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Dynamic systems modeling of the spallation neutron source cryogenic moderator system to optimize transient control and prepare for power upgrades

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Abstract. Through support of the US Department of Energy's Office of Basic Energy Sciences, Oak Ridge National Laboratory has begun applying machine learning methods to improve accelerator and target performance of the Spallation Neutron Source (SNS). These methods are being applied to the control optimization and power upgrade of the SNS Cryogenic Moderator System (CMS). A numerical model of the CMS has been developed to study these optimizations and system modifications using EcosimPro. This paper compares steady-state and transient numerical results with experimental data. Control optimization studies focused on dampening mass flow, temperature, and pressure fluctuations during sudden losses of accelerator beam power. This analysis was conducted by adjusting five proportional-integral-derivative controllers connected to four flow control valves and one heater. Future efforts include power uprate studies focused on increasing the CMS cooling capacity. The current accelerator power is 1.4 MW; the first target station is being upgraded to 2.0 MW as part of the Proton Power Upgrade effort. The CMS cooling capacity is sufficient for 2.0 MW operation.

1. Introduction

The Oak Ridge National Laboratory (ORNL) operates the Spallation Neutron Source (SNS), the world's highest power pulsed neutron source. The SNS accelerator power will be increased from 1.4 MW to 2.0 MW as part of the Proton Power Upgrade (PPU) project [1]. The accelerator uses negatively charged hydrogen ions that reach 90% of the speed of light. Once accelerated, carbon foils are used to strip out the hydrogen electrons, leaving only protons. The proton beam intensity is increased using an accumulator ring and is directed toward the SNS target building with a frequency of 60 Hz. Neutrons are produced through the spallation of mercury by incident protons. Some neutrons are directed through beam tubes to hydrogen moderator vessels at 20 K. Figure 1 presents an overview of SNS.

The Cryogenic Moderator System (CMS) provides the supercritical hydrogen to cool these neutron moderators. The CMS consists of a helium refrigeration system and three hydrogen circulation systems. The helium refrigeration system provides 7,500 W of refrigeration capacity, has a high pressure side at 300 K and 17.4 bara [240 psig], and has a low pressure side at 20 K and 3.75 bara [40 psig] [2]. The hydrogen circulation system consists of three hydrogen loops, one for each moderator. Each system contains a helium/hydrogen heat exchanger which cools the supercritical hydrogen gas to about 20 K at 13.80 bara [186 psig]. Each loop contains a circulator pump, accumulator, and neutron moderator. With the SNS beam currently operating at 1.55 MW, the heat load to moderator loop #1 is approximately 2,200 W, and the heat loads to the two smaller moderator loops are approximately 1,100 W each.

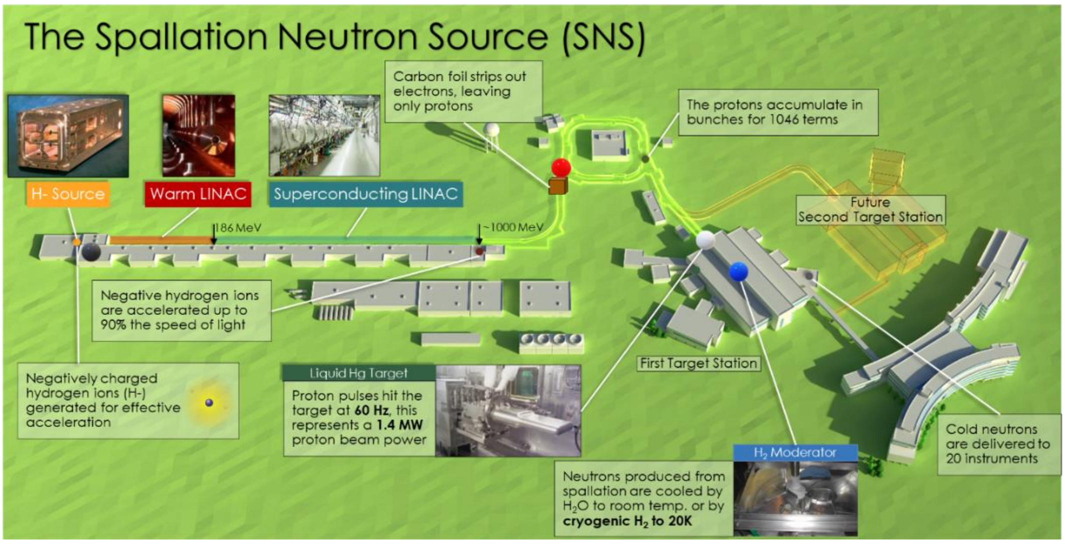

Figure 1. SNS overview including accelerator, target building, and cryogenic moderators.

