Investigation on Numerical Simulation of supercritical CO$_2$ Power Equipment

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Abstract. The supercritical CO$_2$ (S-CO$_2$) Brayton cycle has recently been gaining a lot of attention for application to solar energy. This paper introduces the MATLAB simulation experiment of supercritical carbon dioxide power generation system, and analyses relevant important operation parameters for supercritical CO$_2$ effect of power system performance. The mathematical model of supercritical CO$_2$ power equipment system is established on modular non-linear method using Matlab and its software package Simulink. Using this dynamic simulation model, the loading and unloading process characteristics of supercritical CO$_2$ power device were analyzed. The results show that: the rotor speed, turbine exhaust, motor power and mechanical loss is slowly strengthened with the increase of heating output, then increased to the maximum at the same time immediately. Thereafter, the rotor speed, turbine exhaust, motor power and mechanical loss power is slowly decreased and remain stability. The dynamic matching characteristics of compressor, turbine and other equipment in the system are good, and the operation is stable.

1. Introduction

In the solar power generation and nuclear power generation system, to improve the efficiency of power generation conversion has been the focus of scientific research. And water, helium or organic matter of more working medium are used in power system. In recent years, the supercritical CO$_2$ (S-CO$_2$) has become a new hot spot in the field of refrigeration, power generation [1-2] due to the characteristic of non-toxic, environmental protection, viscosity like gas approximation, with good mass transfer performance, and easy to compress. Using the super-critical state especially in the Brayton closed cycle can make the system to achieve high efficiency, small size, compact structure at the same time [3], and less initial investment, so it is very suitable for distributed solar thermal and nuclear power system. The performance of supercritical Brayton closed cycles using several heat sources were studied experimentally by some researcher [4]. An exergy and energy analysis of CO$_2$ in supercritical Brayton cycle was investigated experimentally by Padilla R V[5] and Q H Deng etc [6]. Current research in S-CO$_2$ is focused on the thermodynamic analysis and system components (turbine design and heat exchangers), but the study of super-critical CO$_2$ power systems at home and abroad is not many, there are few matching design and simulation for the entire system. So in this paper, the modular simulation model of S-CO$_2$ generator is established based on MATLAB/SIMULINK simulation platform, and then the change of performance parameters are respectively obtained with the dynamic simulation of loading and unloading process, which can be
guided experiments and shorten the design period.

2. Mathematical model of the main components
SuperCritical Brayton CO\textsubscript{2} power system is composed of compressor, turbine, heater, cooler, regenerator and motor and other parts. And a highly nonlinear thermal system is used for the simulation of the S-CO\textsubscript{2} equipment, the characteristics of compressor, turbine and heater components are highly nonlinear in the working process. So in this article the modular [7] nonlinear modeling method is adopted to establish the mathematical model of super-critical CO\textsubscript{2} equipment components. The physical model diagram of the super-critical CO\textsubscript{2} mechanism used for the simulation is showed in Figure 1. Please refer to the literature[8] for the specific modular equation calculation, which will not be introduced in detail here.

3. Device simulation model
The main title (on the first page) should begin 13/16 inches (7 pica) from the top edge of the page, centered, and in Times New Roman 14-point, boldface type. Capitalize the first letter of nouns, pronouns, verbs, adjectives, and adverbs; do not capitalize articles, coordinate conjunctions, or prepositions (unless the title begins with such a word). Please initially capitalize only the first word in other titles, including section titles and first, second, and third-order headings (for example, “Titles and headings” — as in these guidelines). Leave two blank lines after the title. The structures of simulation model for super-critical CO\textsubscript{2} equipment is established on the mathematical model, so the simulation model of the corresponding modules is respectively set up in SIMULINK software.

