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START UP MODELING OF KAIST MICRO MODULAR REACTOR COMPRESSOR USING BETA LINE METHOD WITH GAMMA+ CODE

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ABSTRACT

It is usually difficult to model the startup of S-CO_2 turbomachines from zero rotational speed to nominal speed because obtaining the performance characteristics near low speed region is challenging. To infer the performance characteristics of a compressor in the low speed region, similarity law for incompressible fluids are used in this paper. It is assumed that near the low speed region pressure rise is small enough so that the effects of compressibility can be ignored. After the performance map is extended by the similarity law, the extended performance map of the compressor is applied into GAMMA+ code, which is an S-CO_2 system analysis code, by BETA line method. The BETA line method is introduced to be independent from the shape of performance map such as vertical, quadratic and etc. To simulate the startup of an S-CO_2 compressor, the compressor of KAIST Micro-Modular-Reactor which has 19,300 RPM as the design rotational speed, 8MPa and 60°C as compressor design inlet condition is selected as the reference compressor. The startup simulation of the reference compressor shows reasonable results.

INTRODUCTION

A supercritical carbon dioxide Brayton cycle (S-CO_2 cycle) has high thermal efficiency at moderate temperature ranges and can be realized in physically compact size. This is because S-CO_2 is compressed near the critical point where density becomes high but viscosity stays small [1]. The advantages of S-CO_2 cycles on the design point are well known in terms of efficiency, size and so forth. However, the transient analyses of S-CO_2 cycles like startup, load following, shutdown and various incidents are still necessary to improve the controllability, safety and performance of S-CO_2 cycles.

In this paper, the startup procedure of S-CO_2 compressor is selected since not many research works can be found in this area. The reference compressor is KAIST Micro-Modular-Reactor (MMR) which has 19,300 RPM as the design rotational speed, 8MPa and 60°C as the design compressor inlet condition [3]. Figure 1 shows the configuration of MMR. The compressor performance map of MMR was drawn by an in-house code for turbomachinery modeling called KAIST-TMD which generates turbomachinery performance curve based on 1D mean line method [4]. The pre-generated performance map is applied to GAMMA+ code which is modified for the S-CO_2 systems [5]. However, the performance map of turbomachines rarely can be extended to the low speed region because of the unsteady nature of low speed conditions [6]. This becomes troublesome for mapping the turbomachinery performance to a system analysis code, especially during the startup simulation. To resolve this problem Zhao at al. [7] implemented an extention method of a compressor performance map but they did not explain the detail procedure of how to extend the compressor performance map in the low speed region. Moreover, the target system was GT-MHR which is a helium cooled high temperature reactor. Thus, logical assumption and extension method for S-CO_2 systems are needed to deduce S-CO_2 compressor performance map in the low speed region.

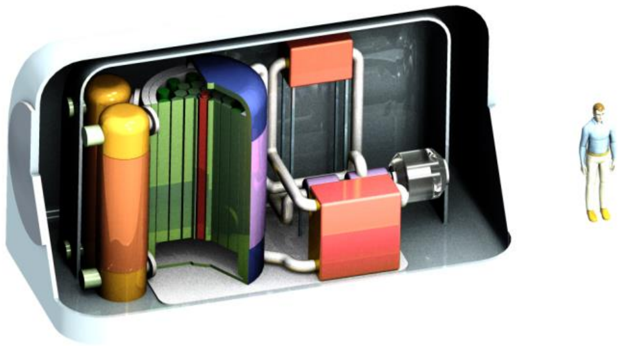

Figure 1. Configuration of KAIST MMR

To develop a method for the S-CO_2 compressor performance map in the low speed region, similarity laws for pump [8] and a method suggested by Agrawal and Yunis [9] are utilized in this paper. The reason why similarity law for incompressible fluid is basically selected is that the pressure rise is small enough that the effects of compressibility can be ignored but the S-CO_2 itself is a meta-compressible fluid so that characteristics of the S-CO_2 compressor such as pressure ratio and isentropic efficiency are reflected by Agrawal and Yunis's similarity laws [6]. Even though the map is fully expanded in the low speed region, if a performance map have vertical line with respect to the corrected mass flow rate, the performance map with respect to mass flow rate becomes difficult [7]. Therefore, BETA line which is an auxiliary coordinate to resolve dependence on shape of performance curve is introduced as the way of mapping the performance map in the system analysis code [10].