The PPU project will increase heat loads by approximately 40%. The CMS was largely designed using steady-state calculations for nominal operation. New numerical models were developed to predict the steady and transient behavior of the CMS at the increased heat load. These models are the focus of this paper. The models will also assist with optimizing the control system during beam trips. These trips significantly perturb the CMS, and their effect is expected to increase at higher beam powers.

2. Numerical approach

Dynamic cryogenic system modeling has been performed for many cryogenic systems, such as the CMS at the European Spallation Source [3], at CERN [4], at ITER [5], at J-PARC [6,] and at the Chinese Spallation Source [7]. All these organizations have pursued predictive capabilities for dynamic systemic response of cryogenic facilities. This type of predictive capability is also needed at the SNS CMS. A literature review of these state-of-the-art research facilities and previous ORNL cryogenic system modeling efforts [8,9] was conducted to determine if in-house or commercially available software would be the most suitable to quantify the SNS CMS steady and dynamic responses during beam transients. Based on that review, a simulation tool called EcosimPro, developed by Empresarios Agrupados [10], was selected. The software provides a graphical user interface and non-causal object-oriented modeling language to model continuous and discrete processes. The primary benefits were the validated cryogenic component models within the CRYOLIB library, the virtual programable logic controller (PLC) library, and the integrated numerical implementation of thermophysical properties from REFPROP and HEPAK [11].

2.1. Computational domain

Figure 2 presents the full model of the CMS within EcosimPro. The full model contains the helium compressor station [300 K], the helium coldbox [20 K], a helium-to-hydrogen heat exchanger module [20 K], a hydrogen pump module [20 K], and neutron moderator vessels [20 K]. Piping components were specified with the diameter, wall thickness, bend radius, length, elevation change, and surface roughness. This information was gathered using engineering drawings, system walkdowns to verify as-built dimensioning and routing, and ultrasonic wall thickness measurements.

All components in this domain were defined using design specifications and as-built configurations. Because this model building approach was not data driven, attempts were made to minimize biases by ignoring typical sensor readings, much like the approach used in a blind benchmark study.

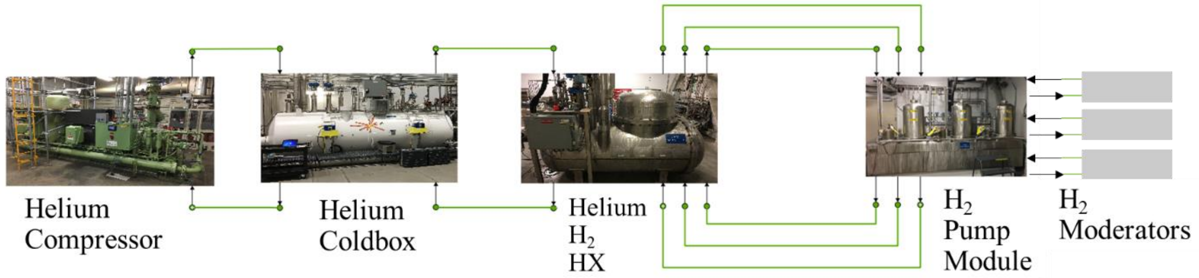

Figure 2. Computation domain of the full SNS Cryogenic Moderator System.

