Dynamic simulation of the target moderator cryoplant and cryogenic transfer line at the European Spallation Source

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Abstract. Large scale helium cryoplant is an important sub-system in large science facilities. Dynamic simulation by computer is proved to be an effective method to design and optimize large scale helium cryoplant. This study builds a dynamic simulation model for the Target Moderator Cryoplant and the cryogenic transfer line in European Spallation Source using Dymola and Modelon library. This cryoplant can provide 30.3 kW cooling power at 15 K. The main parts of the system including the screw compressor, turbine, heat exchanger, warm gas buffer and gas management panel are simulated. The model is verified by the acceptance data. Dynamic simulation is carried out to study the cooling down process and transient heat load scenarios. The influence of the cryogenic transfer line to the cryoplant is analysed according to simulation results. This simulation could predict the response of the cryoplant to transient heat load and benefit the steady operation of the cryoplant.

1. Introduction

The European Spallation Source (ESS) is a world-class neutron science facility located in Lund, Sweden which will be the most powerful neutron source upon completion. In ESS, the proton beam is accelerated in a linear accelerator and hits a rotating tungsten target to produce neutrons. These neutrons pass through a supercritical hydrogen moderator operating at 17.5 K and then are spread to instruments. Cryogenics plays an important role in the whole ESS program. There are three large scale helium cryoplants in ESS which are the Accelerator Cryoplant (ACCP), the Target Moderator Cryoplant (TMCP) and the Test and Instrumentation Cryoplant (TICP) [1]. TMCP is designed to provide required cooling power for the hydrogen moderator around the target. It has five different operation mode and it can provide 30.3 kW at 17.5 K under maximum nominal design mode.

The large helium cryoplant like TMCP features of high initial investment, long construction period and high operation cost. The experiments based on these cryoplants usually takes large amount of time, money and manpower. So with the development of computer calculation methods, simulation has become an effective option for the design and optimization of cryoplants. There have been several commercial softwares which support the simulation of the large scale helium cryoplant. A. Kutzschbach et al. uses simulation software Dymola to simulate a simple Brayton cryocycle and study the dynamic characteristics of it [2]. C. Deschildre et al. build a simulation model of a 400 W at 1.8 K helium cryoplant using Aspen Hysys. The influence of the opening of the JT valve is studied by the simulation [3]. B. Bradu et al. use EcosimPro to build a simulation model of the Large Hadron Collider (LHC) beam screen cooling circuits [4]. Dynamic simulations of the HL-LHC cryogenic system during beam...
operation is also carried out by EcosimPro model [5]. J. Li also builds a simulation model using EcosimPro and CRYOLIB library to study the dynamic behavior of a hydrogen liquefaction cycle [6]. X. Xie et al. study the cool down process of a 250 W at 4.5 K cryoplant using a dynamic simulation model [7]. So dynamic simulation could help to study the characteristics of the cryoplant with rather less cost. Reliable results can be provided with a well-verified simulation model.

2. Model description

Figure 1 shows the layout of TMCP, CTL and hydrogen moderators. TMCP is connected to the hydrogen circulation box by the cryodistribution system. One of the most important components of the cryodistribution system is the cryogenic transfer line (CTL) which is also the main body of it. Because of the layout of the whole ESS site, the TMCP cold box is separated away from the target building so a long CTL is required. According to the design, CTL will have a length of 337 m one-way and 674 m in total.

Figure 1. The layout of TMCP, CTL and hydrogen moderators

Because of the long CTL, there exists large volume and cold mass between the cold box and the heat load. This cold mass brings considerable thermal inertia to the system and causes delayed response of TMCP when heat load changes. The delay will disturb the steady operation of the cryoplant and will also lead to difficulty for the automatic control of the system. In order to understand the influence of CTL to the system and estimate the delay and disturbance to the cryoplant, a dynamic simulation model of the system including TMCP and CTL is built. This model can carry out dynamic simulation for transient heat load scenarios. The simulation results will be a reference to help the steady operation of the system in the future.

Figure 2. The layout of TMCP, CTL and hydrogen moderators
2.1. Simulation software

Software for the systematic simulation of the cryoplant includes EcosimPro, Aspen Hysys, Dymola and so on. In this study, commercial simulation software Dymola is used to build the model and simulate. Dymola is a simulation software based on Modelica language. It has visual interface and can simulate zero or one dimensional system with multi-physics [8]. The simulation work by A. Kutzschbach shows that Dymola could model cryoplant and carry out dynamic simulations [2].

Because the cryoplant includes many specific components like screw compressors, turbines and heat exchangers, so in this study, Modelon library for flow fluid machinery is also employed to set up component models [9].

