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UNCERTAINTY ON PERFORMANCE MEASUREMENT OF S-CO_2 COMPRESSOR OPERATING NEAR THE CRITICAL POINT

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ABSTRACT

Recently, S-CO_2 Brayton cycle technology is an emerging research area for power conversion system development. Thus, various technologies and approaches are applied to component development and anlaysis or demonstration of the whole system. S-CO_2 cycle research team in Korea Advanced Institute of Science and Technology (KAIST) constructed the Supercritical CO_2 Pressurization Experiment (SCO2PE) facility. During the experiment, authors observed high uncertainty on compressor performance measurement and it is found that the large uncertainty is due to large property variation of CO_2 near the critical point and when a compressor with low pressure ratio is being used. Since compressor operating conditions are near the critical point of CO_2 in the S-CO_2 Brayton cycle, performance measurement for low pressure ratio compressor requires different approach to yield low uncertainty in the measurement. In this paper, uncertainty on performance measurement of low pressure ratio S-CO_2 compressor and approach what authors are trying to utilize will be discussed.

INTRODUCTION

The main purpose of constructing a compressor test facility is to obtain reasonable compressor performance map, which contains flow to pressure ratio and flow to efficiency. Flow rate meter, temperature and pressure sensors and other supporting devices are usually installed on the test facility to acquire raw data which will be utilized for the compressor performance calculation. There are many measurement principles for fast and accurate data acquisition. However, some error is always involved in the measurement. The error causes uncertainty of data calculation result and it is critical if uncertainty is too high which reduces the measurement confidence. Thus, measurement devices with high accuracy and resolution are required when sensitive measurement is necessary to reduce the uncertainty. It is true that S-CO_2 compressor which operates near the critical point is obviously one of the most sensitive machineries in the view of performance measurement. This is mainly because the critical point is a sharp point not an area, which means that resolution has to be very high to fully understand the physics at a specific point. Therefore, most of S-CO_2 component test facilities around the world (e.g. Korea Atomic Energy Research Institute facility, Sandia National Laboratories (SNL) facility, Bechtel Marine Propulsion Corporation facility), have installed high accuracy measurement sensors to secure high reliability on the data.

Korea Advanced Institute of Science and Technology (KAIST) constructed S-CO_2 compressor experiment facility which is named as Supercritical CO_2 Pressurization Experiment (SCO2PE). High accuracy measurement devices are installed in SCO2PE facility. However, during experiment data analysis, un-physical results were observed and authors have questioned on reliability of performance data and alternative methods for measuring the performance of a compressor operating near the critical point.

However, there were only a few studies on the relationship with S-CO_2 compressor performance measurement, measurement device uncertainty, properties variation near the critical point and the compressor characteristics. For example, Gregory D. Wahl [5] performed uncertainty analysis on S-CO_2 compressor with different measurement pairs, temperature and pressure, temperature and density, pressure and density, and concluded that applying density measurement provides best result. The author mentioned briefly that higher enthalpy rise (i.e. high pressure ratio) will reduce uncertainty but detail quantitative analysis was not shown.

In this paper, authors performed similar uncertainty analysis to [5] with SCO2PE facility and tried to provide a more quantitative analysis results to clearly understand how multiple variables can affect the compressor performance measurement.

TEST FACILITY DESCRIPTION

SCO2PE facility is academic facility to study S-CO_2 Brayton cycle technology.

Figure 1. SCO2PE facility, (1: Overview, 2: Impeller, 3: Main compressor, 4: Pre-cooler, 5: Booster pump, 6: Vacuum pump [3]

SCO2PE facility was initially constructed for academic researches on S-CO_2 Brayton cycle technology to obtain experience of operating a compressor and a heat exchanger near and far from the critical point to understand physics of flow and heat transfer near the critical point. Currently SCO2PE facility has been upgraded with additional measurement stations and upgraded for securing potential of modifying the loop in the future to test various components.

SCO2PE facility can measure flow rate, temperature and pressure. Even after facility upgrade was conducted, density measurement wasn't involved in the list of upgrading items. It is true that density measurement will be the best option for component alone test facility. Unfortunately due to the limitation in the funding the installation of a density meter was delayed to the next year. However, discussion of measurement uncertainty with temperature and pressure measurements alone is still valid, since the actual system will not have density meter since it will have negative economic effect due to additional pressure drop in the system.

Calibrated RTD sensors, Rosemount 3051S and Rheonik RHM 20 were installed for temperature, pressure and mass flow rate measurement, respectively.