2.2. *Warm helium compressor station [300 K]*

Figure 3 presents the warm helium compressor station. An ideal compressor was selected to approximate the screw compressor installed in the CMS. This idealized component outputs a constant temperature and volumetric flow rate. The mass flow rate of the compressor is thus a function of the inlet pressure and density of the helium gas. It is therefore important to control the compressor inlet and outlet pressures. The outlet pressure is regulated by two valves connected to either a source or sink boundary. Two PIDs for these valves use a split range control. A third PID regulates the inlet pressure to a desired setpoint value; a bypass valve is included to recirculate the compressor outlet flow back into the inlet.

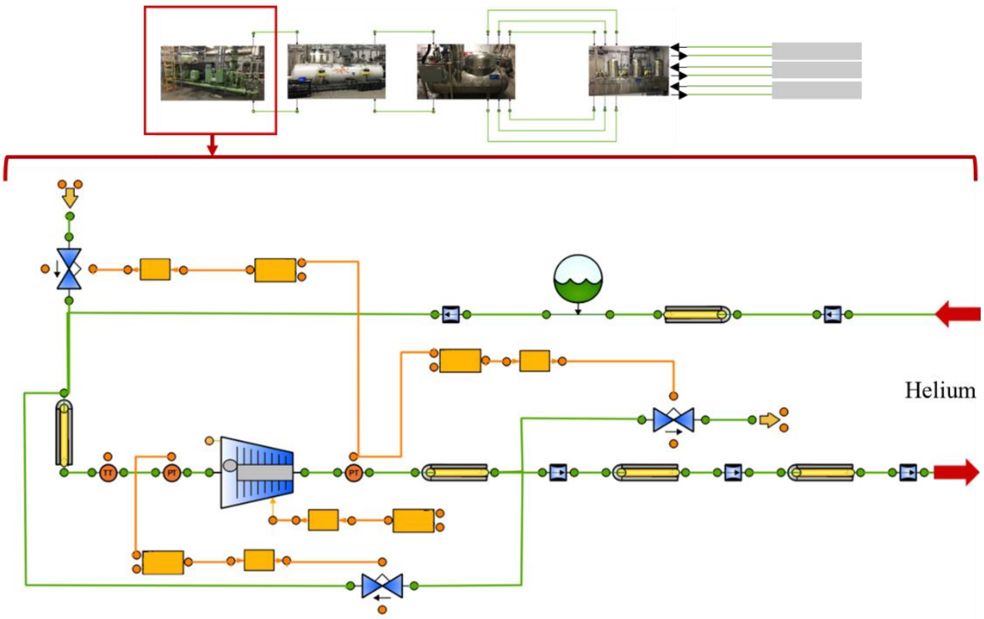

Figure 3. Computation domain of the warm helium compressor station [300 K].

2.3. *Helium coldbox [20 K]*

Figure 4 shows the schematic representing the helium coldbox. The components of this subsystem are the helium-to-helium regenerative heat exchanger, the turbine, the bypass valve, and the electrical heater. Design specifications were obtained from component vendors and used to populate the associated CRYOLIB library components.

The regenerative heat exchanger's high-pressure side has inlet and outlet temperatures of 300 K and 28 K, respectively. For the low-pressure side, the inlet fluid temperature is 22 K, and it exits at 295 K.

This component was highly instrumented with upstream and downstream temperature and pressure sensors on both high- and low-pressure sides. This type of sensor resolution and positioning would be useful to include on each physical component to aid future system modeling efforts.

The turbine removes energy from the system by rotating at approximately 67,000 rpm and removes energy from the system via work performed by the helium flow on the turbine blades. The turbine speed is not controlled with an inlet throttle valve. Instead, the rotation speed is a function of the pressure drop across the component. The temperature typically decreases from 28 to 20 K across the turbine.

A bypass valve downstream from the turbine provides a flow path that bypasses the helium-to-hydrogen heat exchangers. This bypass flow remains colder than the fluid returning from the heat exchangers. The bypass valve position is actively controlled with a PID to achieve a constant pressure difference between the turbine outlet and heater outlet of 0.275 bar [4 psi].

The electrical heater has an 8,000 W capacity. It functions as a variable energy source to balance heat removal of the constant speed helium refrigeration loop when the SNS linear accelerator is ramping power, shut down, or inadvertently tripped. The heater power is actively controlled with a PID to achieve a constant helium-to-helium regenerative heat exchanger low-pressure inlet temperature of 22 K.

