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An Aerodynamic Study of NACA Airfoil 6-Digits under CO_2 Environment by Two-dimensional Computational Fluid Dynamics

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1. Introduction

Nowadays, people all over the world are facing an enormous increase of energy demand for industries and transportations. In the response of this demand, there have been great improvements regarding the power capacity and efficiency of a power plant. However, at the same time, the perception for energy has changed among the common public. Especially, the concerns for environmental issues have increased drastically.

Accordingly, energy sources have been diversified from conventional fossil fuels to other energy sources such as renewable energy, advanced fossil fuel and nuclear energy. Nuclear energy is carbon-free and can be supplied by abundant fission materials. In addition, the knowledge from traditional power plants can be applied extensively.

Since the advent of nuclear power plant, nuclear reactors such as PWR, CANDU and BWR based on a steam power cycle technology have mainly served as a power source in many countries. However, recently, the move to develop more efficient and compact power conversion cycle has drawn attention. In contrast to steam Rankine cycle, Brayton cycle can utilize higher temperature more effectively and employ compact turbomachinery, possibly resulting in better efficiency and compact system layout.

Noticeably, the supercritical carbon dioxide (S-CO_2) power cycle is a promising application of Brayton cycle for nuclear power. One of the benefits of S-CO_2 cycle is reduced compression work near the critical point, where thermodynamic properties changes drastically [1]. This reduced compression work makes the cycle operate with pump-like compression and gas turbine expansion on the supercritical state.

In spite of all these advantages, the noble characteristics of S-CO_2 make a design of turbomachinery challenging, especially for a compressor working near the critical point. Thus, it is natural to investigate the fundamental characteristics in more detail. In this paper, a study of airfoil was performed based on NACA 65-series airfoil data, but under CO_2 environment by 2-D computational fluid dynamics.

NACA airfoil series are the shapes of airfoils appropriate for air, developed by National Advisory Committee for Aeronautics (NACA), the predecessor of National Aeronautics and Space Administration (NASA). At the early stage of aeronautical engineering, it was not an easy task to design and optimize an airfoil shape for its purpose. However, NACA reports were published and pointed out that successful airfoils have similarities [2], which later were reflected on NACA airfoil series. Since their development, the wide range of airfoils have been well validated through experiments in wind tunnel cascades and are used for designing turbomachinery and aircraft wings. As a result, these experiences give valuable information such as drag, lift and stall angle, which are the performance of airfoils.

Therefore, it is expected that an aerodynamic study of NACA airfoils under CO_2 environment can facilitate the procedure of designing turbomachinery for S-CO_2 power cycle. For this purpose, NACA 65-series [3], a variation of 6-digits for axial compressor design, was selected for the analysis presented in this paper. It would be ideal to investigate the behavior of airfoils in a supercritical CO_2 wind tunnel, but this is not possible due to lack of resources so far. Alternatively, a computational fluid dynamic model in Star-CCM+ was constructed and validated against the air condition, and then the result for supercritical CO_2 condition will be compared to that of air condition.

2. Methods

2.1 Benchmark model

The analysis conditions were extracted from NACA technical report for 65-series [3]. The report documented the result of airfoil cascade experiments such as pressure coefficient, turning angle and lift/drag coefficient, according to various combinations of angle of attack, inlet angle, solidity and different airfoil, in an attempt to represent compressor operations. The method suggested here is to validate the model for supercritical CO_2 condition from air condition. It was assumed that if the constructed model can reproduce the behavior of air experiment, then the model is likely to do so under the supercritical CO_2 conditions as well.

2.2 Model geometry and mesh

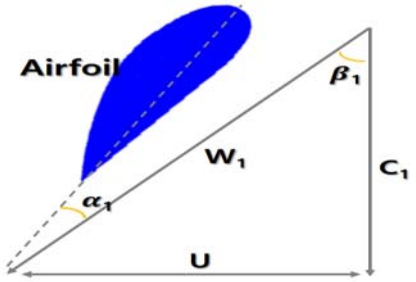

Fig 1. Typical vector diagram for a compressor rotor inlet

Fig 1. shows a typical vector diagram for compressor. The compressor intake velocity is C_1, but because of the rotating velocity U of rotor, the fluid approaches to the airfoil with velocity W_1 and inlet angle β_1. Additionally, the angle between the relative inlet flow and the camber line is angle of attack α_1. This diagram was transformed into a stationary airfoil cascade in Fig 2.

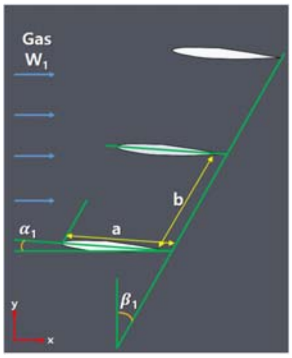

Fig 2. Analysis model geometry

The fluid flows with velocity W_1, at the same time α_1 and β_1 were taken into account for the similarity. The distance between each airfoil was considered as b/a, solidity. To solely observe the phenomena around a single airfoil, the forward, backward and lateral spaces of cascade should be prescribed sufficiently, and the airfoil in the middle was the major area of interest.

Mesh was generated by Star-CCM+ mesh tool as shown in Fig 3. The meshes in the airfoil surroundings and wake region were finely constructed. Particularly leading edge and trailing edge regions were more finely constructed.