Table 1. Accuracies of sensors

Sensor type	**Accuracy**
RTD	±0.2^{o}C
Pressure transmitter	±0.09%
Mass flow meter	±0.16%

CASES OF EXPERIMENT DATA

Two cases are utilized for uncertainty analysis. Since thermodynamic property of S-CO_2 varies dramatically as fluid condition approaches to the critical point, data from near critical point operation case and far critical point operation case are selected to compare the effect of inlet conditions. Far from the critical point operating condition was at 8300kPa, 40^{o}C inlet condition (Case 1). 7450kPa, 32.5^{o}C compressor inlet condition was selected as near critical point operating condition (Case 2).

Table 2. Experiment data of two selected cases

	Mass flow rate (kg/s)	**Inlet pressure (kPa)**	**Outlet pressure (kPa)**	**Inlet temperature (^{o}C)**	**Outlet temperature (^{o}C)**	**RPM**
Case 1	2.001	8294.7	9119.3	39.869	45.775	4620
	1.519	8295.1	9111.1	39.876	45.906	4620
	0.955	8291.4	9064.6	39.894	46.070	4620
	0.502	8296.8	9025.0	39.835	46.689	4620
Case 2	2.863	7443.5	8649.5	32.550	38.251	4620
	1.986	7440.0	8658.0	32.502	38.232	4620
	1.545	7444.9	8650.3	32.504	38.196	4620
	0.998	7447.9	8633.6	32.446	38.161	4620

UNCERTAINTY ANALYSIS

Uncertainty represents reliability of 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].

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

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

$$PR = \frac{P_{out}}{P_{in}} \quad (2)$$

$$\eta = \frac{h_{out,ideal} - h_{in}}{h_{out} - h_{in}} \quad (3)$$

Both stagnation condition and static condition can be utilized for compressor performance calculation. Stagnation condition performance is important in the view of overall cycle design while static condition analysis should be involved for the analysis on compressor itself. In this paper, stagnation condition will be used.

Static and stagnation

In SCO2PE, the measured temperature is a median value of stagnation temperature and static temperature due to recovery effect on temperature measurement. The measured pressure is static pressure. However the fluid velocity at compressor inlet and outlet is about 6.5 m/s and the Mach number is in the order of 0.01. Thus static temperature is very close to the total temperature. According to actual static to stagnation calculation with NIST property database [4], there are only 0.05^{o}C of maximum difference between stagnation temperature and static temperature for the abovementioned case. So it is reasonable to utilize measured temperature as both total temperature and static temperature.

For static to stagnation conversion, precise energy conservation equation should be used to obtain accurate results. Because of dramatic property change near the critical point of S-CO_2, ideal gas assumption based conversion doesn’t provide correct conversion results between static condition and stagnation condition. When ideal gas assumption was utilized for static to stagnation calculation on the data cases above, up to 1.5^{o}C of over prediction was observed on stagnation temperature while prediction error on stagnation pressure is up to 45kPa.

Uncertainty of pressure ratio

Relative uncertainty of pressure ratio can be derived from eqn. (4).

$$\frac{\omega_{PR_o}}{PR_o} = \left[\left(\frac{\omega_{P_{o,out}}}{P_{o,out}} \right)^2 + \left(-\frac{\omega_{P_{o,in}}}{P_{o,in}} \right)^2 \right]^{1/2} \quad (4)$$

Uncertainty of stagnation pressure can be calculated with eqn. (5)

$$\varpi_{P_o} = \left[\left(\frac{\partial P_o}{\partial h_o} \omega_{h_o} \right)^2 + \left(\frac{\partial P_o}{\partial T_s} \omega_{T_s} \right)^2 + \left(\omega_{P_s} \right)^2 \right]^{1/2} \quad (5)$$

Uncertainty of efficiency

Relative uncertainty of total to total isentropic efficiency can be obtained from eqn.(6).

$$\frac{\omega_\eta}{\eta}=\left[\left(\frac{1}{h_{o,out,isen}-h_{o,in}}\omega_{h_{o,isen}}\right)^2+2\left(\frac{h_{o,out,isen}-h_{o,out}}{\left(h_{o,out}-h_{o,in}\right)\left(h_{o,out,isen}-h_{o,in}\right)}\omega_{h_{o,in}}\right)^2+\left(\frac{(-1)}{h_{o,out}-h_{o,in}}\omega_{h_{o,out}}\right)^2\right]^{1/2}$$

(6)