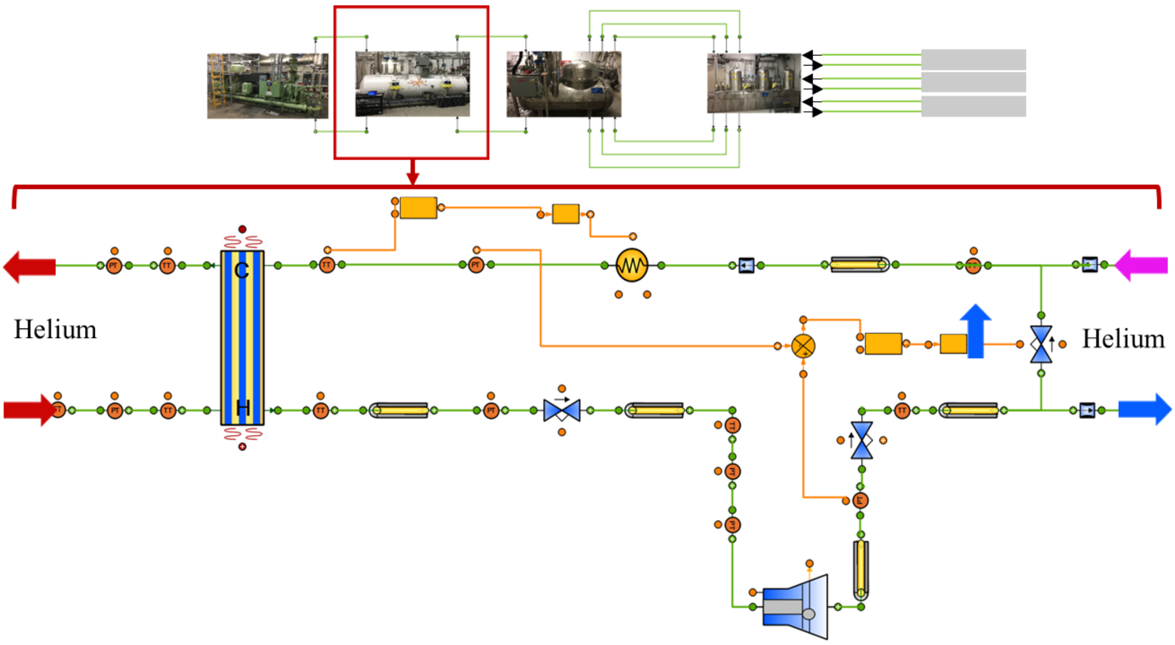

Figure 4. Computation domain of the helium coldbox [20 K]

2.4. *Helium-to-hydrogen heat exchanger module [20 K]*

This subsystem is presented in Figure 5. The helium enters the heat exchanger module and a piping manifold splits the cold helium flow from a single mass stream into three mass streams for each helium-to-hydrogen heat exchanger. Each heat exchanger's cold side inlet has a flow control valve to vary the pressure drop and subsequent mass flow rate through each heat exchanger. The flow control valve positions are actively controlled by PIDs that monitor each associated hydrogen loop pressure at the inlet of the hydrogen circulators in the pump module. Isolation valves are also located at each heat exchanger cold side outlet. These are maintained at a constant fully open position during normal operation.

2.5. *Hydrogen pump module and moderator vessels [20 K]*

The pump module contains three hydrogen loops. Each loop is a constant mass system that experiences transient heat loads. Circulators provide forced flow between moderator vessels (heat sources) and the helium-to-hydrogen heat exchangers (heat sinks). Each accumulator dampens the loop from pressure spikes related to sudden beam ramps and trips. These have compressible helium-backed metal bellows that translate to balance pressure. Figure 6 presents the schematic for this subsystem.

