Comparison of CFD results for a supercritical CO_2 compressor with compressible and incompressible working fluids

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1. Introduction

As the generation IV reactors are being researched, the supercritical carbon dioxide (S-CO_2) Brayton cycle is identified as one of the promising power conversion cycles. The S-CO_2 cycle has several advantages: (1) high efficiency (2) it has compact cycle components and (3) simple layout [1]. It can be also used for a power conversion system of sodium-cooled fast reactor (SFR) since it can eliminate potential safety issue of the sodium-water reactions. Moreover, the S-CO_2 cycle can be used for small modular reactors (SMR) application since it occupies small footprint and it can designed as an economical dry-cooling system for SMRs.

Design of a compressor is the major technical issue in development of S-CO_2 cycle. Therefore, KAIST research team constructed S-CO_2 pressurizing experiment (SCO_2PE) facility as shown in Fig. 2. Main purposes of this experiment are to accumulate operating experience of the S-CO_2 loop, and to obtain fundamental data for the compressor design optimization near the critical point. However, inside the compressor, it is hard to know flow parameters by measurements. Therefore, the authors performed a CFD analysis to obtain useful flow parameters inside the compressor.

The main goal of this paper is studying the flow parameters of pump-derived type compressor with S-CO_2, water, and air fluids to enhance understand how S-CO_2 can behave from conventional working fluid. The S-CO_2 fluid has a characteristic of meta-incompressible fluid, which means compressibility factor of S-CO_2 is between the air and water [2]. The authors compared flow parameters of S-CO_2 compressor with various fluids to investigate fluid characteristic of S-CO_2, and performance of pump-derived type (shrouded impeller) compressor.

2. Geometry and computational mesh

The geometry of shrouded impeller is shown in Fig. 2. This type of closed impeller geometry is derived from the water pump design. The impeller rotates in 4620 rpm counter-clock wise. After the fluid gain the pressure in the rotor, the ring diffuser and outlet diffuser guide the fluid into the outlet pipe, and restore its static pressure by diffusion process.

The tetrahedral, and hexahedral elements with 18 prism layers were generated in the computational domain. The prism layers were produced to meet the wall function requirement. The wall function validity range with k-ω SST turbulence model is $30 \leq y^+ \leq 100$. After perform the mesh sensitivity study, converged mesh was used for CFD analyses. The optimized mesh has 1,813,726 nodes, and 4,867,877 elements.

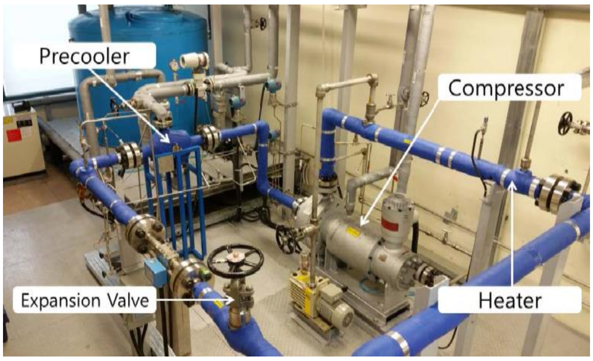


Fig. 1. SCO_2PE facility.

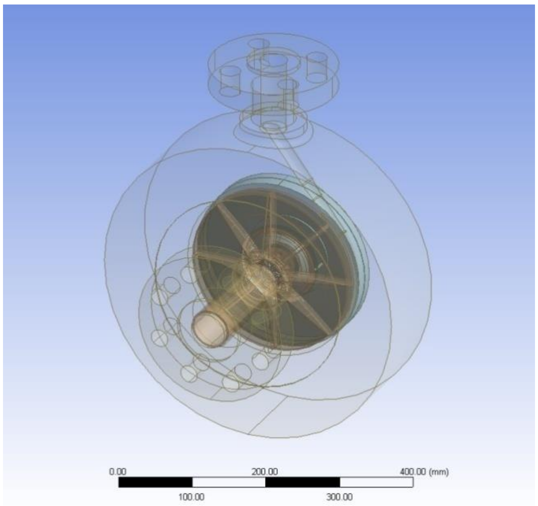


Fig. 2. 3-D geometry of the compressor and impeller.