LOW SPEED EXTENSION METHOD OF COMPERSSOR PERFORMANCE MAP

The similarity laws of pump (i.e. incompressible fluid) are written as follows [6]:

The mass flow relationship,

$$\frac{\dot{m}_{new}}{\dot{m}_{ref}} = \left(\frac{N_{new}}{N_{ref}}\right)^{1} \tag{1}$$

The work relationship,

$$\frac{W_{new}}{W_{ref}} = \left(\frac{N_{new}}{N_{ref}}\right)^{2} \tag{2}$$

The power relationship,

$$\frac{P_{new}}{P_{ref}} = \left(\frac{N_{new}}{N_{ref}}\right)^{2.75} \tag{3}$$

The reason why similarity laws for pump is able to be applied to the S-CO_2 compressor is that the pressure rise is small enough that the effects of compressibility can be negligible in the low speed region [6]. In equations (1) to (3), subscript 'new' represents the extended performance value and subscript 'ref' means reference point which is the lowest speed line of the original performance map.
From these similarity laws, Agrawal and Yunis [9] derived pressure ratio and isentropic efficiency of air fan and compressor map based on the ideal gas assumptions.

$$\Pr_{new} = \left(1 - \frac{W_{new}}{C_{p,in}T_{in}}\eta_{ref}\right)^{\frac{\gamma}{\gamma-1}} \tag{4}$$

Where W_{new} in equation (4) can be obtained from equation (2) and η_{ref} means the isentropic efficiency of the lowest speed line of original performance map. The isentropic efficiency also can be derived [6].

$$\eta_{new} = \frac{\dot{m}_{new}C_{p,in}T_{in}(\Pr_{new}^{\frac{\gamma-1}{\gamma}} - 1)}{P_{new}} \tag{5}$$

Since equation (5) are fully derived from the ideal gas assumption and related thermodynamics relations, it is better to use the reference point to obtain the extended performance curve because the reference point already reflects features of an S-CO_2 compressor obtained from KAIST-TMD code. Therefore, the extended isentropic efficiency can be obtained as follows:

$$\eta_{new} = \eta_{ref}\frac{P_{ref}\dot{m}_{new}(\Pr_{new}^{\frac{\gamma-1}{\gamma}} - 1)}{P_{new}\dot{m}_{ref}(\Pr_{ref}^{\frac{\gamma-1}{\gamma}} - 1)} \tag{6}$$

From these similarity laws, extended performance curve is shown as Figures 2 and 3.

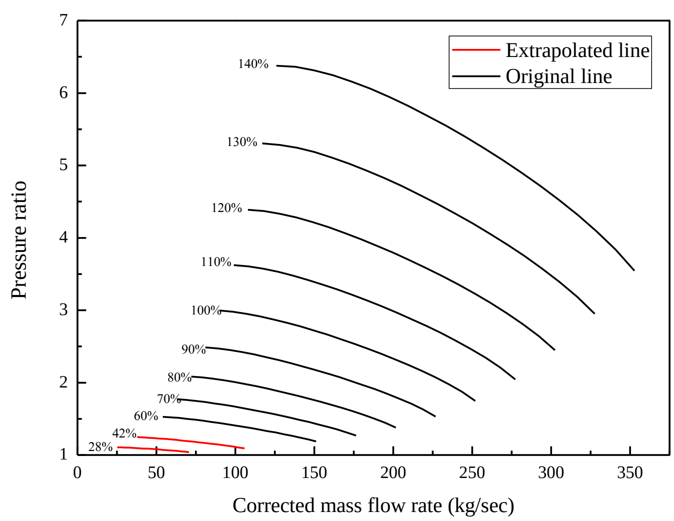

Figure 2. Pressure ratio with respect to corrected mass flow rate of MMR compressor