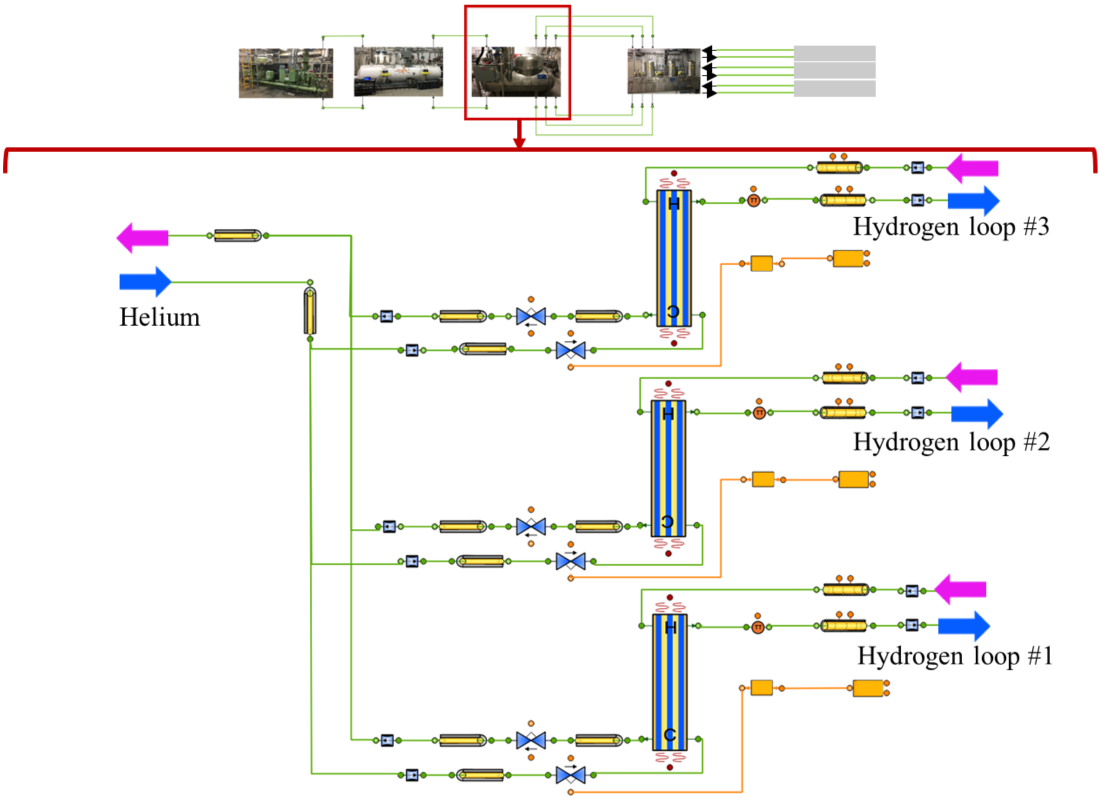

Figure 5. Computation domain of the helium-to-hydrogen heat exchanger module [20 K].

