to its competitive efficiency even with the moderate temperature heat sources (540~750°C) [1]. The high efficiency of the S-CO_2 cycle, facilitated by the real gas effects of CO_2 near the critical point (30.98°C, 7.3MPa), enables the design of compact turbomachinery. Turbomachinery, including compressor and turbine, is the key component to optimize the S-CO_2 cycle efficiency. Thus, turbomachinery is designed with several loss models to reflect the real component performance with small uncertainty.

The losses can be divided into two types: internal and external losses. Internal losses occur in the main flow paths during expansion and compression, whereas external losses occur in the minor flow paths. Figure 1 illustrates external losses in a radial turbine, where such losses lead to increased motor load, reduced shaft work, and heat generation within the turbomachinery [2].

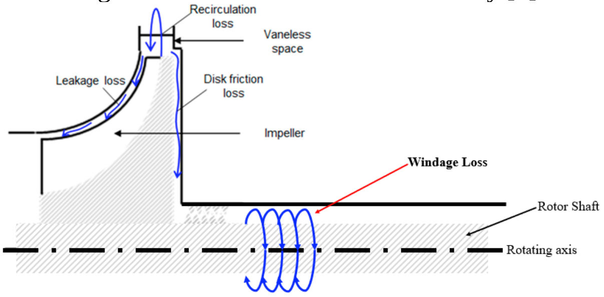

Figure 1. External Loss Clarification in radial turbine [2]

Among all external losses, windage loss is the most significant in S-CO_2 turbomachinery. This loss type has been extensively studied, with various models developed to predict actual turbomachinery performance. Notably, Kim et al. modified Mack's model to develop a windage loss model for S-CO_2

$$W_{wind} = C_f \pi \rho \omega^3 r^4 l \quad (1)$$

$$C_f = \frac{1.8}{Ta_{crit}^{0.4} C_r^{-1.25}} \frac{(1+C_r)^2}{(1+C_r)^2 - 1} Ta_{inlet}^{-0.1} \left(\frac{\gamma_{inlet}}{\gamma_{air}}\right)^{-0.4051} \quad (2)$$

This model incorporates additional $\left(\frac{\gamma_{inlet}}{\gamma_{air}}\right)^{-0.4051}$ term to reflect the change in properties of the working fluid due to viscous heating [3]. Although validated using experimental data from an Active Magnetic Bearing (AMB) test rig, this rig only reflects the turbomachinery section of the S-CO_2 power cycle. Comprehensive validation using the Autonomous Brayton Cycle (ABC) loop, designed to replicate a simple recuperated S-CO_2 Brayton Cycle, is essential. This paper presents a thorough analysis of the existing windage loss model under actual cycle operating conditions and proposes a revised model based on experimental data to enhance model accuracy and practical applicability.

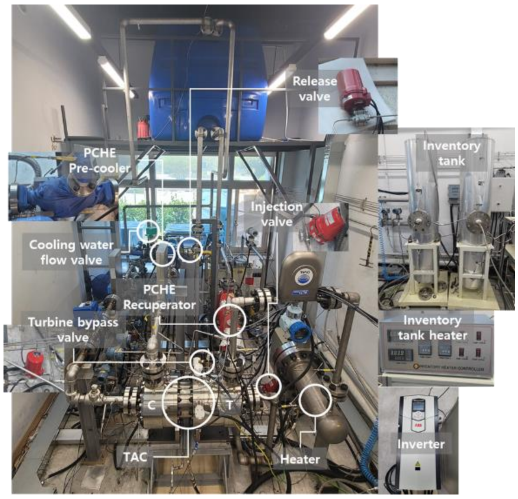

Figure 2. ABC Loop Overview

2. Methods and Results

2.1 Validation of Previous Model

To validate the existing windage loss model further, it is applied in actual operating scenario. Due to fluctuation of the electricity demand, the power cycle may need to operate under off-design conditions. In case of S-CO_2 cycle, the inventory control is mainly used, because it allows high cycle efficiency during off-design operation [4]. The ABC loop's inventory control scenario, involving CO_2 charging and discharging, demonstrates significant turbine efficiency fluctuations compared to shaft rotational speed, as shown in Figure 3. During the experiment, the shaft rotational speed only varies maximum 3% from the designed value, whereas the turbine efficiency ranges from 10% to 70%. This discrepancy highlights the need for a revised model.