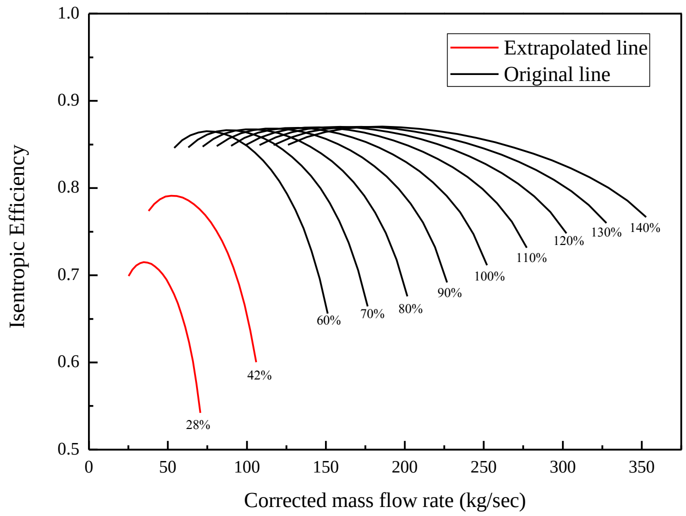

Figure 3. Isentropic efficiency with respect to corrected mass flow rate of MMR compressor

APPLICATION OF BETA LINE METHOD

Fortunately, pressure ratio map of the MMR compressor does not have a steep slope as shown in Figure 2, so that each mass flow rate point has a single pressure ratio at given speed line. However, if the pressure ratio has a steep slope with respect to mass flow rates, each mass flow rate can has numerous pressure ratio values at given speed line. Figure 4 is the artificial pressure ratio curve which has a steep slope in some regions for the illustration purpose. This is to show that one can have simulation problems when a pressure ratio value is interpolated for a given mass flow rate. Even though the steep pressure ratio curve in Figure 4 is artificially made, for axial compressor the vertical pressure ratio line at the tail frequently occurs.

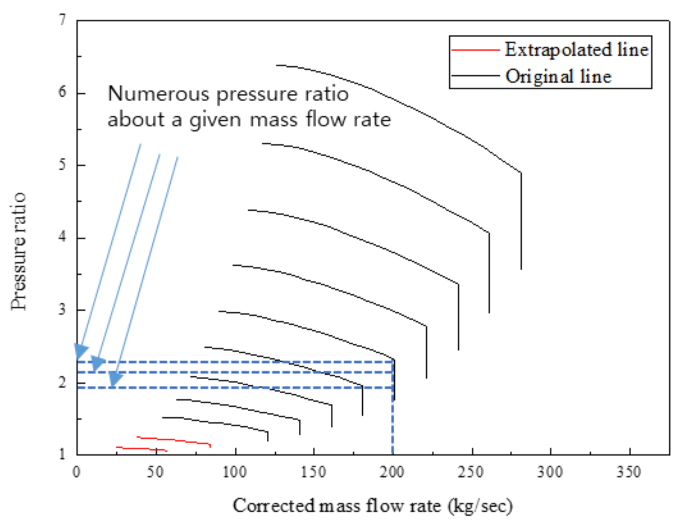

Figure 4. Artificial pressure ratio to show the difficulty of pressure ratio interpolation based on mass flow rate on a steep slope curve

BETA line method utilizes an auxiliary coordinate for the pressure ratio map as the following figure:

