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Uncertainty issues on S-CO_2 compressor performance measurement

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1. Background

As a part of the next generation nuclear power system development, active research on Supercritical CO_2(S-CO_2) Brayton cycle technology development has been performed by KAIST research team. Since higher cycle efficiency and compactness of whole system are most attractive characteristics of the S-CO_2 Brayton cycle. An additional economic benefit is expected by applying the S-CO_2 Brayton cycle to power conversion system of the next generation nuclear power system.

Even the concept of S-CO_2 Brayton cycle power conversion system was discovered in early 1970s, active development activities were not present due to the technical limitations at that time. Owing to the rapid growth of heat exchanger and auxiliary system technologies, realization of the S-CO_2 Brayton cycle became more feasible nowadays. Thus, active research works on the S-CO_2 Brayton cycle development have been conducted around the world.

In 2012, KAIST research team constructed S-CO_2 Pressurization Experiment(SCO2PE) facility to demonstrate elementary technology of the S-CO_2 Brayton cycle in a lab scale. Main reason why the elementary technology demonstration was required is due to the special characteristics of CO_2 thermodynamic property variation near the critical point. Since there is a sharp peak region for the specific heat near the critical point, conventional design and analysis methodologies which are based on ideal gas assumptions (constant specific heat) should be verified with S-CO_2 condition.

Currently, SCO2PE facility operation is focused on the main compressor performance measurement to accumulate back up data for the validation and verification of a compressor design and analysis code.

In the process of the data post-processing, the authors found out that the S-CO_2 compressor performance experiment has an issue of uncertainty on the performance measurement. In this paper, the uncertainty analysis results with various compressor inlet conditions for SCO2PE facility will be discussed

2. Performance measurement

Regarding the compressor performance measurement, the main concerns are pressure ratio and isentropic efficiency of a compressor for various flow rates.

$$PR = \frac{P_{out}}{P_{in}} \qquad (1)$$

$$\eta = \frac{h_{o,out,isen} - h_{o,in}}{h_{o,out} - h_{o,in}} \qquad (2)$$

Thus, pressure and temperature measurement sensors and a mass flow meter are installed on the compressor performance test facility. Sometimes, density meter is used for the measurement. In SCO2PE facility, Rosemount 3051S pressure transmitter and PT100ohm RTD sensors are installed to measure pressure and temperature respectively.

Table 1. Accuracy of each sensors on SCO2PE facility

Sensor type	Accuracy
RTD	±0.2°C
Pressure transmitter	±0.09%
Mass flow meter	±0.16%

The turbomachinery isentropic efficiency measurement is related to the enthalpy values. Since direct measurement cannot be made for enthalpy values, NIST fluid property database was utilized with the measured temperature and pressure. For the pressure ratio measurement, it can be directly calculated with the compressor inlet pressure and the outlet pressure measurement.

3. Uncertainty Analysis

The uncertainty represents reliability of the experiment data which is associated with accuracies of independent measurements. When equation for data manipulation is a function of independent measurement variables, $f = f(x_1, x_2, .., x_i)$, relative uncertainty can be obtained by the sum of partial derivatives of f with each variables.[1]

$$\frac{\omega_f}{f} = \left\{ \sum \left[\left(\frac{\partial f}{\partial x_i} \right)^2 \omega_{x_i}{}^2 \right] \right\}^{1/2} \qquad (3)$$

Thus, relative uncertainty of the pressure ratio can be calculated by equation (4) while equation (5) represents relative uncertainty of the efficiency.

$$\frac{\varpi_{PR}}{PR} = \left[\left(\frac{\varpi_{P_{out}}}{P_{out}} \right)^2 + \left(\frac{\varpi_{P_{in}}}{P_{in}} \right)^2 \right]^{1/2} \qquad (4)$$

$$\frac{\omega_\eta}{\eta}=\left[\begin{array}{l}\left(\dfrac{1}{h_{out,isen}-h_{in}}\omega_{h_{out,isen}}\right)^2+\left(\dfrac{(-1)}{h_{out}-h_{in}}\omega_{h_{out}}\right)^2\\ +2\left(\dfrac{h_{out,isen}-h_{out}}{\left(h_{out}-h_{in}\right)\left(h_{out,isen}-h_{in}\right)}\omega_{h_{in}}\right)^2\end{array}\right]^{1/2} \qquad (5)$$

3. Results

Relative uncertainty of pressure ratio measurement is affected by the accuracy of a pressure transmitter only. Thus, very low uncertainty can be obtained as long as a high accuracy pressure transmitter is used for the pressure measurement. Actual uncertainty calculation result of the pressure ratio is below 0.01(1%) for most of considered compressor inlet conditions, 20^{o}C to 50^{o}C of temperature and 3000kPa to 9000kPa of pressure range.