However, CO_2 near the critical point has large variation of thermodynamic properties. It is expected that individual uncertainty terms on eqn. (6) will have high value and it can cause large uncertainty. Thus, authors considered eqn. (7) as an alternative for the efficiency calculation since less reliance on properties can reduce effect of large property variation on measurement uncertainty.

$$\eta=\left(h_{o,out,isen}-h_{o,in}\right)\frac{\dot{m}}{\dot{W}} \tag{7}$$

Relative uncertainty of eqn. (7) can be calculated from;

$$\frac{\omega_\eta}{\eta}=\left[\left(\frac{1}{h_{o,out,isen}-h_{o,in}}\omega_{h_{o,out,isen}}\right)^2+\left(\frac{-1}{h_{o,out,isen}-h_{o,in}}\omega_{h_{o,in}}\right)^2+\left(\frac{1}{\dot{m}}\omega_{\dot{m}}\right)^2+\left(\frac{-1}{\dot{W}}\omega_{\dot{W}}\right)^2\right]^{1/2} \tag{8}$$

For the case of SCO2PE facility, approximation on efficiency calculation was attempted. Loss mechanism in turbomachinery can be categorized with internal loss and external loss. Losses occurred through primary paths of working fluid in a machinery are categorized as an internal losses while external losses are generated from the exterior of primary paths [2]. Thus isentropic efficiency can be expressed with

$$\eta=\frac{\Delta h_{th}-\Delta h_{loss,int}}{\Delta h_{th}+\Delta h_{loss,ext}} \tag{9}$$

If external losses which is generally oriented from rotor and disk back face friction are greater than internal losses, isentropic efficiency can be approaches to eqn. (10)

$$\eta=\frac{\Delta h_{th}-\Delta h_{loss,int}}{\Delta h_{th}+\Delta h_{loss,ext}}\approx\frac{\Delta h_{th}}{\Delta h_{th}+\Delta h_{loss,ext}}=\frac{U_2{}^2\dot{m}}{\dot{W}} \tag{10}$$

It is fair assumption that S-CO_2 compressor operates near the critical point has high external losses since high density of S-CO_2 causes high frictional losses generally. Since main compressor in SCO2PE facility has low specific speed design for impeller, diameter is relatively larger while rotation speed is slower than optimum impeller design. Thus abovementioned approach can be acceptable.

Uncertainty analysis results

Table 3 shows relative uncertainty calculation results. Required thermodynamic properties were referred from REFPROP database.

Table 3. Relative uncertainties for test results

	Case 1, Supercritical operation				**Case 2, Near critical operation**			
Mass flow rate kg/s	**2.002**	**1.519**	**0.955**	**0.502**	**2.863**	**1.986**	**1.545**	**0.998**
PR	1.099	1.098	1.093	1.088	1.162	1.164	1.162	1.159
$\frac{\omega_{PR}}{PR}$	0.0073	0.0073	0.0072	0.0072	0.0086	0.0087	0.0087	0.0087
η of equation (3), %	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]
ω_η / η of equation (3)	0.688	0.521	0.543	0.641	0.651	0.653	0.675	0.721
η of equation (7), %	36.071	28.757	18.935	10.187	58.603	45.788	37.160	24.901
ω_η / η of equation (7)	0.541	0.546	0.570	0.615	0.531	0.532	0.549	0.583
η of equation (10), %	46.102	37.116	25.688	14.742	50.631	39.241	32.322	22.184
ω_η / η of equation (10)	0.0135	0.0135	0.0135	0.0135	0.0135	0.0135	0.0135	0.0135

*[1] : Even near the steady state, a large fluctuation (50%-150% Range) of efficiency was observed due to very small background noise in temperature and pressure measurement. Thus it is not possible to report efficiency based on equation (3).

Uncertainty of pressure ratio is reasonably low, which all results are under 1%. However, uncertainty of efficiency is very high for all cases except approximate efficiency. As expected before, uncertainty result with eqn. (7) is slightly better than that of eqn. (3) in overall, but the uncertainty is still too high. Even for the supercritical operating condition, in addition, high uncertainty is predicted. The operating condition of Case 1, 8300kPa and 40^{o}C of compressor inlet condition, which is on the peak region of property variation and it causes high uncertainty. On the other hand, uncertainty of eqn. (10) is low enough to secure high reliability of experiment data. Although efficiency calculation results with eqn. (7) are highly unreliable, eqn. (10) efficiency calculation results are reasonably similar to that of eqn. (7). Thus, careful observation can be made that approximation on efficiency calculation can be an alternative way for measuring the compressor performance when it is operating near the region where thermodynamic properties change dramatically.