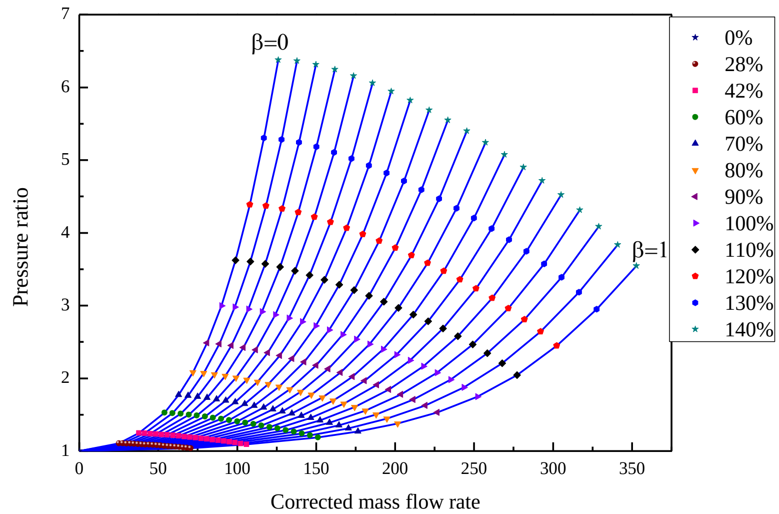

Figure 5. Pressure ratio map with respect to BETA value and compressor rotational speed

As shown in Figure 5, the independent parameters to interpolate pressure ratio and isentropic efficiency become compressor speed, N and BETA value, β as in the following equation.

$$PR = f(N, \beta), \quad \eta = f(N, \beta) \tag{7}$$

This means the interpolation of pressure ratio with respect to the corrected mass flow rate becomes non-sensitive to the shape of pressure ratio curve after BETA line is newly introduced. For a given speed line, a single BETA value has a single pressure ratio even though pressure ratio curve has a steep slope with respect to the corrected mass flow rate as shown in Figure 6.

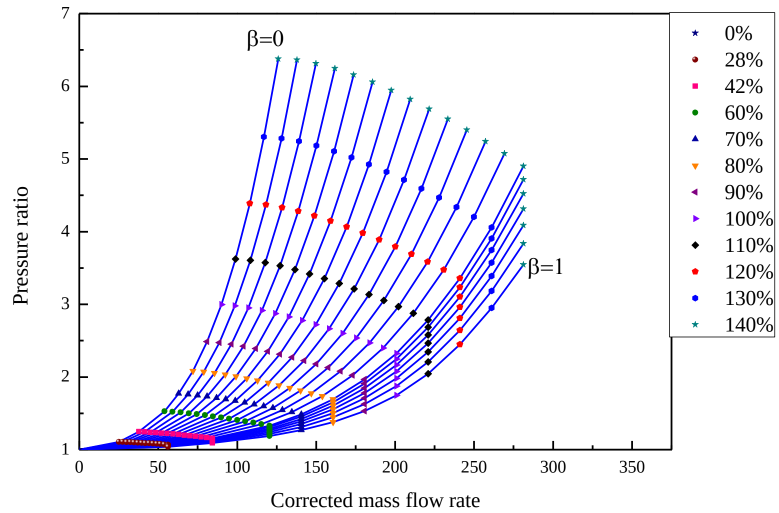

Figure 6. Pressure ratio map with respect to BETA value and compressor rotational speed