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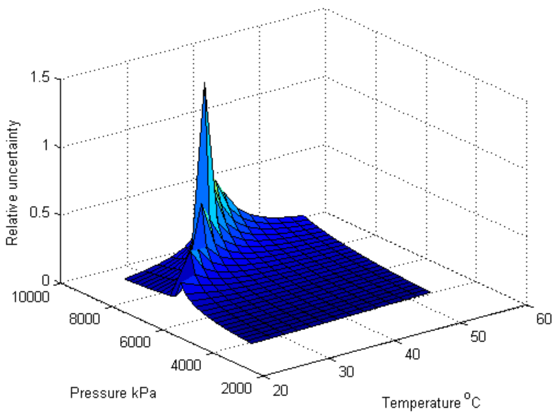

Figure 1. Uncertainty analysis result of efficiency measurement with temperature and pressure measurement for various compressor inlet conditions

The efficiency uncertainty analysis result shows that very high relative uncertainty on efficiency measurement is observed near the critical point and it reduces as the compressor inlet condition moves away from the critical point. The reasons for high relative uncertainty on the efficiency measurement can be summarized into three issues.

1. Since uncertainty analysis is a sum of partial derivatives, sharp change of enthalpy causes high relative uncertainty.
2. Low enthalpy difference between compressor inlet and outlet causes high relative uncertainty
3. A temperature and pressure measurement pair was utilized for the performance measurement.

The first issue is inherent characteristics of CO_2 near the critical point. Thus, there is no solution to solve this issue since it is natural phenomena.

The second issue is facility dependent. The main compressor of SCO2PE has a low enthalpy rise since relatively slow rotational speed of impeller. Small numerator on equation (5) causes high relative uncertainty.

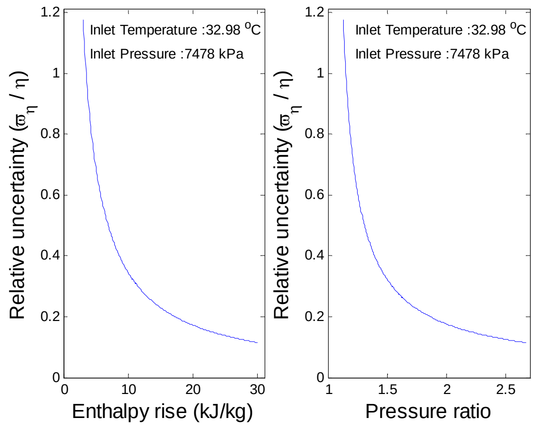

Figure 2. Uncertainty analysis result of efficiency measurement with various compressor pressure ratio

Ref. [2] discussed regarding the third issue. If temperature and pressure measurement pair is replaced with density and pressure measurement pair, relative uncertainty on the efficiency measurement can be improved.

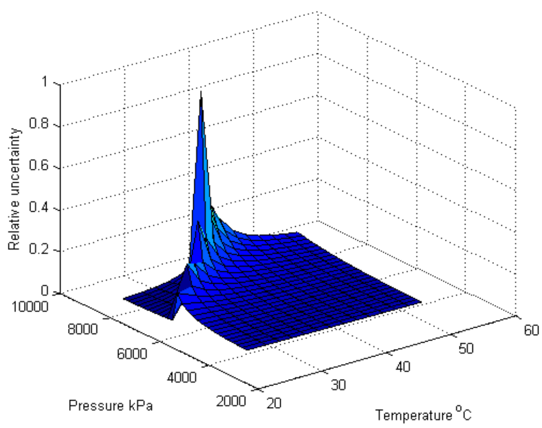

Figure 3. Uncertainty analysis result of efficiency measurement with density and pressure measurement for various compressor inlet conditions

However, applying density measurement to SCO2PE didn’t provide remarkable improvement for the compressor performance measurement.

4. Summary and further works

Due to dramatic change on thermodynamic property of CO_2 near the critical point, very high uncertainty was predicted for the near critical point operation. This is related to the property variation, pressure ratio and measurement method.

Since SCO2PE facility operates near the critical point with a low pressure ratio compressor, one of the solutions to improve measurement uncertainty is utilizing a density meter. However, additional two density meters on compressor inlet and outlet measurement didn't provide remarkable improvement on the overall uncertainty.

Thus, the authors think that different approach on the performance measurement is required to secure measurement confidence.

As further works, identifying appropriate approximation on efficiency equation and applying direct measurement of compressor shaft power for the efficiency calculation will be considered.

ACKNOWLEDGMENTS

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