2.2. Modelling procedures

2.2.1. TMCP model. The reliability of the TMCP model depends on the modelling of the key components. For TMCP, these key components are screw compressors, turbines and heat exchangers. Table 1 lists the connectors and main input parameters of these component models.

| Component          | Block icon | Connectors                  | Main input parameters             |
|--------------------|------------|------------------------------|-----------------------------------|
| Compressor         |            | Inflow at LP side           | Rotating speed                    |
|                    |            | Outflow at HP side          | Maximum displacement volume       |
|                    |            | Rotating speed              | Efficiency maps                   |
| Turbine            |            | Inflow at HP side           | Rotating speed                    |
|                    |            | Outflow at LP side          | Maximum volume                    |
|                    |            | Rotating speed              | Mass flow rate map                |
|                    |            |                             | Efficiency maps                   |
| Heat exchanger     |            | Inflow at HP side           | Geometry dimensions               |
|                    |            | Outflow at HP side          | Effective heat transfer area       |
|                    |            | Inflow at LP side           | Friction characteristic            |
|                    |            | Outflow at LP side          | Heat transfer effectiveness map    |

Besides these components mentioned above, control system is inevitable if the system model can carry out dynamic simulation. So PID controller and the valves they controlled are also modelled using the PID block in Dymola. The coefficients of PID controller model are set according to the real controller. On the compressor side, the gas management panel formed by the loading valve, unloading valve, bypass valve, helium buffer and their controller is simulated. Figure 3 shows the TMCP model in which the yellow part is the warm compressor station and gas management panel, the blue part is the cold box and the red part is the heat load.

Figure 3. The TMCP model in Dymola
When modelling TMCP, some ideal assumptions are applied to improve the efficiency of the calculation. The first assumption is neglecting the connecting pipes in the cold box because their volume and cold mass is rather small comparing with CTL. The cold mass of the components is not accurately calculated because it’s also small comparing with CTL. The heat leak to the cold box from the ambient temperature is estimated to be around 1 kW.

2.2.2. CTL model. CTL has an outer pipe as a vacuum jacket (DN150) and an inner pipe (DN80) which is the flow regime of cold helium gas. The length of the whole CTL is 674 m. When building CTL model, there are three main considerations. The first one is the inner process pipe and the helium inside. The second one is the heat leak from the environment to the helium and the third one is the pressure drop through CTL. Figure 4 shows the CTL model.

![The CTL model in Dymola](image)

Discretized pipe model in Modelon library is used to model the process pipe. The model is further customized and modified to include not only the flow regime but also the pipe wall which considers the interaction between the wall and the helium flow.

The heat leak is considered to include radiation through multi-layer insulation (MLI) and conduction through support structures. According to the design of CTL and the calculation of radiation, the heat leak is estimated to be 1.2~2.0 W/m for the whole CTL.

The pressure drop also includes two parts which are friction in straight pipes and pressure drop through elbows. Both two pressure drops are calculated according to the Reynolds number of the helium flow using pressure drop correlations. The bellows installed in CTL is not considered. The model will be modified to include the bellows when the installation of CTL is finished.

2.2.3. Whole picture model. By adding the CTL model to the TMCP model, the whole picture TMCP and CTL system model is shown in Figure 5. The yellow part is the warm compressor station and gas management panel, the blue part is the cold box, the green part is the CTL model and the red part is the heat load. The orange solid line indicates the helium flow path and the green dash line indicates the control signal flow.

![The TMCP and CTL model in Dymola](image)
3. Model verification
TMCP in ESS has been tested and operated for two years. There is plenty of acceptance test data which can be used to verify the model. The simulation of the model is calculated using built-in Esdrik45 solver in Dymola which can solve the non-linear ODE equations more efficiently [10]. The output time step is set to be 0.5 s. Figure 6 shows the temperature gradient of six heat exchangers under maximum nominal design mode. The blue solid line is calculated by the simulation model and the red dash line is from the acceptance test.

![Figure 6. The temperature gradient of heat exchangers](image)

According to the diagram, the simulation results show good agreement with the test data. The reason why the simulation results is slightly higher than the test data is that ideal assumptions are applied when building the model. Besides the heat exchanger performance, the simulated operation parameters of compressors and turbines all fit the acceptance test data. So it is believed that the model can simulate TMCP and can also simulate the TMCP and CTL system.

4. Dynamic simulation results

4.1. Simulation results of the cool down process
Based on the established simulation model, the cool down process of only TMCP and the cool down process of TMCP and CTL system from ambient temperature for the maximum nominal design mode are simulated. Figure 7 shows the simulated temperature at the inlet and outlet if the heat load for these two cool down processes.

![Figure 7. The simulated temperature curve during cool down process](image)
According to the temperature curves, when CTL is connected, TMCP could still cool down to the design temperature and supply 15 K helium flow with 30.3 kW heat load. However, the TMCP and CTL system takes much longer time to cool down to steady state than only TMCP. The large cold mass of CTL slow down the cool down process of the whole system by almost seven times.

