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"Dynamic modeling and analysis of a closed-loop steam compressor test rig for industrial heat pump applications"

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Abstract

Heat pumps are expected to play a primary role in electrification of thermal users in the residential and industrial sectors. Dynamic compressors are widely used in large size heat pumps, thanks to their industrial replicability, compact size, affordable costs, and good performance in terms of efficiency. The instability, which may occur in a compressor installed in closed loop cycle such as in a heat pump, is quite different from the classic open loop configuration involving dynamic compressors. Therefore compressors should be tested before getting into operation to make sure that its thermodynamic behaviour is stable. This study investigates the dynamic behavior of a steam compressor integrated into an innovative closed-loop test rig. A dynamic model of the system, developed, represents the coupled interaction among a steam generator, expansion valve, compressor, back-pressure valve, and water bath cooler. A proportional integral controller regulates the vapor fraction within the cooler by modulating an environmental bypass valve to ensure stable operation during transients. The model is used to analyze the startup process, stability under varying compressor speeds, and controller response to disturbances. The results show that the system starts smoothly, reaches steady operation without oscillations, and maintains stability following rapid compressor speed variations. The compressor operating points remained within the valid map range, confirming accurate representation of its performance. The developed model provides a validated and flexible framework for the future design and experimental testing of steam compressors and advanced high-temperature heat pump systems. Future steps will encompass building a laboratory scale test rig to validate the model and to be a standard test rig for testing compressors in the future.

Keywords: Steam; Compressor test rig; Closed-loop steam cycle; System stability; Industrial decarbonization

1. Introduction

Industrial steam remains a cornerstone of many process industries such as food processing, chemical manufacturing, and pulp and paper production where it is used for heating, cooking, and drying. However, steam is still predominantly produced by fossil-fueled boilers, making it a major contributor to industrial CO_2 emissions. To decarbonize these processes, steam-generating heat pumps (SGHPs) have emerged as a promising alternative, capable of upgrading low-grade waste heat into valuable process steam while significantly reducing primary energy use and emissions. Recent reviews and techno-economic assessments highlight SGHPs as one of the most promising technologies for medium- to high-temperature heat recovery, delivering steam at temperatures above 150 °C with high efficiency [1-3].

Closed-loop vapor compression systems using steam as the working fluid attached growing attention due to their potential for efficient heat recovery and reduced operational costs in high-temperature applications. In such systems, the steam discharged from the compressor is not released to the environment but instead cooled, expanded and recirculated, forming a self-contained thermodynamic cycle. Several studies have investigated the behavior and design challenges of steam compressors in closed or semi-closed cycles, emphasizing the large specific volume, high discharge temperatures, and condensation control requirements unique to water vapor compression. Recent reviews by Hu et al. and Lachner et al. highlight the thermophysical constraints of

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water vapor as working fluid, particularly in relation to compressor efficiency and achievable pressure ratios [4-5]. Advanced system studies, such as those by El Samad et al. and Meroni et al., have explored high-temperature steam compression and centrifugal compressor design for closed steam heat pumps, demonstrating the feasibility of maintaining stable operation through controlled condensation and intercooling [6-7]. Moreover, Klute et al. and D'Alessandro et al. reviewed steam-generating heat pump architecture that inherently rely on closed vapor compression loops for steam recirculation and temperature lift [1],[8]. Collectively, these works establish that closed-loop steam compression not only enables experimental flexibility and energy savings

At the core of SGHP systems lies the steam compressor, which largely determines the thermodynamic performance, reliability, and stability of the overall cycle. Several compressor configurations such as reciprocating, rotary, screw, and centrifugal types have been explored for steam compression in both open and closed-loop architectures. Prototype development and field demonstrations have confirmed their technical feasibility and industrial potential. However, most existing studies have concentrated on steady-state performance and machine design, while transient behavior including startup, load variations, and stability during closed-loop operation has received limited attention. This lack of dynamic analysis is critical, as transient phenomena govern the safe operation and control response of compressors integrated into industrial heat pump systems [9-10].

Accurate dynamic modeling is essential to predict such transient interactions and to design robust test rigs and control systems. Dynamic compressors installed in closed loops can experience complex interactions between fluid accumulation, thermal inertia, and control feedback, potentially leading to oscillations or instability if not well understood. Object-oriented modeling tools such as Modelica/Dymola have proven highly effective for transient simulations of vapor compression and heat pump systems, as they enable the coupling of thermodynamic, mechanical, and control domains within a single framework. Despite these capabilities, few studies have presented reusable, physics-based transient models dedicated to steam compressors operating in closed-loop configurations, as typically found in SGHP applications [11-13].

