Effect of Large Backswept Angle S-CO_2 Compressor to System Part Load Performance

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1. Introduction

According to UK National Nuclear Laboratory 2014 report and Canadian SMR roadmap, the potential market demand of SMR was approximately evaluated for 100~500 billion USD at 2035 [1, 2]. Among them, market of electric power supply to islands and remote regions occupies about 20 billion USD. To supply energy to the islands, and remote regions, KAIST research team has proposed a concept of small modular reactor, called KAIST Micro Modular Reactor, MMR [3]. KAIST-MMR is required to have capability to be transported by trailers, or barges in order to operate in the target areas where setting construction infrastructure is very expensive. To achieve this, the reactor adopts direct energy conversion configuration using supercritical CO_2 (S-CO_2) fluid as reactor coolant and cycle's working fluid. S-CO_2 power cycles have received attentions in terms of compactness and high thermal cycle efficiency. Since the cycles compress the fluid near the critical point where fluid becomes liquid-like state and operate above the critical pressure 7.38MPa, compression work can be substantially reduced and power density of fluid is higher than ordinary gases. These characteristics cause compact and simple cycle configuration, and high thermal efficiency [4, 5].

Nevertheless, MMR has around 30% thermal cycle efficiency because the cycle layout is a simple recuperated cycle whose thermal efficiency is compromised with the compactness. Moreover, the compressor inlet temperature of the system is selected for 60^{o}C because it was designed to cool by air for being independent on the regional environment. However, this temperature is quite far from the critical point so that the power cycles require larger compression power to operate the compressor. This means that the cycle performance is more sensitive with respect to the compressor efficiency. Therefore, high efficiency compressor becomes more important for KAIST-MMR to enhance the overall system performances. The study to increase compressor efficiency was conducted by Cho et al. [6], applying large backswept angle compressor. However, the system transient analysis was not assessed in his work. Previously, the transient analysis of KAIST-MMR was implemented to confirm whether it is regulated satisfyingly under load following conditions, and kept integrity under hypothetical accidents [7]. The results showed that KAIST-MMR has enough ability to treat various transient situations.

Thus, part load performance will be modeled after adopting large backswept angle compressor in this paper. Especially, large backswept angle compressor's performance map has more abrupt inflection near the design point compared to the conventional compressor. As a result, it is predicted that the part load performance can be substantially different.

2. Methods and Results

2.1 Effect of large backswept angle

Back swept angle is defined as the blade's backward angle at the impeller exit in a centrifugal compressor as shown in Fig 1.

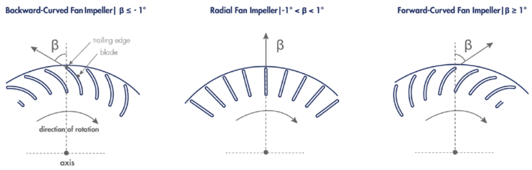

Fig. 1. The definition of back swept angle of centrifugal compressor.

According to Cho et al. [6], the S-CO_2 centrifugal compressor showed the best efficiency at -70^o back swept angle, which is larger than the typical design value for the air centrifugal compressor, -50^o as shown in Fig 2. In the figure, the cases represents that the how CO2 fluid has the characteristics of ideal gas as the Z is close to 1.0. This means that the S-CO_2 compressors have high efficiency when the back swept angle is larger regardless of the inlet conditions.

In case of air and helium, the backswept angle is generally limited to -50^o due to high tip speed in the low density fluid compressors. However, S-CO_2 requires only a few hundredth of the enthalpy of air when it increases the same amount of pressure. It means that the work consumption for compression is significantly reduced when the S-CO_2 compressor increases the same amount of pressure compared to the air compressor. Thus, smaller tip speed occurs in S-CO_2 compressors and this leads to smaller centrifugal stress on the impeller of the S-CO_2 compressor.

