A Preliminary Study for Prediction of Supercritical CO_2 Compressor Surge Line

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1. Introduction

The necessity of the next generation nuclear reactors has been constantly brought up as part of efforts to resolve the global warming, reuse the spent fuel, and enhance the safety level. A supercritical CO_2 (S-CO_2) Brayton cycle has been considered as a potential solution for those nuclear reactors due to high thermal efficiency at moderate turbine inlet temperature (450~650 ^oC), simple layout of power conversion unit, small component volume (i.e. turbomachineries and heat exchangers), and the mitigation of turbine blade erosion compared to the conventional steam Rankine power cycle [1]. In spite of these advantages, some technical challenges (i.e. compressor operation near the critical point, sealing and bearing technology, and system control procedures) need to be overcome so that the S-CO_2 Brayton cycle can arrive at successful demonstration.

To adopt an S-CO_2 power cycle as the power conversion unit, safety issues as well as the demonstration should be considered. One of the serious problems in terms of cycle operation is compressor surge, which can lead to severe noise and structural vibration and it is a requirement for stable operation. Several approaches are used to predict it. The most conservative and convenient way is to trace pressure ratio gradient of a compressor when the rotation speed is constant. Lieblein and Horlock proposed low speed stall and flow resistance, respectively. In this paper, the Lieblein's methodology will be re-examined and the methodology will be suggested while considering S-CO_2 fluid characteristics through a commercial Computational Fluid Dynamics (CFD) code.

2. Methods

In this section the existing Lieblein's approach is described [2, 3]. From this, the parameter considering the real gas effect is introduced. The S-CO_2 property table is made to reflect thermodynamic property variation near critical point (304.13 K, 7378 kPa).

2.1 Lieblein's Model

It is empirical model based on the low speed stall around blades. It is a correlation between the diffusion ratio V_{max}/V_{TE} and the wake momentum-thickness to chord ratio, θ/l at the reference incidence angle. This correlation represents Eq. (1) and is fitting curve of the mean curve in Fig. 1. When (θ/l) goes to ∞, the diffusion ratio at the stall, which is aerodynamically unstable state causing the compressor to surge. The value is generally known to be 2.35. When it is utilized to predict the compressor surge, the ratio of velocities is substituted into the relative shroud velocity at rotor inlet to the relative velocity at rotor exit ratio, $W_{1,s}/W_2$.

$$\frac{\theta}{l} = 0.004 / \left\{ 1 - 1.17 \ln\left(\frac{V_{max}}{V_{TE}} \right) \right\} \qquad (1)$$

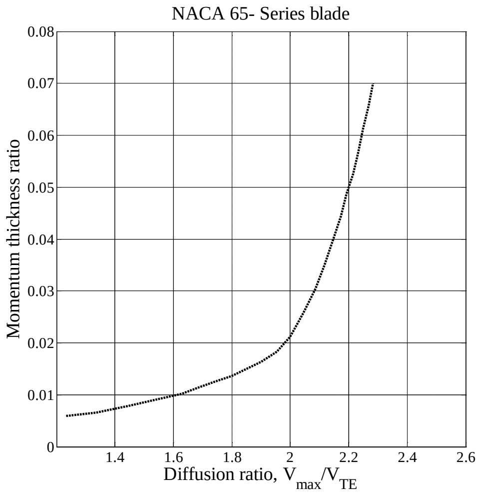

Fig. 1. Lieblein correlation of wake momentum thickness with upper-surface diffusion ratio at reference incidence condition

2.2 Diffusion Ratio

It is a parameter to represent pressure recovery or velocity deceleration while the flow passes blades. Likewise, the pressure coefficient shown in Eq. (2), C_P, is widely used in aerodynamics application [4]. Since ideal gas has constant density, the diffusion ratio represents the velocity ratio V/V_∞ instead of the pressure coefficient. Although the low speed air behaves like ideal gas, the density of S-CO_2 near the critical point changes dramatically as shown in Fig. 2. Thus, this study proposes the diffusion ratio of Eq. (3) instead of the velocity ratio.

$$C_P = \frac{p - p_\infty}{q_\infty} = 1 - \frac{V^2}{V_\infty{}^2} \qquad (2)$$

$$DR = \frac{C_{P,TE}}{C_{P,\max}} \quad (3)$$

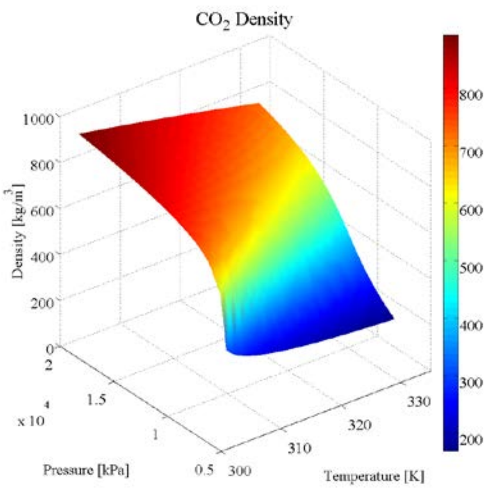

Fig. 2. CO_2 density variation above critical point with temperature range (303.15K ~ 333.15 K) and pressure range (7400kPa ~ 20000kPa)

2.3 CFD Analysis

A commercial CFD code, Star-CCM+ V10.06 was utilized in this study [5]. The flow fields of NACA 65-serise was analyzed to conduct preliminary study. This is because this airfoil is often used as the compressor blades. The entire geometry including NACA 65-1012 [6] and rectangular enclosure was converted to the fluid domain. SST k-ω turbulence model was used. Inlet temperature, inlet pressure, inlet velocity, and incidence angle were determined considering wind tunnel experiment and numerical convergence.