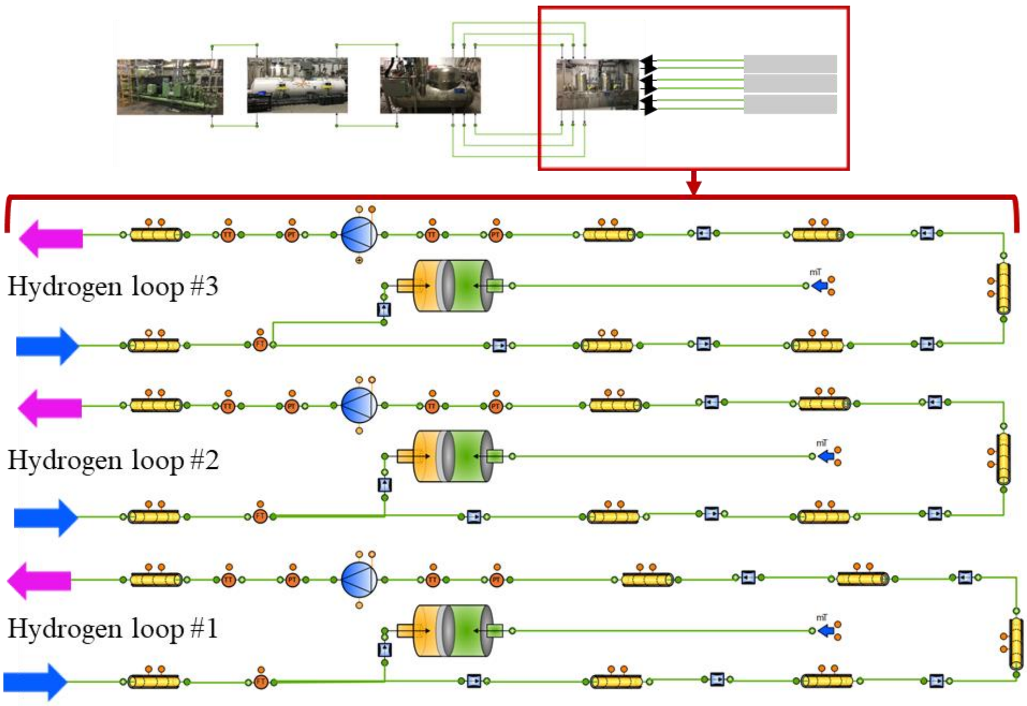

Figure 6. Computation domain of the hydrogen pump module and moderator vessels [20 K].

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2.6. Converting beam power to neutron energy deposition in the moderator vessels

To specify a heat load boundary condition on the moderators, the beam power was converted to a neutron energy deposition rate using Monte Carlo N-Particle simulations. A linearly proportional scaling was applied to derive deposition rates at off-nominal powers relative to the steady 2 MW rates.

2.7. Expanding the CRYOLIB library with accumulator development

The pressure dampening accumulators were developed in collaboration with the software developer. Three versions were developed and are presented in Figure 7. The first maintained a constant system pressure but had no compressive feedback related to bellows motion. The second and third included compressibility and heat transfer between the two fluids. The third included a spring constant to tune the bellows response. J-PARC has a similar pressure dampening accumulator and used a Newton-Raphson method to conserve mass and balance pressures in their implementation [12].

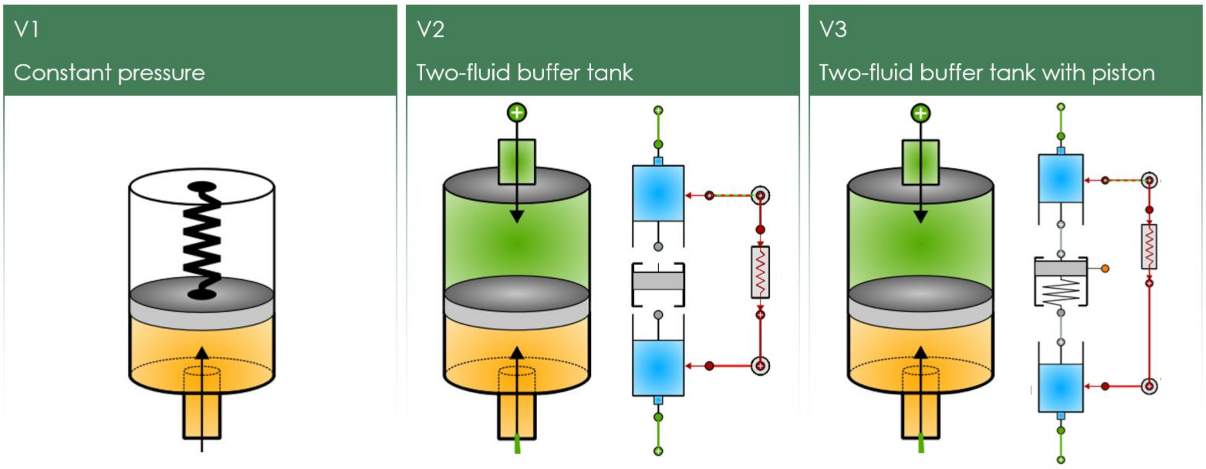

Figure 7. Development of the helium bellows-backed pressure dampening accumulator component.

2.8. Expanding the PLC library with Allen-Bradley Logix5000™ Enhanced PID controller logic

The default PID controllers apply the proportional, integral, and derivative gain terms on the error between the process value and setpoint. The CMS architecture uses Allen-Bradley Logix5000™, which includes enhanced PID (PIDE) controller logic. The PIDE algorithm uses a velocity form where the gain terms are applied to the change in the error over time, not the error itself.

