Effect of Various Stagnation to Static Conversion Approximations for Obtaining CO_2 Properties Near the Critical Point

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1. Introduction

Recently, S-CO_2 Brayton cycle technology is an emerging research area for power conversion system development due to attractive advantages of S-CO_2 Brayton cycle, high efficiency and compactness. Thus, various technologies and approaches are applied to component development and analysis or demonstration of the S-CO_2 Brayton cycle system. For nuclear power plant field, applying S-CO_2 Brayton cycle to Sodium cooled Fast Reactors and Small Modular Reactors are currently considered and it is an active research area. As a part of research activities on S-CO_2 Brayton cycle development for nuclear power system, the KAIST research team is currently working on innovative Sodium cooled Fast Reactor (iSFR) development which accepts S-CO_2 Brayton cycle as its power conversion system.

However, technical issues caused from a dramatic change on thermodynamic property of CO_2 near the critical point still remain to be addressed. One of the issues on thermodynamic property handling is stagnation to static conversion and it can cause significant impact on S-CO_2 cycle analysis and component design results. Thus, a study on stagnation to static conversion approximations was carried out and the observation will be discussed.

2. Real Gas Approaches

Since high efficiency of S-CO_2 Brayton cycle can be achieved when the inlet condition of main compressor is near the critical point of CO_2, static condition of inlet of the main compressor is usually set to just above the critical point. Thus stagnation to static conversion should be correctly performed to secure reliability of the compressor inlet condition prediction, which influences the compressor design significantly. During the compressor design process, the accuracy of stagnation to static conversion is very important. While working fluid flows through a flow passage of compressor, both acceleration and deceleration occur. Since Mach number of near unity is assumed during a compressor design (as maximum operation limit), fluid velocity is high enough to lead to a large error on compressor design results when stagnation to static process is not correctly applied.

Three different stagnation to static conversion methods were identified so far that can be utilized for a S-CO_2 compressor design and analysis. The most promising stagnation to static conversion method is the definition based stagnation to static conversion. This conversion method is performed with the definition of total enthalpy that the total enthalpy is the sum of the static enthalpy and the kinetic energy, and the entropies of stagnation and static are the same.

$$h_o = h_s + \frac{v^2}{2} \tag{1}$$

Applying the definition based stagnation to static conversion approximation provides the most accurate conversion result and it can be the reference for other conversion approximations [1]. The downside of this method is that it consumes more computing time and complexity to the calculation results.

Common practice for stagnation to static conversion process for most gases is based on ideal gas assumption and its relation is described as following equations [2].

$$\frac{p_o}{p_s} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{2}$$

$$\frac{T_o}{T_s} = 1 + \frac{\gamma - 1}{2} M^2 \tag{3}$$

However, it is hard to apply above equations for S-CO_2 near the critical point since specific heat ratio and compressibility factor vary significantly near the critical point.

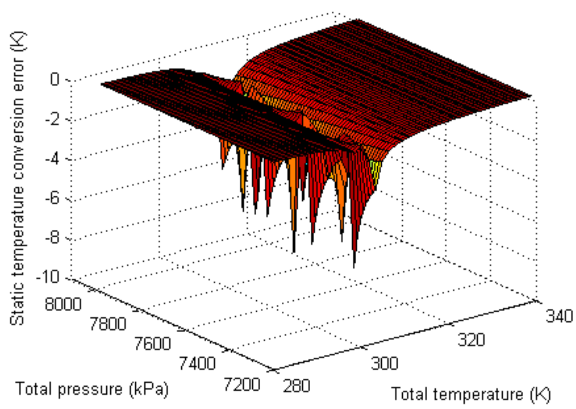

Fig. 1 Static temperature conversion error of ideal gas based conversion results to definition based conversion result

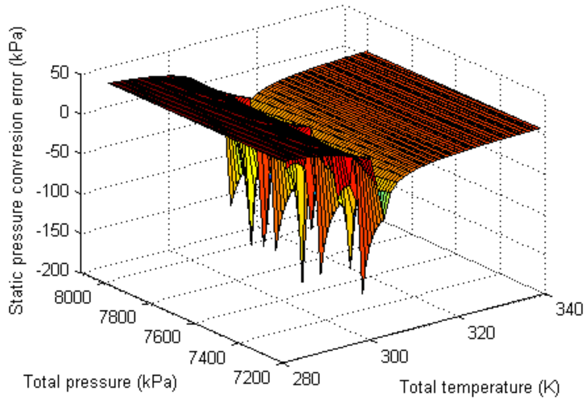

Fig. 2 Static pressure conversion error of ideal gas based conversion results to definition based conversion results

As shown in Fig. 1 and Fig. 2, up to 8K of static temperature conversion error was observed while 150kPa of static pressure conversion error was predicted with ideal gas based stagnation to static conversion process. 8K of temperature and 150kPa of pressure difference near the critical point can cause significant error on the cycle analysis result since thermodynamic property changes dramatically near the critical point.