To reflect real gas properties of S-CO_2, the property data table was made from the NIST REFPROP 8.0 database. The table contains density(T,P), dynamic viscosity(T,P), enthalpy(T,P), entropy(T,P), speed of sound(T,P), and thermal conductivity(T,P). The table mainly used for simulation has ranges of 0.1-20MPa, 253-2000K with 1000 by 1000 resolution. The relative errors of properties are less than 0.4%.

The polyhedral mesh with 14 prism layers was generated in the Star-CCM+. The stretching ratio of the layers was 1.4. The mesh mainly used in this study composed of 110,225 cells and 550,033 nodes. The y+ value of the cell near the wall was y+ < 1. Fig. 3 shows the mesh generation result.

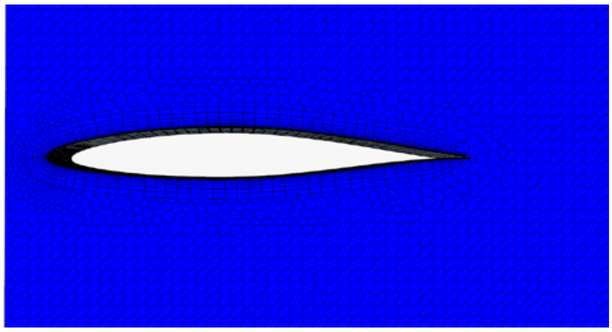

Fig. 3. Mesh generation of NACA 65-1012 airfoil

3. Results and discussion

The normalized pressure coefficients on blade surface according to working fluids are depicted in Fig. 4. Despite thermodynamic property difference between two fluids, the results correspond with each other. The magenta and red symbols represent values on lower surface or pressure surface. The blue and black symbols are values on upper surface or suction surface.

These results can explain by introducing the property conversion error between the ideal gas assumption and REFPROP database. S-CO_2 reference conditions in this study are far from regions causing thermodynamic property variation. Figs. 5 and 6 show relative pressure and temperature errors when those are calculated through the correlations based on the ideal gas assumption shown as Eqs. (4) and (5). Each error in reference conditions is around 1%, respectively. It represents S-CO_2 behaves like ideal gas and the significant difference could not be seen in this region.

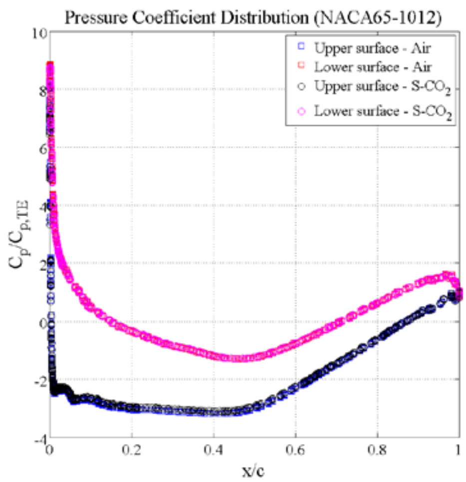

Fig. 4. Pressure coefficient comparison between air (T_{in} = 288.15K, P_{in} = 101 kPa) and S-CO_2 (T_{in} = 313.15 K, P_{in} = 8000 KPa)

$$\frac{P_o}{P_s} = \left(\frac{T_o}{T_s}\right)^{\frac{\gamma}{\gamma-1}} = \left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}} \quad (4)$$

$$\frac{T_o}{T_s} = 1 + \frac{V^2}{2C_p T_s} = 1 + \frac{\gamma - 1}{2} M^2 \qquad (5)$$

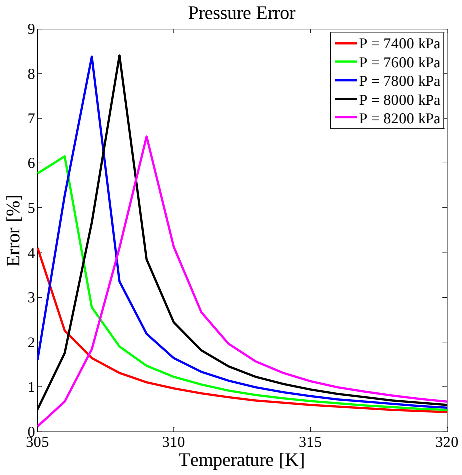

Fig. 5. Pressure conversion error of ideal gas assumption with REFROP

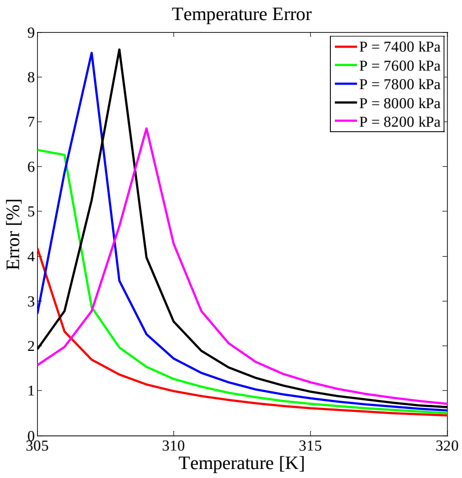

Fig. 6. Temperature conversion error of ideal gas assumption with REFROP

4. Summary and further works

In this paper, the existing methodology on surge prediction was reviewed and new parameter was proposed in order to reflect real gas effect. The commercial CFD code was utilized to resolve the pressure distribution problem on compressor blades. Despite using different fluids, the results corresponded with each other very well. This reason is S-CO_2 behaves like ideal gas in the analyzed condition, which is far from the critical point. This was expected.

As further works, the momentum thickness ratio given the same condition will be estimated as the next step. Also the diffusion ratio and the momentum thickness ratio will be studied when the inlet conditions approach the critical point where the real gas effect becomes more pronounced.

ACKNOWLEDGEMENT

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