3. Results and discussion

The CMS reaction to a beam trip can be observed in Figure 8 where the beam power steps from 1.2 MW to 0.0 MW **(a)**. This decrease in heat source can be witnessed by a decrease in the hydrogen pressure **(e)**. Controllers monitoring pressure command flow control valves on the helium side of the helium-to-hydrogen heat exchanger to close **(f)**. The valve closings increase the pressure drop across the helium loop **(b, c)**. The control action for a high-pressure drop is to open the bypass valve **(d)**. Simultaneously with other PVs, the helium temperature decreases as a result of the decrease in the heat source **(g)**. Heater power is raised to return the helium temperature to its desired setpoint value **(h)**.

3.1. Comparison of steady-state numerical result with ensemble-averaged experimental data

Before investigating the dynamic behavior of the numerical model, a steady-state comparison was made with ensemble-averaged data at 1.4 MW obtained during a period of statistically steady operation. In this comparison, the virtual PID controllers and moderator energy depositions were fixed to the averaged experimental data. Table 1 provides the relative difference (RD) between virtual and physical sensors.

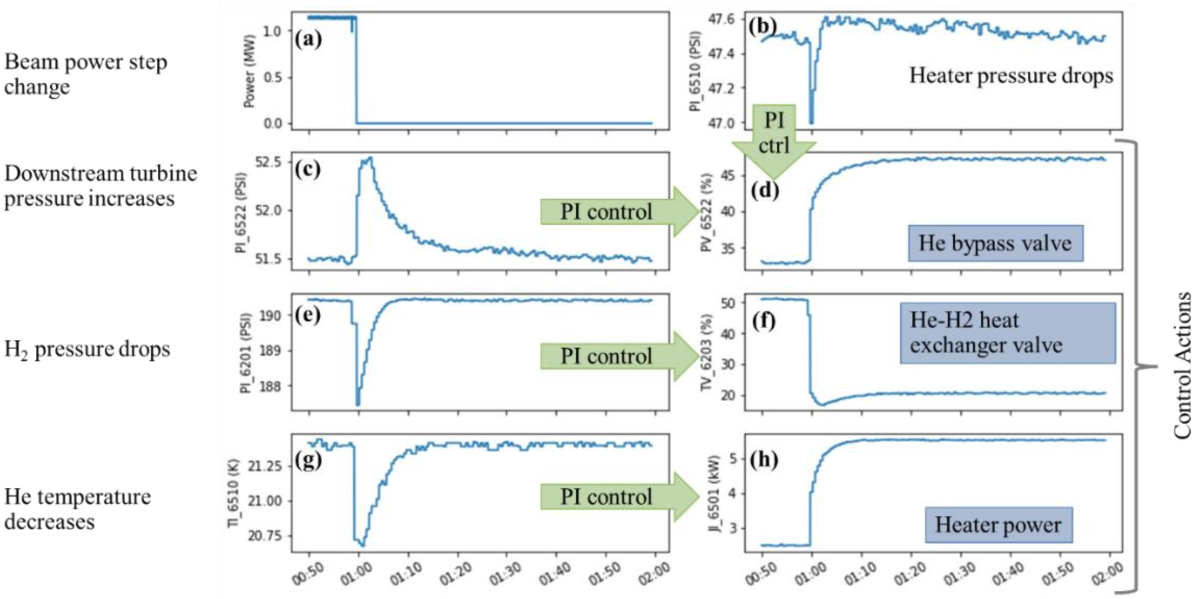

Figure 8. The reaction to a beam trip, change of PVs, and actions of heater and valve controllers.

Table 1. Relative difference between data and numerical results for steady comparison at 1.4 MW.