4. The simulation and the result analysis
The control method in the progress of dynamic regulation for super-critical CO\textsubscript{2} is mainly controlling the heating output for the heater, which can change the turbine inlet temperature, and then the mass flow, expansion ratio, output power are adjusted. Speed is decided by the power rate, which is generally constant in generation as the feedback signal. Because the speed module is not added in this simulation model, so the open-loop control simulation is only proceeded to simulate the change of the parameter when the isotherm is changed, then dynamic matching performance is attained at some time. Please refer to the literature[8] for the specific modular equation calculation, which will not be introduced in detail here.
4.1 Loading process
According to the change rule of the heating output for the heater as shown in Figure 2, loading process is simulated for super-critical CO$_2$ system, the change of other parameters in equipment is shown in Figure 3 to Figure 5.

It is seen that the heating output is equal-slope changed from 104.8 kW to 144.5 kW, and then remained unchanged from 50 s to 200 as shown in Figure 2.

From Figure 3 it is seen that the rotor speed is increased rapidly with the increase of the heating output, the slope is reduced in 200 s, and then stable in 250 s, so the overshoot phenomenon is not appeared. Figure 4 shows that the change of turbine exhaust is relatively stable, which is increased starting from 50 s, reached the peak in 200 s, then a slight decreased and stable. Figure 5 show change curve of mechanical loss power. Mechanical loss is increased slowly, then rapidly increased, and reached peaked in 220 s, then decreased and remained stable.

4.2 Unloading process
It can be seen that the change rule of turbine exhaust in unloading process are opposite compared with loading process as shown Figure 6 to Figure 9. Rotor speed is relative increased and is stable in 225s. Mechanical power loss is stable in the 200s compared with the loading process, its response
speed is also increased, and then remained stable, no overshoot phenomenon is appeared.

![Figure 7. The change curve of the rotor speed (unloading)]()

![Figure 8. The change curve of the turbine exhaust (unloading)]()

4.3 Drawing and analysis of loading line and unloading line

The simulation results are drawn on the diagram of compressor characteristic and compared with the balance condition as shown in Figure 10.

![Figure 9. The change of the mechanical power loss (unloading)]()

![Figure 10. The curve of the compressor characteristic for loading and unloading](

From Figure 10 it is seen that loading line and unloading line are located above and below the balance work line, and the whole change law is opposite. In the simulation model, the compressor outlet pressure is the input of the compressor module, which is connected with the outlet of the heater. When the heating output is increased, the response of the heater outlet pressure is rapid, and the pressure ratio is increased at first, while the response of speed is relative lagged. Compress mass flow is calculated by compressor performance module to use the relation of speed and pressure ratio, on the characteristic figure, the constant speed and pressure ratio increase will inevitably lead to the decrease of the mass flow. Later, the mass flow is increased gradually until smooth due to the constraint relationship between components, so the loading line is above the balance conditions. The analysis of
the unloading process will not repeat them because its change rule is opposite to the loading process.

5. Conclusions
Based on the idea of modular modeling, the super-critical CO\textsubscript{2} plant is divided into turbine module, heater module, the compressor and mechanical loss and rotor module etc, and the dynamic mathematical model of each module are established according to the actual working process of the parts through the reasonable assumptions. Then the characteristics of compressor and turbine are processed and the simulation model of each component of the supercritical CO\textsubscript{2} system was established based on the MATLAB/SIMULINK software platform. At last, the loading and unloading process of the whole device is simulated by simulation model. The results showed that with the increase or decrease of the heating quantities the, the change of rotor speed, turbine exhaust, motor power and the loss of mechanical work are the same as the heating output both in loading and unloading, the overshoot phenomenon is not appeared. The loading line and the unloading line on the compressor characteristic diagram are located at the top and bottom of the balance working line. When the heating output is increased, the pressure ratio is increases firstly, and the response of the outlet pressure for the heater is rapidly, the mass flow is decrease firstly and then increase gradually until smooth, so the loading line is above the balance operation condition. The change of the unloading process is opposite with the loading process. The whole law shows that the match of various components in supercritical CO\textsubscript{2} equipment is reasonable, and the operation is stable.

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