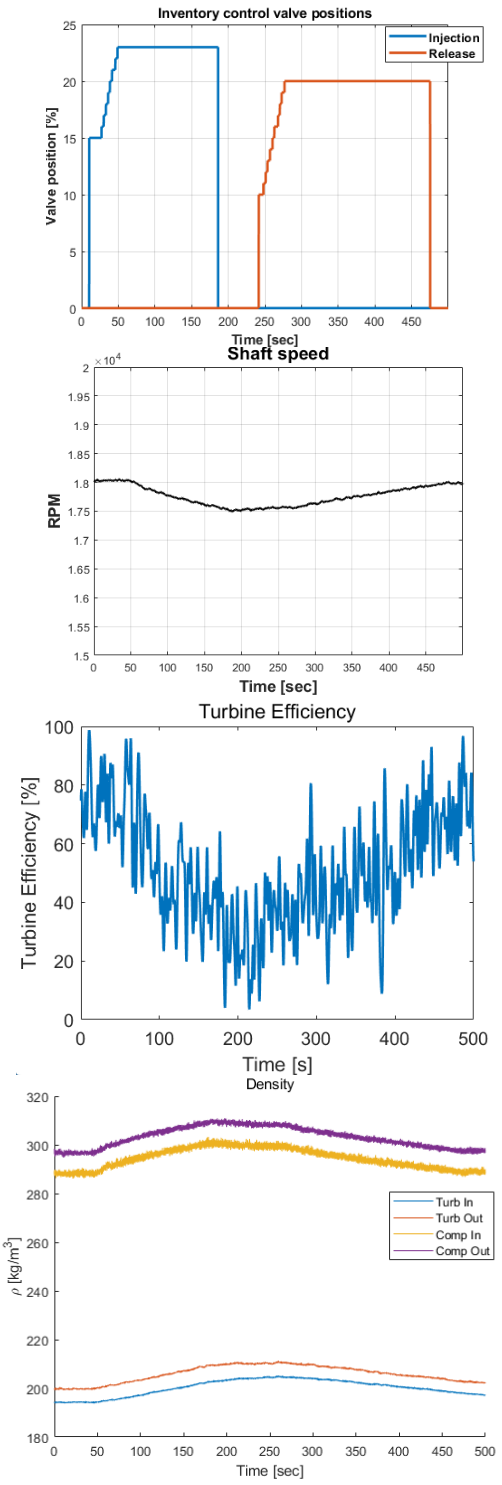

Figure 3. Inventory Test Experiment Data

2.2 Suggestion of Revised Model

As the injection valve opens, the CO_2 is charged to the loop and discharged as the release valve opens. During the charging/discharging of the CO_2, the density at the inlet/outlet of the turbomachinery changes. Since the windage loss is dependent on the density, as shown in Equation 2, the newly proposed model needs to include a term to reflect the change in properties of the working fluid due to density variation. Three candidate models are proposed for the modified windage loss model based on Kim's model.

$$C_{f,modified1} = \frac{1.8}{Ta_{crit}^{0.4} C_r^{-1.25}} \frac{(1+C_r)^2}{(1+C_r)^2-1} Ta_{inlet}^{-0.1} A * \left(\frac{\gamma_{inlet}}{\gamma_{air}}\right)^B \left(\frac{\rho_{CO_2}}{\rho_{air}}\right)^C \quad (3)$$

$$C_{f,modified2} = \frac{1.8}{Ta_{crit}^{0.4} C_r^{-1.25}} \frac{(1+C_r)^2}{(1+C_r)^2-1} Ta_{inlet}^{-0.1} A * \left(\frac{\gamma_{inlet}}{\gamma_{air}}\right)^B \left(\frac{\rho_{Inlet}}{\rho_{Outlet}}\right)^C \quad (4)$$

$$C_{f,modified3} = \frac{1.8}{Ta_{crit}^{0.4} C_r^{-1.25}} \frac{(1+C_r)^2}{(1+C_r)^2-1} Ta_{inlet}^{-0.1} A * \left(\frac{\gamma_{inlet}}{\gamma_{air}}\right)^B \left(\frac{v_{Inlet}}{v_{Outlet}}\right)^C \quad (5)$$

These models adjust the base model by incorporating terms that reflect density changes. The least squares method is used to determine coefficients A, B, and C, with the results summarized in Table 1 and Figure 4-5.

Table 1. Result of the Least Square Method

	A	B	C	R^2
Modified 1	0.00461	-0.3866	1	0.998
Modified 2	0.5324	0.1598	0.456	0.975
Modified 3	0.5955	0.04878	-0.529	0.982