To deduce the reason of high uncertainty on eqn. (7), quantities of each term in eqn. (8) are listed on Table 4.

Table 4. Quantities of each term in equation (8)

	Case 1, Supercritical operation				Case 2, Near critical operation			
Mass flow rate kg/s	**2.002**	**1.519**	**0.955**	**0.502**	**2.863**	**1.986**	**1.545**	**0.998**
$\left(\frac{\omega_{h_{o,out,ideal}}}{h_{o,out,ideal}-h_{o,in}}\right)$	0.444	0.448	0.468	0.504	0.427	0.428	0.440	0.463
$\left(\frac{-\omega_{h_{o,in}}}{h_{o,out,ideal}-h_{o,in}}\right)$	-0.309	-0.312	-0.325	-0.353	-0.316	-0.317	-0.329	-0.354
$\left(\frac{\omega_{\dot{m}}}{\dot{m}}\right)$	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
$\left(\frac{-\omega_{\dot{W}}}{\dot{W}}\right)$	-0.004	-0.004	-0.004	-0.005	-0.003	-0.003	-0.003	-0.004

As shown on Table 4, most of uncertainty comes from the first and the second terms on eqn. (8). In other words, high uncertainty results are caused by low ideal enthalpy rise (i.e. pressure ratio) of compressor and high uncertainty of enthalpy terms

Ideal enthalpy rise of main compressor on SCO2PE facility is 3136 J/kg when no losses are concerned since impeller outlet diameter is 234mm and rotates at 4620 RPM. To verify effect of ideal enthalpy rise on efficiency uncertainty, uncertainty prediction with various ideal enthalpy rises are performed.

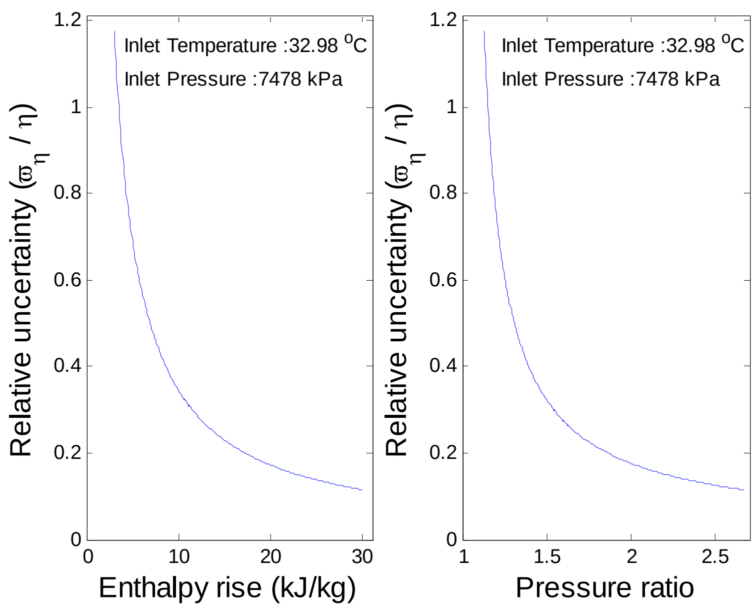

Figure 2. Enthalpy rise and pressure ratio dependence on uncertainty of efficiency calculation

As a result, relative uncertainty is highly dependent on ideal enthalpy rise of compressor. As ideal enthalpy rise of compressor increases, outlet condition moves further away from the critical point and gradual property change can result in lower relative uncertainty.

Based on the observation that performance measurement uncertainty of S-CO_2 compressor is affected by thermodynamic properties, results of relative uncertainty prediction with various compressor inlet conditions were compared to thermodynamic properties. Among thermodynamic properties, specific heat at constant pressure has very similar variation trend to relative uncertainty prediction results, which shows that there is a very strong correlation with specific heat and measurement uncertainties.