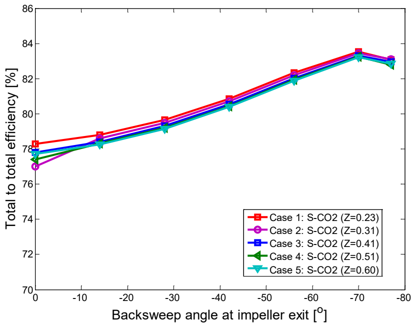

Fig.2. Total to total efficiency for backswept angles

In order to understand the reason why the backswept angle change affects the efficiency, the compressor loss distribution with varying angle was analyzed as shown in Fig 3. Blade loading loss, clearance loss and mixing loss are associated with the pressure loading on the blade. The blade loading loss is due to the flow separation resulting from the pressure load difference between the suction side and the pressure side. In this respect, the inclination of the blades to the radial direction reduces the pressure loading and it alleviates the secondary flow and the tip clearance flow. Thus, as the backswept angle increases, less pressure loading per unit length on the blade is expected, which results in reducing the strength of the vortex at the blade tip. This means that the clearance loss decreases as the backswept angle increases. Mixing loss is derived from mixing of the high momentum fluid on the pressure side and the low momentum fluid on the suction side. Decrease of pressure loading means a reduction in difference of fluid momentum between pressure side and suction side, and the mixing loss decreases as the backswept angle increases. Slip loss assumes that the flow cannot be perfectly guided by impeller blades. It causes the flow angle at the impeller exit leans to the opposite direction of the rotating direction. Therefore, as the backswept angle is larger, the slip loss is insensitive. The skin friction loss, the leakage loss and the disk friction loss tend to increase because the diameter of the impeller is increased to maintain the same outlet pressure so that the area becomes larger as the backswept angle increases.

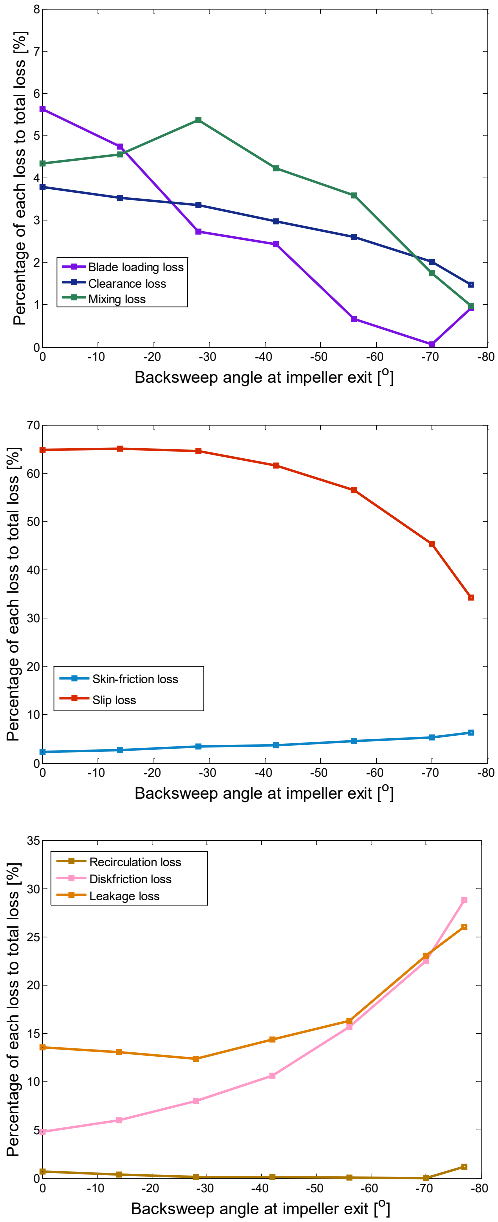

Fig. 3. Distribution of internal and external losses with backswept angle variation

Finally, the high compressor efficiency of large backswept angle comes from the relatively low losses.

2.2 KAIST-MMR

A simple recuperated cycle is chosen for the layout of KAIST-MMR due to compactness and simplicity. In terms of high cycle efficiency, 550°C for turbine inlet temperature and 60°C for compressor inlet temperature were chosen as design conditions. Table I shows the design results of KAIST-MMR.

Table I. Design results of KAIST-MMR

	Parameter	Value
Power Cycle	Q_{core}	36.18MWth

	η_{cycle}	33 %
	Mass flow rate	187.0 kg/sec
Turbomachinery	η_{turb}	94%
	TI condition	550 ºC / 20 MPa
	η_{comp}	84%
	CI condition	60 ºC / 8.2 MPa
Heat Exchanger	$V_{precooler}$	4.86 m^3
	$V_{recuperator}$	6.85 m^3

To assess the effect of back swept angle, two compressors with -50º and -70º were designed by KAIST-TMD a turbomachinery design in house code.