SIMULATION RESULTS

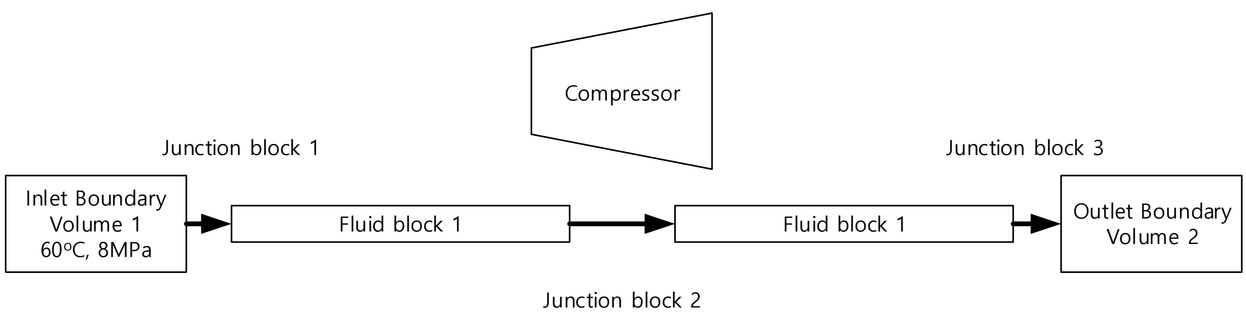

Figure 7. Compressor test section in GAMMA+ code for startup simulation

In Figure 7, the inlet boundary volume is the boundary condition for the modeling, which prescribes constant pressure and temperature condition for the compressor inlet. The outlet boundary volume properties are changing during the simulation. The pressure ratio map in Figure 5 is applied to the compressor test section in Figure 7 for startup simulation. Another boundary condition of the startup simulation is the increase of compressor speed. It is assumed that an external motor engages to increase the rotational speed of the compressor for 5 seconds. Table 1 contains design points of MMR compressor and Figures 8 to 11 show the result of startup modeling of the MMR compressor. After 5 seconds of operation, the compressor approaches the design conditions successfully.

Table 1. On-design points of MMR compressor

Rotational speed	Mass flow rate	Outlet pressure	Outlet temperature
19,300 RPM	180 kg/sec	20 MPa	142.2 °C