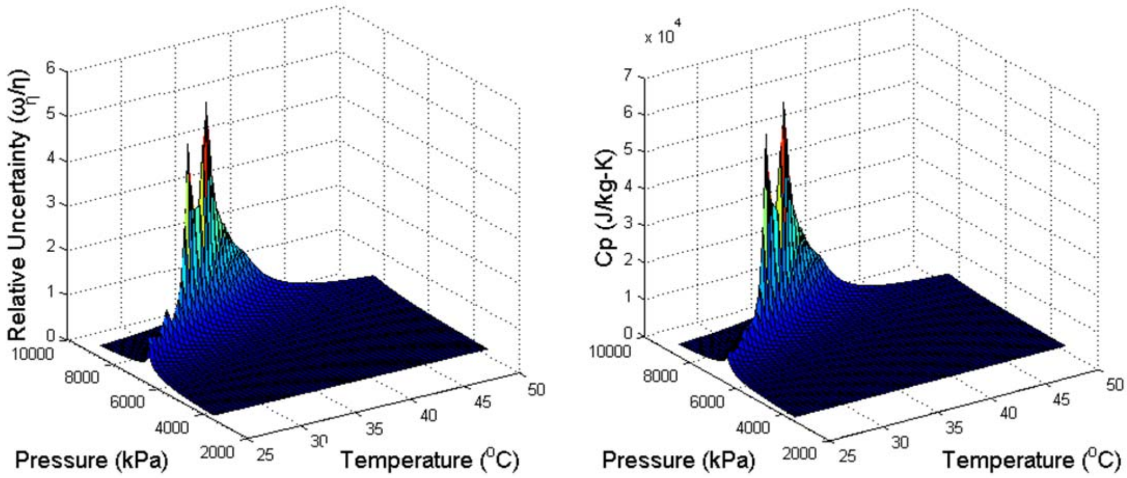

Figure 3. Predicted relative uncertainty of efficiency calculation (left) (At same ideal enthalpy rise for each pressure and temperature condition), Constant pressure specific heat variation (right)

Since the effect of dramatic change on thermodynamic property of CO_2 near the critical point cannot be evaded easily, high uncertainty on performance measurement is always expected when the compressor operates near the critical point. High uncertainty issue becomes worse when low pressure ratio compressor is utilized.

Thus, it can be necessary to apply alternative performance parameter if low pressure ratio compressor is required for the system. For the case of SCO2PE facility, eqn. (10) is utilized for compressor performance prediction so that operators are able to secure performance data with low uncertainty. It doesn't represent actual isentropic efficiency of machinery. However, eqn. (10) will have reasonable agreement for the cases with external losses dominant compressor (e.g. SCO2PE compressor).

CONCLUSIONS

Uncertainty analysis on S-CO_2 compressor operating near the critical point was summarized and the results are discussed in this paper. Utilized experiment data were obtained from SCO2PE facility which has low pressure ratio S-CO_2 compressor.

Two cases of operating condition was concerned, near critical point operation and supercritical state operation. As a result, very high uncertainty was predicted on isentropic efficiency calculation. The results can be explained with two different ways.

1. Dramatic change on thermodynamic property of S-CO_2 near the critical point causes very high uncertainty and it is more critical as the operating condition approaches to the critical point.
2. Small isentropic enthalpy rise of low pressure ratio compressor amplifies high uncertainty results.

Since the effect of property variation on uncertainty is inherent issues when the compressor operates near the critical point, utilizing high pressure ratio compressor is a reasonable solution for component experiment of S-CO_2 Brayton cycle. It seems reasonable to utilize a compressor with pressure ratio value more than 2 to reduce the effect of uncertainty in the performance measurement.

Fortunately, well known optimum pressure ratio of S-CO2 recompression cycle layout is around 2.7 pressure ratio, and a 2.7 pressure ratio compressor will have an acceptable uncertainty range. 0.1 of relative uncertainty was predicted with temperature and pressure measurement pair and it can be reduce by applying density meter [5].

If the system should have low pressure ratio S-CO_2 compressor and operates near the critical point, high uncertainty on performance measurement cannot be resolved. One of alternative methods for performance measurement on low pressure ratio S-CO_2 compressor is using an approximate form of efficiency. However, individual loss phenomena should be understood to use approximated form. As further works, authors will try to analyze each loss model to make better approximation on performance measurement.

NOMENCLATURE

A	=	Area
D	=	Diameter
h	=	Enthalpy
$\dot{m}$	=	Mass flow rate
P	=	Pressure
PR	=	Pressure ratio
T	=	Temperature
V	=	Velocity
$\dot{W}$	=	Power
η	=	Efficiency
ρ	=	Density
ω	=	Uncertainty
Δh_{th}	=	Theoretical enthalpy rise

Subscript

ext	=	External
$loss$	=	Enthalpy loss
int	=	Internal
in	=	Inlet
out	=	Outlet
o	=	Stagnation condition
s	=	Static condition
$ideal$	=	Isentropic process

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