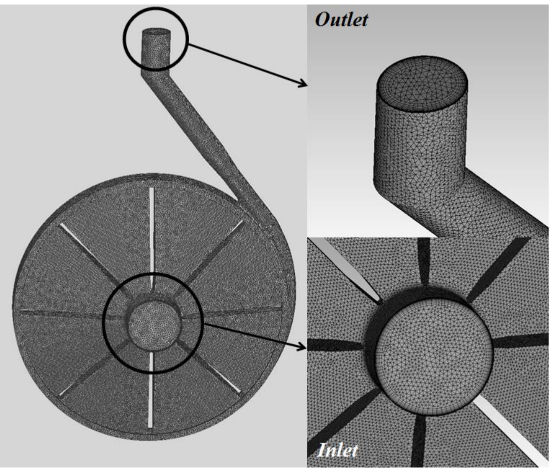


Fig. 3. Mesh of the S-CO_2 compressor fluid domain.

3. Problem setup

The authors utilized a commercial CFD code, ANSYS CFX 14.5 [3]. The k–ω SST (Shear Stress Transport) model with the scalable wall-function was used. Total energy equation with viscous work term was employed for energy conservation. At the inlet of the compressor, 5% of turbulence intensity was applied. The inlet condition of total pressure, total temperature was set to be 8.3MPa, 40°C, which is the same condition of a SCO_2PE experiment. All the cases have same flow coefficient, therefore the volumetric flow rate of each case is the same. The CO_2 properties were implemented by using the RGP table generated from the NIST REFPROP 8.0 database [4].

4. Results

The non-dimensional velocity u and non-dimensional pressure $\dot{P}$ were calculated by using following expressions. Also, the dimensionless parameters related to the performance of compressor such as flow coefficient, ideal head coefficient were considered to compare compressor performance among the various fluids.

Fig. 4. shows the non-dimensional pressure, and velocity distribution along the stream-wise locations from the inlet to the outlet. In the diffuser region, dynamic pressure is converted to the static pressure. The non-dimensional velocity is similar among the different fluids cases because volumetric flow rate was set to be the same. However, non-dimensional pressure shows large difference between the fluids. As shown in Table 1, the flow coefficients of the cases are the same, but pressure ratio and isentropic efficiency were different. The compressibility factor of CO_2 in this case (40°C) is around 0.4-0.45 as shown in Fig. 5. The compressibility of water is close to zero since it is an incompressible fluid. Therefore, the meta-incompressible, and high density S-CO_2 fluid caused high isentropic efficiency (0.346) as much as water case (0.355) while air case showed low efficiency (0.269). Otherwise, pressure ratio of S-CO_2 case showed intermediate value between the water and air cases.

As a result, the authors think that the pump-derived shrouded type compressor can be used as S-CO_2 compressor. It is noteworthy to mention that this compressor geometry is derived from the water pump technology, it is not an optimized geometry for S-CO_2 fluid, and rotating speed is low (4620 rpm).

$$u=\frac{v}{v^*}\qquad \dot{P}_{static}=\frac{P_{static}}{P_{static^*}}\qquad \dot{P}_{total}=\frac{P_{total}}{P_{total^*}}$$

$v^*: inlet\ velocity$, $P_{static^*}: Static\ pressure\ of\ inlet$

$P_{total^*}: Total\ pressure\ of\ inlet$

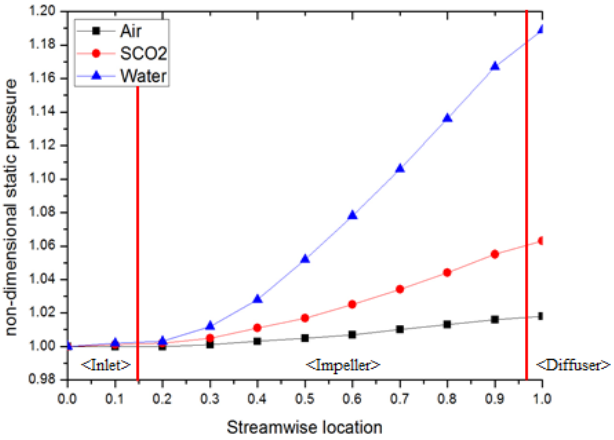
$$Flow\ coefficient: \Phi=\frac{Q}{N\times D^3}$$