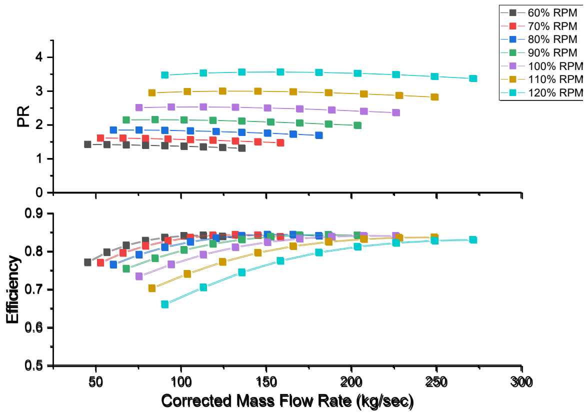

Fig. 4. Compressor performance map with -50º back swept angle

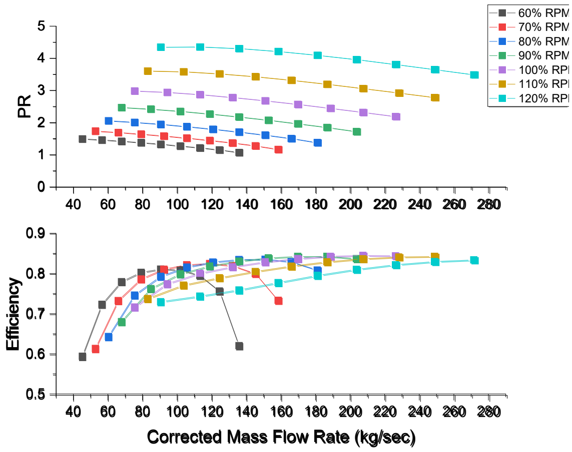

Fig. 5. Compressor performance map with -70º back swept angle

Analyzing performance maps of two compressors, -50º back swept angle compressor has flatter pressure ratio and efficiency with respect to the mass flowrate compared to -70º while the efficiency at design point is slightly higher in case of large back swept angle (-50º: 83.9%, -70º: 85.0%). Especially, the off-design performance at low rotational speed is much lower in case of the compressor with -70º back swept angle.

2.3 Comparison of Part load modeling of KAIST MMR in case of -50º and -70º back swept angle compressor

Among many nuclear system codes, GAMMA+ code has been selected for KAIST-MMR modeling. This is because GAMMA+ code was fully demonstrated to have excellent analysis capability from the previous works [7, 8]. Secondly, the code is equipped with two-phase water system analysis module as well as single phase fluid analysis module, and capability to model various control logics. Using this GAMMA+ code, KAIST-MMR was modeled with the following nodalization as shown in Fig 6.

The part load scenario starts with reduction from the full power operation system to 50% power level within 100 seconds and then, maintaining the state for 200 seconds.