SUBSYSTEM	ID TAG	EXPERIMENT	SIMULATION	RD [%]
Helium compressor	PI_6401	3.74	3.73	0.2
	TI_6402	298.9	298.3	0.2
Helium coldbox	TI_6519	25.2	25.1	0.3
	PI_6522	4.29	4.40	-2.8
	SI_6501	1164	1175	-0.9
	TI_6522	17.7	17.3	2.7
Helium-hydrogen HX	TI_6103	18.9	17.6	6.6
	TI_6203	20.9	19.7	5.7
	TI_6303	18.8	18.6	0.8
Hydrogen pump module	FI_6101	0.075	0.075	0.3
Moderator loop #1 only	TI_6101	20.9	20.8	0.4

3.2. Comparison of transient numerical results with experimental data

Figure 9 presents comparisons of data with behavior predicted by the numerical model. These results were produced using the EcosimPro PLC library PID algorithm and not the Allen-Bradley enhanced PIDE. The root mean standard error (RMSE) between the data and numerical results was calculated. Temperature RMSEs were within 1 K and 2 K for the helium and hydrogen loops, respectively. Pressure RMSEs were less than 0.1 bar. Components with the largest RMSE were the flow control valves. The numerical valves move with a temporal delay. This is most likely due to the PID algorithms difference.

4. Conclusions

To study control optimization and quantify system capacity for the PPU project, a model of the CMS was developed using EcosimPro. The model consists of four main subsystems: the warm compressor station, the helium coldbox, the helium-to-hydrogen heat exchanger module, and the hydrogen pump module. Comparisons of both steady and transient scenarios have been made.

Future work includes completing the implementation of the Allen-Bradley Logix5000™ PIDE control algorithm and recalculating RMSE values to observe whether the temporal response can be achieved. Finally, the model will be interfaced with PyTorch and TensorFlow to optimize controller parameters that yield minimal system perturbation during accelerator beam ramps and trips.

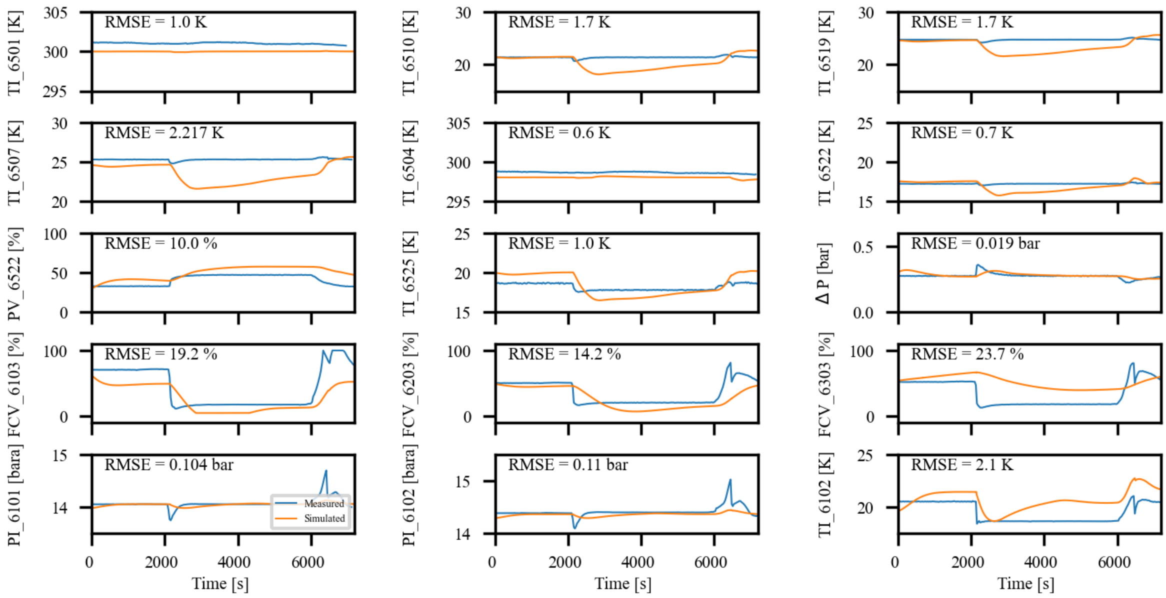

Figure 9. Comparison of experimental data with transient behavior predicted by the CMS numerical model using the EcosimPro PLC library PID algorithm instead of the Allen-Bradley enhanced PIDE.

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