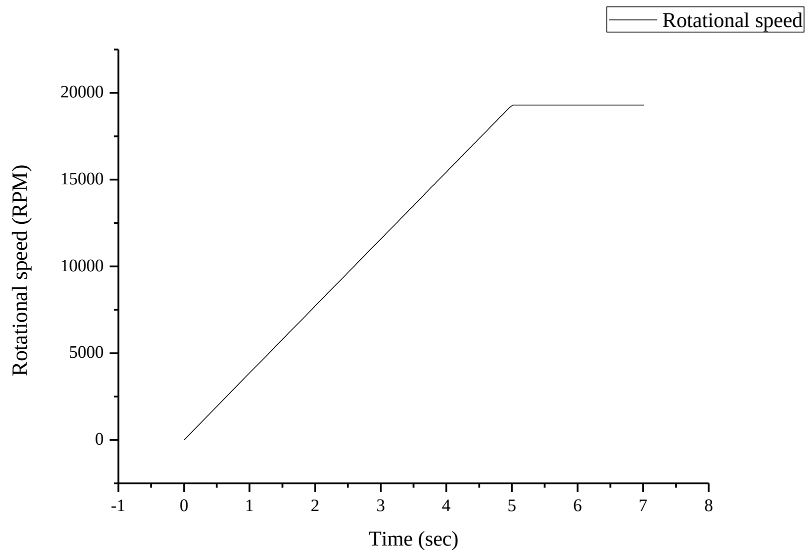

Figure 8. Compressor rotational speed vs. time during startup

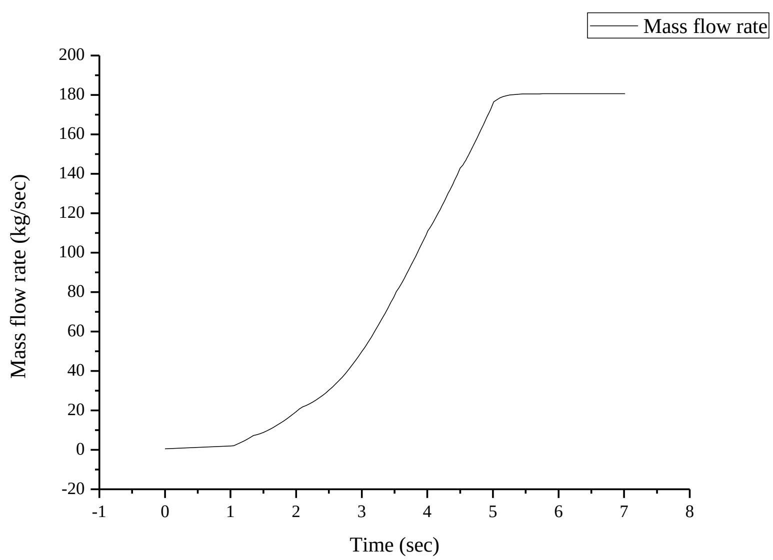

Figure 9. Compressor mass flow rate vs. time during startup

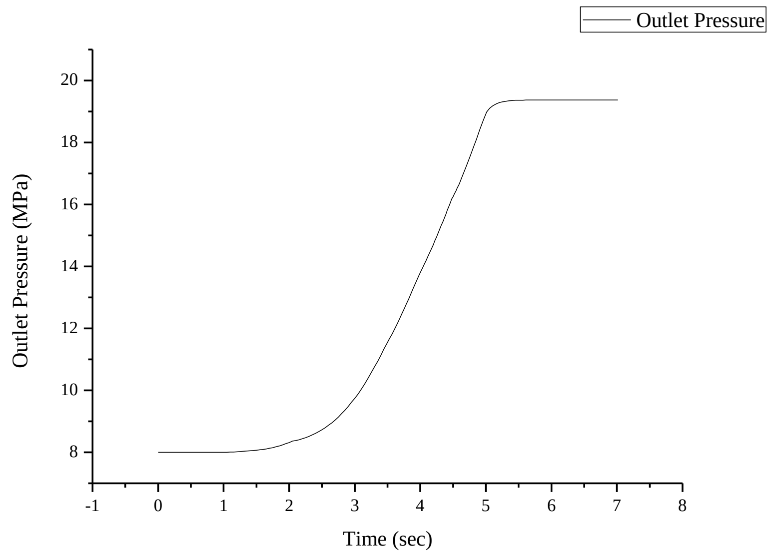

Figure 10. Compressor outlet pressure vs. time during startup

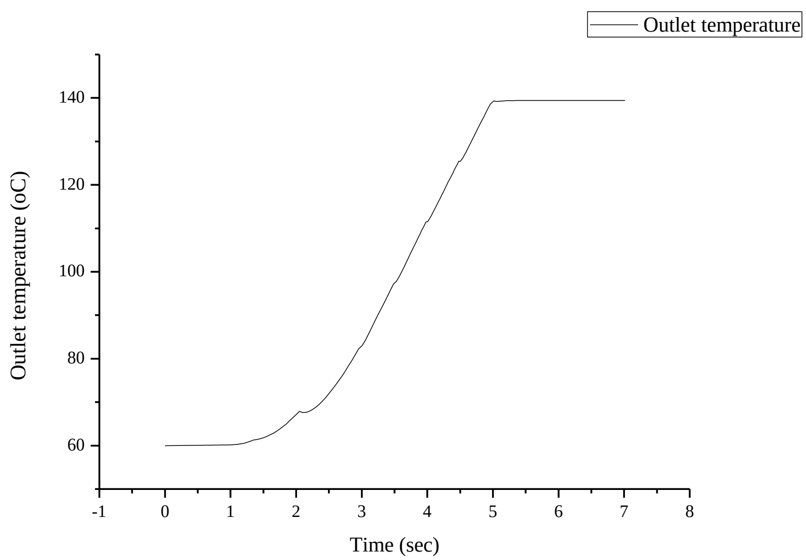

Figure 11. Compressor rotational speed vs. time during startup

The trend of Figures 9 to 11 is very similar to the previous dynamic simulation performed by Sandia National Lab [2], which is encouraging to use this method further for the full system analysis cases.

CONCLUSIONS

To model the startup of an S-CO_2 compressor, similarity laws of pump are used to extend the performance map to the low speed region with higher accuracy. After the performance map is extended, the BETA line method is introduced to the S-CO_2 system analysis code to further enhance the simulation stability and accuracy. This is because a compressor pressure ratio map may have a vertical line for the pressure ration with respect to the mass flowrate which the system analysis code cannot obtain the pressure ratio for a given mass flow rate and speed lines only. After the BETA line method is utilized, obtaining characteristics of the compressor becomes less sensitive to the shape of a compressor pressure ratio map. After these procedures, the MMR compressor startup is quickly simulated by the gas system analysis code, GAMMA+ code. It shows reasonable results with respect to simulation time. A full startup simulation of the whole 12MW system will be next performed and some information on this will be shared in the conference.

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