Other alternative option for stagnation to static conversion is to apply real gas isentropic exponents [3]. Since compressibility factor is assumed as a constant for ideal gas, isentropic exponent appears as γ for pressure exponent while $(\gamma-1)/\gamma$ represents temperature exponent. However, compressibility factor of S-CO_2 near the critical point changes dramatically. Thus, isentropic exponents should be expressed as

$$n_s = \frac{\gamma}{\beta_T P}, \text{ where } \beta_T = \frac{1}{p} - \frac{1}{Z}\left(\frac{\partial Z}{\partial p}\right)_T \quad (4)$$

$$m_s = \frac{\gamma-1}{\gamma}\frac{\beta_T P}{\beta_p T}, \text{ where } \beta_p = \frac{1}{T} + \frac{1}{Z}\left(\frac{\partial Z}{\partial T}\right)_p \quad (5)$$

And stagnation to static conversion can be carried out with the following relations.

$$\frac{p_o}{p_s} = \left(1 + \frac{n_s - 1}{2} M^2\right)^{\frac{1}{n_s - 1}} \quad (6)$$

$$\frac{T_o}{T_s} = \left(1 + \frac{n_s - 1}{2} M^2\right)^{\frac{m_s n_s}{n_s - 1}} \quad (7)$$

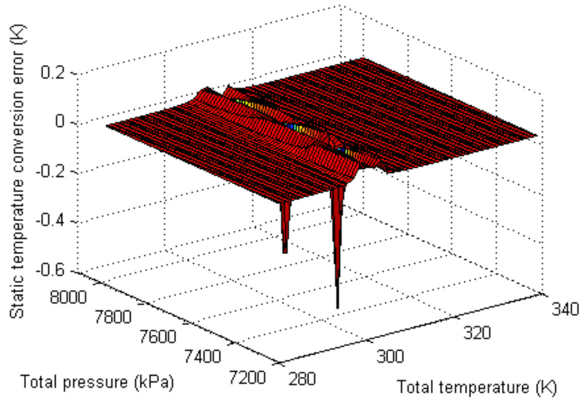

Fig. 3 Static temperature conversion error of real gas isentropic exponent based conversion results to definition based conversion results

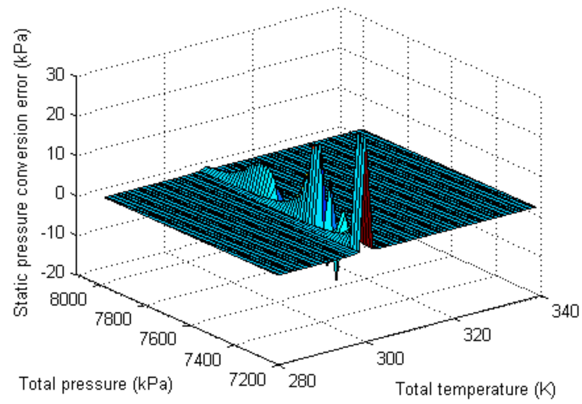

Fig. 4 Static pressure conversion error of real gas isentropic exponent based conversion results to definition based conversion results

Applying real gas isentropic exponents for the conversion considers the compressibility factor variation on stagnation to static conversion. Thus, it provides better conversion results than ideal gas based stagnation to static conversion results as shown in Fig. 3 and Fig. 4. Up to 0.5K of static temperature conversion error and 25kPa of static pressure conversion error are generated compared to the reference. These results seemed to be acceptable since the conversion error has the same order of industrial measurement error. However, it should be noticed that static enthalpy conversion results still have some errors up to 14% as shown in Fig. 5.

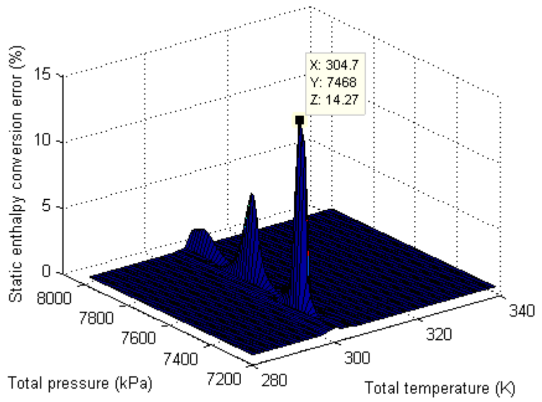

Fig. 5 Static enthalpy conversion error of real gas isentropic exponent based calculation results to definition based calculation results

3. Summary and Further works

Different stagnation to static conversion methods were investigated for the S-CO_2 power system design. This is to study accuracy of each conversion method compared to the definition based conversion method. Ideal gas based stagnation to static conversion method has a large error for both of static temperature conversion and static pressure conversion near the critical point of CO_2 . Alternative method which accepts real gas isentropic exponents provides better conversion results. However, up to 14% of static enthalpy conversion error was observed.

It is clear that use of definition based stagnation to static conversion is the best option for thermodynamic property handling near the critical point of S-CO_2. However, real gas isentropic exponent based conversion method can also provide reasonable agreement and it provides better applicability for conventional component design methodologies.

As further works, study on effect of stagnation to static conversion methods for a compressor stage design will be performed. This is because high fluid velocity at impeller outlet can have larger sensitivity to the stagnation to static conversion.

ACKNOWLEDGMENT

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