To address this gap, the present study develops a comprehensive dynamic model of a closed-cycle steam compressor test rig using Modelica in the Dymola environment. The system integrates a steam generator, expansion valve, compressor, back-pressure valve, and water bath cooler to reproduce a realistic closed-loop compression process. During startup, the steam generator provides the initial vapor supply, but once steady-state operation is established, the system recirculates and condenses the steam internally, eliminating the need for continuous steam generation. This configuration minimizes steam consumption while allowing controlled investigation of compressor performance and stability [5],[14].

The contributions of this work are twofold. First, it establishes a flexible, modular simulation framework that can be adapted for different compressor types and operating conditions, supporting both virtual testing and future experimental implementation. Second, it applies this model to representative transient scenarios including startup, load steps, and speed variations to analyze how compressor dynamics interact with auxiliary components and control systems in a closed-loop environment. Through this analysis, the study identifies the mechanisms governing system stability, control response, and compressor operating range.

The novelty of this work lies in developing a generic, transient test-rig model for steam compressors operating within a closed-loop configuration, which has not yet been addressed in the literature. By capturing the coupled thermo-fluid and control dynamics of such systems, this research bridges the gap between steady-state compressor studies and dynamic experimental design. The insights gained provide a foundation for the design of a future pilot-scale test facility, contributing to the advancement of high-temperature steam compression systems and supporting the broader transition toward industrial electrification and decarbonization.

2. Methodolgy

2.1. Modeling environment and libraries

The dynamic modeling of the compressor test rig was performed using the Modelica language within the Dymola simulation environment (Dassault Systèmes). Modelica is an object-oriented, equation-based modeling language developed for the simulation of complex multi-domain physical systems. Its acausal formulation allows direct representation of physical laws such as the conservation of mass, momentum, and energy, providing a modular and reusable modeling framework. The Dymola platform offers efficient numerical solvers, symbolic manipulation, and a graphical interface, making it particularly suited for dynamic thermodynamic simulations.

To represent the thermodynamic behavior of the system, several open-source Modelica libraries were integrated. The Modelica Standard Library (MSL) was used for generic components such as sensors, connectors, and boundary conditions, while the Buildings Library extended the thermal modeling capabilities and supported the coupling between thermal and fluid subsystems [15]. The ThermoPower Library was employed to model turbomachinery and power-cycle components, including the compressor, and heat exchangers [16]. This library enables detailed representation of flow dynamics and performance maps based on real machine data, making it ideal for dynamic compressor modeling within energy systems.

2.2. Dynamic compressor test rig model

The developed model represents an innovative closed-loop compressor test rig designed to evaluate compressor performance and stability under realistic dynamic conditions. The test rig serves as a virtual prototype for a future experimental facility, providing a foundation for optimizing design parameters and control strategies prior to construction.

As illustrated in Figure 1, the test rig consists of a steam generator, an expansion valve, a compressor, and a water bath cooler, connected in a closed-loop configuration. The steam generator initiates the cycle by producing high-pressure steam, which is throttled by the expansion valve to the desired compressor inlet pressure. The compressor then raises the vapor pressure and temperature before the flow enters the water bath cooler, where it is partially condensed by direct contact with cooling water. The cooler features one water inlet and an outlet vapor stream that is recirculated to the compressor inlet