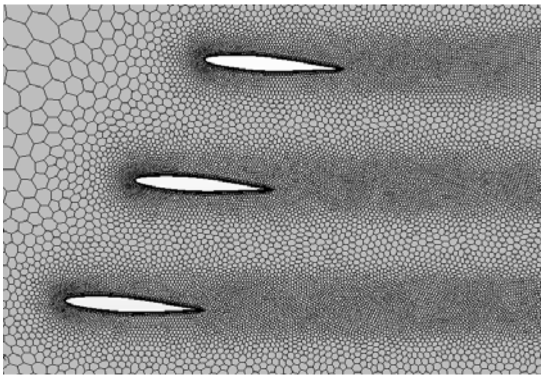

Fig 3. Constructed mesh

2.3 Physical models

Table 1. Selected physical model

Material	Gas
Flow solver	Segregated flow
Equation of State	Ideal gas (Air) Tabulated NIST data (CO_2)
Time	Steady
Dimension	2-D
Reynolds-Averaged Turbulance	k-w SST

The physical models were selected for the simulation. For turbulence modeling, k-w SST model was used, which is widely accepted for turbomachinery analysis. To simplify the problem, analysis dimension was set to 2-D since spanwise effect can be considered to be negligible. Regarding fluid property, air was modeled as ideal gas and CO_2 property was implemented by tabulated NIST refprop.

3. Result and summary

Table 2. Analysis condition

fluid	air	CO_2
Pressure	101.3kPa	8MPa
Temperature	300K	315.15K
Compressorbility	0.9997	0.4866
density	1.1767kg/m^3	277.9kg/m^3
Inlet velocity	28.956m/s (95ft/s)	
Type of airfoil	NACA 65-010	
Inlet angle(**β_1**)	Angle of attack(**α_1**)	Solidity(b/a)
30°	4°	1

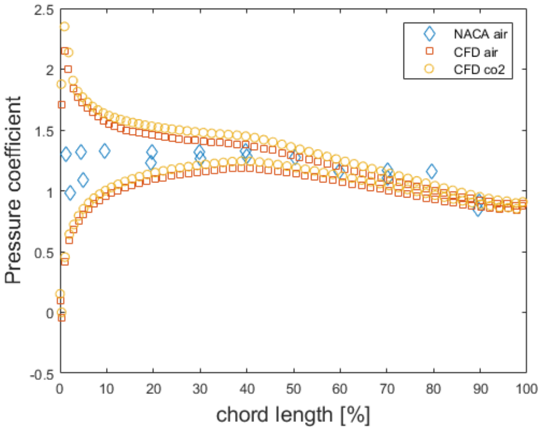

Fig 4. Pressure coefficient distribution

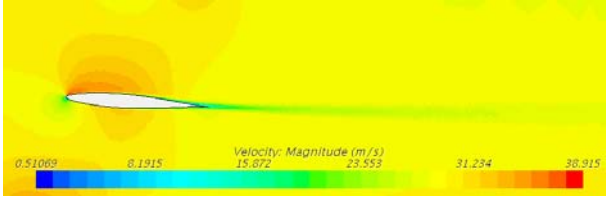

Fig 5. Velocity scalar field (Air)

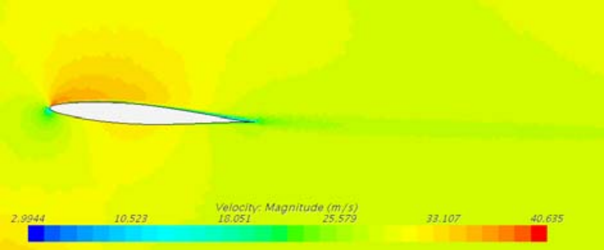

Fig 6. Velocity scalar field (CO_2)

The analysis condition is tabulated in table 2. In the NACA report [3], NACA 65-010 is chosen for the analysis. Although geometries and inlet velocity were given explicitly in the report, the inlet thermodynamic condition was not specified, so the inlet air condition was assumed. In case of CO_2, a supercritical state, 40℃ and 8MPa was selected and it is more dense as well as difficult to compress than the air.

The results are presented in Fig 4 by using pressure coefficient. The pressure coefficient is defined in equation (1), which is the ratio of local dynamic pressure and upstream dynamic pressure. When CFD air case is compared to NACA experiment, the comparison did not show a good agreement near the leading edge region. Switching to different turbulent model can improve the agreement in this region, since the flow is not fully developed from laminar to turbulent flow near the leading edge. On the contrary, CFD air and CO_2 showed a very similar trend in Fig 4. In the view of equation (1), this can be visualized as velocity distribution in Figs 5 and 6.

$$pr\_coeff = \frac{P_{total,upstream} - P_{static,local}}{P_{total,upstream} - P_{static,upstream}} \quad (1)$$

To design a turbomachinery, the wide range of NACA airfoil shapes and data have been exploited extensively. Therefore, it is natural to investigate the effect of airfoil under CO_2 environment to design a turbomachinery operating in S-CO_2 power system. The study of airfoil under two very different environments was conducted by using CFD approach, assuming the validated model for air condition could reasonably describe the aerodynamics of airfoil under supercritical CO_2 conditions. The two result showed similar trend. However, to generalize the performance of airfoils under CO_2 environment, more cases should be tested, including cases near the critical point (31°C, 7.39 MPa).

3. Acknowledgements

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