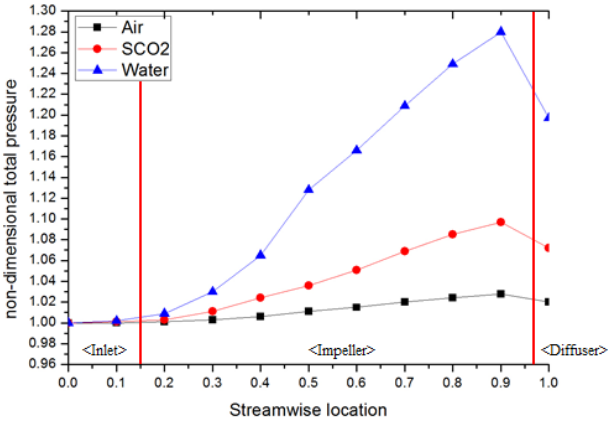
$$Ideal\ head\ coefficient: \psi=\frac{\Delta h}{U^2}$$

$Q: Volumetric\ flowrate[m^3/\mathrm{sec}]$, $N: Angluar\ velocity\ of\ blade\ tip[1/\mathrm{sec}]$

$D: Blade\ tip\ diameter[m]$, $h: Enthalpy[J/kg]$,

$U: Blade\ tip\ velocity[m/\mathrm{sec}]$





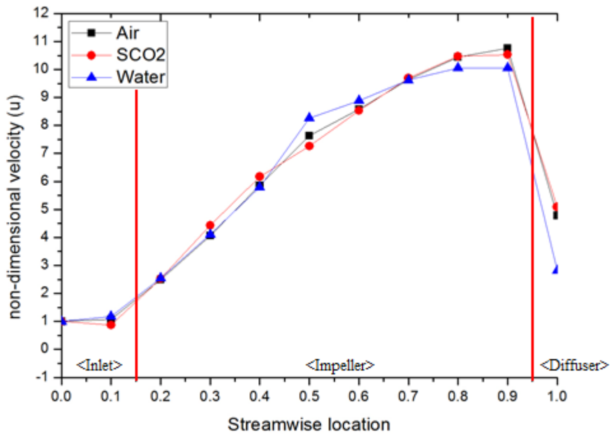


Fig. 4. Non-dimensional (a) static pressure, (b) total pressure, (c) velocity plot along a stream-wise location.

Table 1. Comparison of CFD analyses results with S-CO_2, water, and air fluids in the same flow coefficient.

Case	Mass flow rate [kg/s]	Volumetric flow rate [m^3/s]	Outlet velocity [m/s]	Reynolds number
Water	8.474	0.00849	22.02	329,900
Air	0.707	0.00849	19.98	968,418
S-CO_2	2.604	0.00849	19.63	2,919,000

Case	Flow Coefficient	Ideal head coefficient	Pressure ratio	Isentropic efficiency
Water	0.00137	0.2660	1.280	0.355
Air	0.00137	0.3198	1.028	0.269
S-CO_2	0.00137	0.2527	1.097	0.346

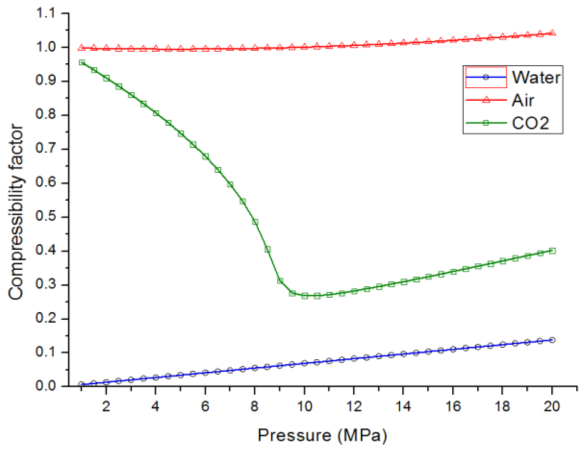


Fig. 5. Compressibility factors of the water, air, and CO_2 in various pressure conditions (40°C).

5. Conclusions

The CFD results showed that the isentropic efficiency of CO_2 case has a comparable performance in comparison to the water since S-CO_2 has a meta-incompressible characteristic near the critical point. Because of the low rotating speed and non-optimized geometry of impeller, the pressure ratio of the compressor is low. However, the authors confirmed that this shrouded type impeller for S-CO_2 compressor showed good performance as much as water case. This results will be reflected in the future S-CO_2 compressor design.

ACKNOWLEDGEMENT

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