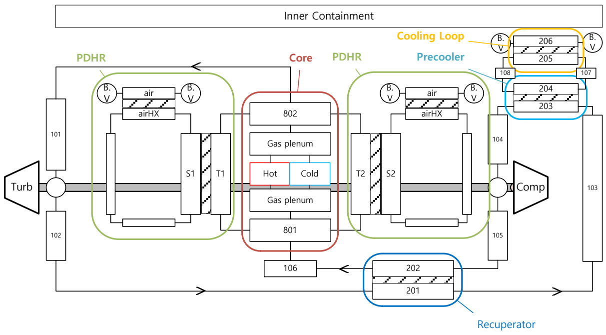

Fig. 6. Nodalization of KAIST-MMR

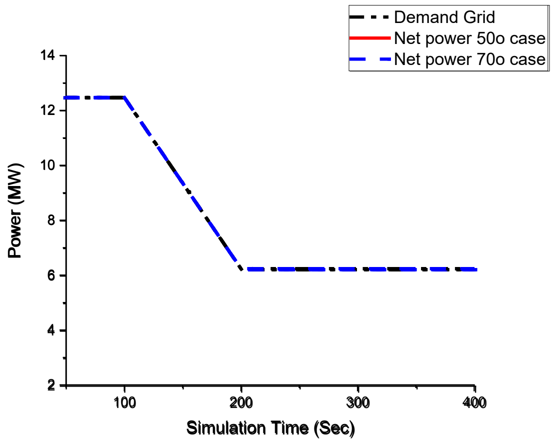

Fig. 7. Grid demand and net power of -50º and -70º back swept angle cases

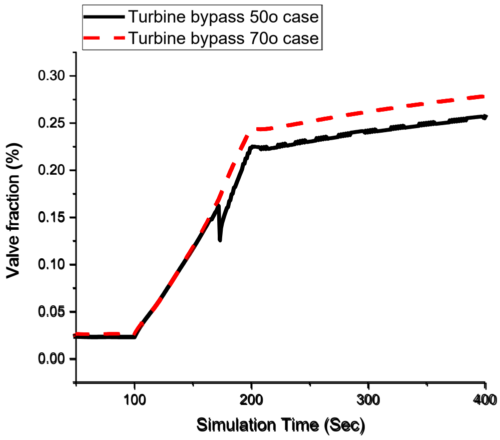

Fig. 8. Turbine bypass valve fraction of -50° and -70° back swept angle cases

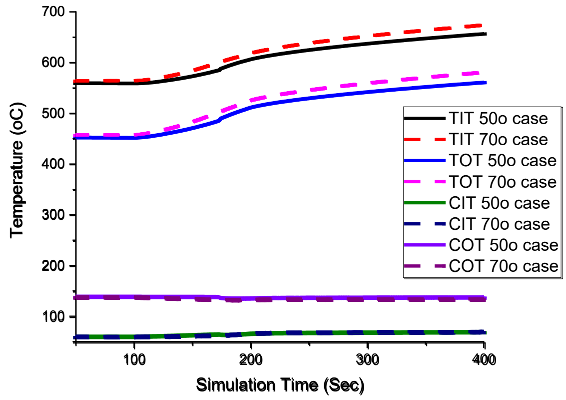

Fig. 9. Temperatures at major components of -50° and -70° back swept angle cases

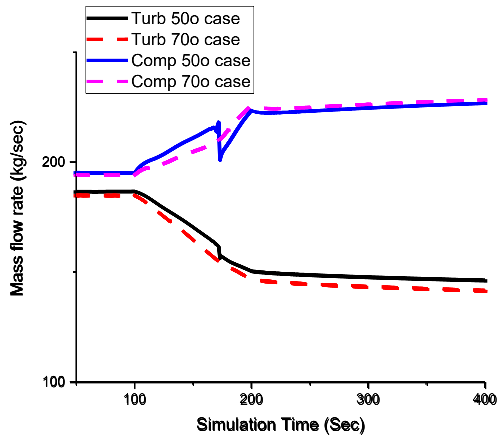

Fig. 10. Mass flow rate of -50° and -70° back swept angle cases

Fig 7 shows the boundary condition of this scenario and both systems with different compressors well follow the grid demand. Fig 8 shows the turbine bypass valve's fraction during the part load operating conditions. Since -70° compressor has larger pressure ratio as the compressor mass flow rate decreases, the part load condition of -70° compressor has larger turbine bypass fraction compared to -50° compressor when the demand load is reduced. In Fig 9, temperatures at major components show similar trend because the compressor efficiency maps are similar for both -50° and -70° compressors under the rated compressor rotational speed as shown in Fig 5 (Purple line). Fig 10 shows the mass flow rate of two systems with different compressors. Due to the inventory control and turbine bypass valve operations, both systems have similar behavior during the part load conditions but the spike occurs in case of 50° back swept angle compressor. This is because there are same controllers are reflected for the scenarios so that each different controllers should be optimized. Even though the large back swept angle compressor has high on-design efficiency, the off-design efficiency is low so that the systems which are usually operated on the rated condition without part load operation might be suitable to select the large back swept angle compressors.

3. Conclusions

To apply a high efficiency compressor to the S-CO_2 cooled KAIST Micro Modular Reactor, compressors with -50° and -70° back swept angle were designed by KAIST-TMD and tested numerically. The performance map of a large back swept angle compressor shows higher efficiency at the design point but the off-design performance of the compressor is more sensitive to the mass flow rate change. To assess the effect of a large back swept angle compressor on the system scale, the grid demand reduction scenario with constant rotational speed was simulated with GAMMA+ code. The overall results show similar trend for -50° and -70° cases because the performance map at the rated rotational speed is similar for two compressors. For further works, the scenario with rotational speed change will be analyzed to confirm the effect of different performance of a large back swept angle compressor to the system.

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