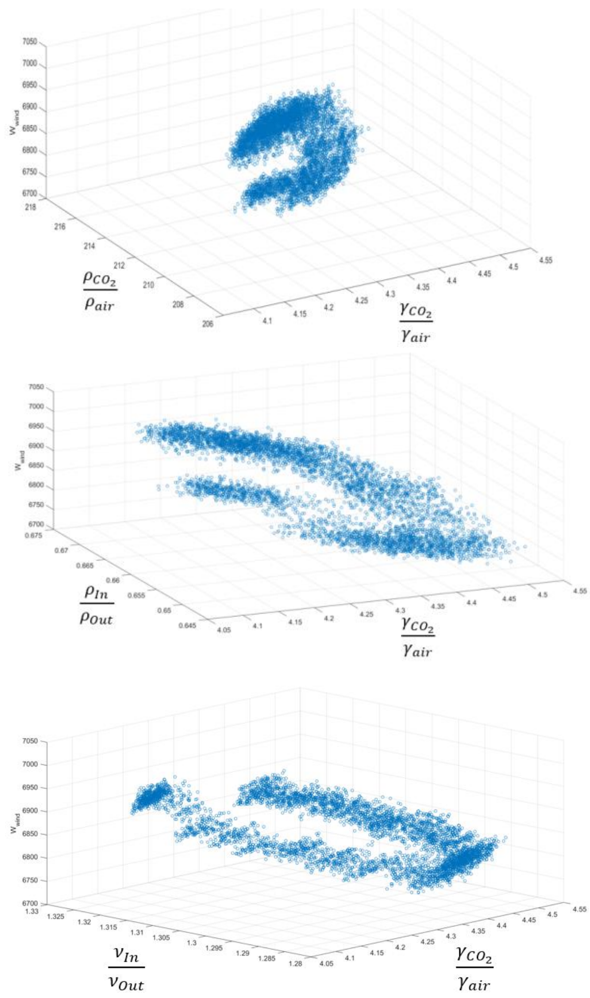

Figure 4. Windage loss vs. different variables

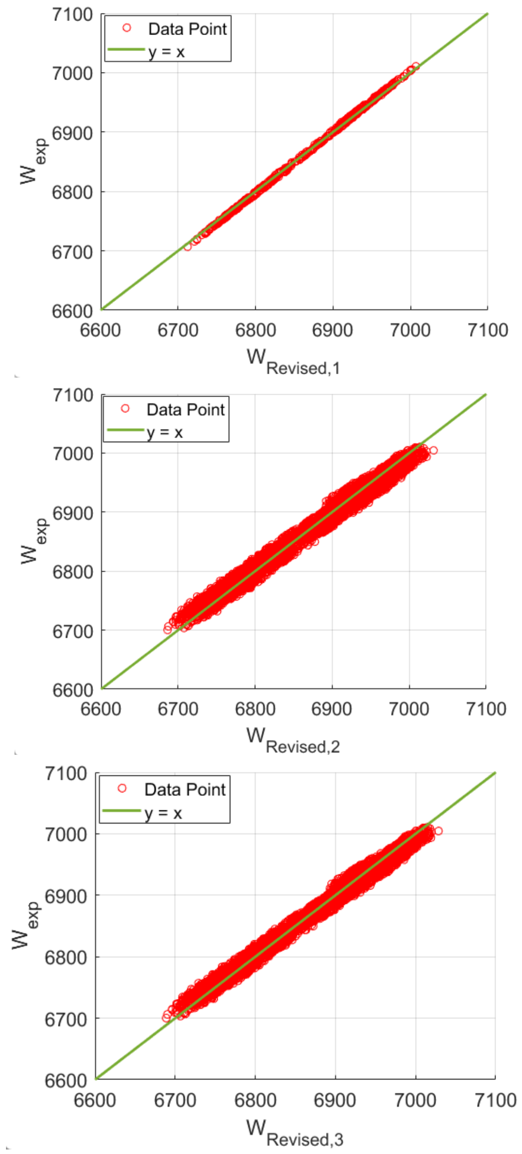

Figure 5. Experimental Windage Loss vs. Calculated Windage Loss

3. Summary and Conclusions

In this research, the validity of the proposed model is further evaluated using ABC loop with inventory control experiment data. During the inventory control experiment, the CO2 were charged/discharged from the loop, influencing the density of the fluid at the inlet/outlet of the turbomachinery. Based on the data, the windage loss model needed an additional term to reflect the change in properties of the working fluid due to density variation. Thus, three candidates were suggested to revise the windage loss model based on Kim's model. Based on the experimental data, the revised model enhances the accuracy and applicability of the windage loss model in real operating scenarios. For the further work, additional experimental cases using ABC loop are needed to further enhance the reliability of the suggested model.

NOMENCLATURE

Symbol [Unit]	Definition
W_{wind} [W]	Windage loss
C_f [-]	Skin Friction Coefficient
ω $\left[\frac{rad}{sec}\right]$	Rotational Speed
r $[m]$	Radius
l $[m]$	Shaft Length
ρ $\left[\frac{kg}{m^3}\right]$	Density
Ta [-]	Taylor Number
C_r [-]	Clearance Ratio
γ [-]	Cp/Cv Ratio
ν $\left[\frac{m^2}{s}\right]$	Kinematic Viscosity

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