Figure 8 shows the high pressure and low pressure variation in the cold box and Figure 9 shows the mass flow rate variation at the inlet and outlet of CTL during cool down process. It can be found that both high pressure and low pressure rises when the compressor starts at the beginning of the cool down. When the rotating speed of the compressor reaches designed value, the pressure gradient can be established, high pressure and low pressure can be stabilized at designed value of 21 bar and 4.9 bar by the controller and the valves in the simulated gas management panel. The mass flow rate of CTL can also reach the designed 1 kg/s according to the simulation. The simulation result of the mass flow rate in CTL is larger than that out of CTL during the cool down process. This is because CTL has a large inner volume. When the CTL cools down, the density of the helium in CTL increases which means the mass of the helium in CTL increases. So during the cool down process, more and more helium is accumulated in CTL. The cool down process of the TMCP and CTL system is more like a liquefaction process.

![Figure 8. The simulated pressure curve during cool down process](image1)

![Figure 9. The simulated mass flow rate curve during cool down process](image2)

When the system cools down to the steady state, the pressure drop through CTL is calculated to be 3.2 kPa and the temperature rise of helium flow through CTL is at 0.1 K level caused by heat leak. This temperature rise is very small because of the large mass flow rate of helium and large heat capacity of cold helium flow.

4.2. Simulation results of the transient heat load scenarios
The heat load for TMCP is closely related to the beam in the accelerator. Considering the long term operation of the accelerator, the influence of transient heat load to TMCP and CTL system should be studied. For example, if the beam suddenly stops, the heat load for TMCP could rapidly drops by an order of magnitude which could cause failure of the cryoplant and target hydrogen cooling circuit. So dynamic simulations of transient heat load scenarios are carried out when the system cools down to steady state. The heat load is firstly reduced from 30.3 kW and to 1 kW and then recovered back to 30.3 kW. Figure 10 and Figure 11 shows the temperature curves of the inlet and outlet of CTL supply line and return line when heat load drops and then recovers.
As shown in Figure 10, when heat load drops, the temperature of CTL return line drops instantly. When that temperature reaches the temperature of CTL supply line, both CTL supply line and return line start to be further cooled down. In order to avoid the temperature of CTL drops too low to cause failure on hydrogen side, a PID controller which controls the opening of the inlet valve of the second stage turbine is added. It can be seen that when CTL is cooled down to the set point of the controller, the controller is activated and decreases the opening of the second stage turbine’s inlet valve. Less helium goes into the second stage turbine so the cooling power is reduced which helps prevent the further cooling down of the system.

Then as shown in Figure 11, when the heat load is recovered back to 30.3 kW, the temperature of CTL rises and the controller increases the opening of the second stage turbine’s inlet valve. So the mass flow rate of helium into the second stage turbine rises back to the designed value of 1kg/s and TMCP and CTL system is able to be recovered back to the normal steady state. It can also be found from the temperature curve that the large cold mass of CTL causes a delay of about 20 minutes for the temperature response at the TMCP cold box side to the dropping heat load.

Figure 12 and Figure 13 show the mass flow rate of the helium goes into the second stage turbine. The function of controller and how it helps to stabilized the system can be seen in Figure 12 and Figure 13.
5. Conclusion
A dynamic simulation model of TMCP and CTL system in ESS is established using Dymola and Modelon library. The model is verified by the acceptance test data. Based on the simulation model, dynamic simulations of cool down process and transient heat load scenarios are carried out. The main conclusions are

1) The simulation results for maximum nominal design mode shows good agreement with the acceptance test data which verifies the correctness of the simulation model.

2) When connected to CTL, TMCP can still cool down to the designed cooling temperature with designed amount of heat load. But the time of the whole cool down process of TMCP and CTL system is nearly six times longer than that of only TMCP because CTL has a large cold mass.

3) The simulated PID controller realize the automatic control for the high pressure, low pressure and mass flow rate during cool down process and transient heat load scenarios. The high pressure and low pressure can be stabilized at 21 bar and 4.9 bar. The mass flow rate in CTL can reach the designed value of 1 kg/s.

4) When the heat load suddenly drops, the whole system will be further cooled down. A PID controller is added to control the opening of the second stage turbine inlet valve to stabilize the TMCP and CTL system at the allowable lowest temperature. The large cold mass of CTL causes a delay of about 20 minutes for the temperature response at the TMCP cold box side to the dropping heat load.

5) When the heat load is recovered, the added PID controller will increase the opening of the second stage turbine inlet valve and the TMCP and CTL system can also be recovered back to the designed steady state condition.

The dynamic model presented in this study can be used to predict the operation of TMCP and CTL system under certain scenarios. The dynamic simulation results by this model will help the tests of TMCP when CTL is completed and tested in the future. The modelling method using Dymola can also be applied for the simulation of other similar cryoplants.

6. References
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