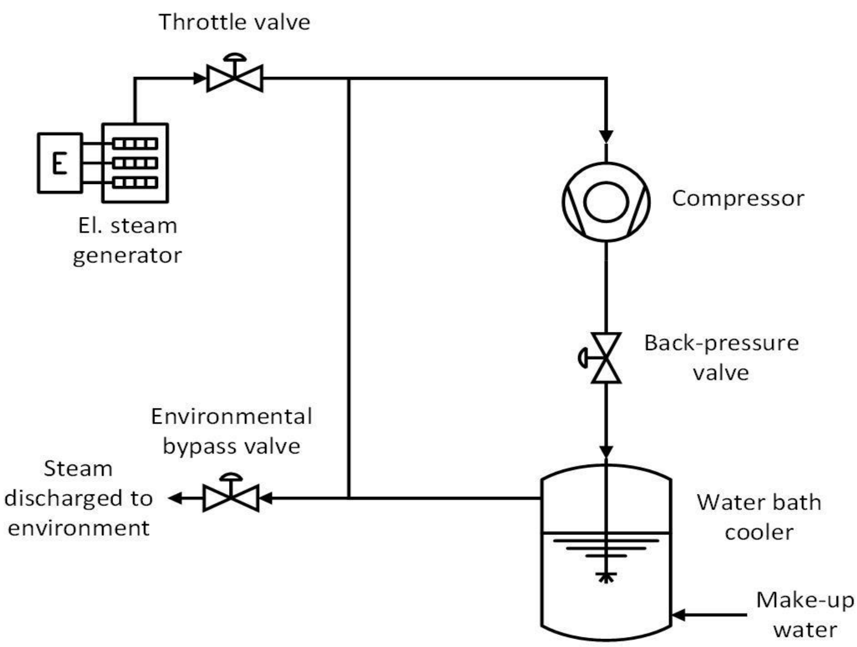

Figure 1. Layout of the closed-loop compressor test rig.

The closed-loop configuration reduces the continuous load on the steam generator by reusing vapor already circulating within the system. To prevent over-pressurization and maintain stable operation, an environmental bypass line releases excess vapor when pressure or vapor fraction exceeds the set limits. A proportional integral (PI) controller regulates the vapor fraction within the cooler by adjusting the bypass valve opening. When excess vapor is detected, the controller increases the bypass flow to discharge steam, and the removed vapor is compensated by makeup water. This feedback mechanism maintains the liquid vapor balance and ensures stable operation during both transient and steady conditions.

Instrumentation is integrated throughout the model to monitor key process variables, including pressure, temperature, and mass flow rate. These signals are used to evaluate the system's dynamic behavior, particularly during startup, control actions, and transient disturbances. The model thereby captures the interaction between thermodynamic processes, component dynamics, and control responses under realistic conditions.

2.3. Compressor modeling

The compressor model was developed using the ThermoPower library's turbocompressor component, which represents a quasi-steady, lumped-volume model. The outlet thermodynamic state is determined from the inlet pressure, temperature, and mass flow rate, based on tabulated pressure ratio (PR) and isentropic efficiency (η_{isen}) maps. The model defined the compressor performance through three key non-dimensional parameters shown in Eq. (1), Eq. (2), and Eq. (3): the flow coefficient (φ), pressure ratio (PR), and isentropic efficiency (η_{isen}). These parameters are expressed as function of the corrected rotational speed (N_T) and a dimensionless interpolation paramater (β), allowing smooth transitions between speed lines and stable interpolation across the full operating range. The compressor behavior is defined by the following relationships:

$$PR = f(N_T, \beta) \quad (1)$$

$$\varphi = g(N_T, \beta) \quad (2)$$

$$\eta_{isen} = \frac{h_{isen} - h_{suc}}{h_{dis} - h_{suc}} \quad (3)$$

where $PR = {p_{out}}/{p_{in}}$, φ is the flow number, N_T is the normalized shaft speed, β is an interpolation parameter, $h_{suc}, h_{dis}, h_{isen}$ are the inlet, actual discharge, and isentropic discharge specific enthalpies, respectively.

The performance maps were derived from CFD simultions of the same compressor geometry conducted by Kajasa et al. [17]. These maps were provided in dimensionless form based on turbomachinery similarity relations and included speed lines ranging from 70,000 to 105,000~rpm. The data were implemnted in Dymola using two-dimensional lookup tables, allowing real-time interpolation of performance values as a function of the instantaneous corrected mass flow rate and rotational speed.

The model calculates the instantaneous outlet pressure, mass flow rate, and efficiency by interpolating the map data and applying the thermodynamic relationships defined above. This enables accurate coupling with the other components of the closed-loop system allowing realistic transient simulations of the steam compression test rig. The implemented model was subsequently matched the original CFD-derived maps to verify its accuracy and ensure consistency of the interpolation approach.

2.4. Compressor model consistency and robustness

To ensure that the implemented compressor model accurately reproduces the behavior of the CFD-derived maps, a matching exercise was performed. The compressor maps generated from CFD simulation were compared directly with the corresponding Dymola implementation. Figure 2 and Figure 3 compare the compressor performance characteristics obtained from CFD simulations (dashed lines) as the reference and Dymola dynamic simulations (solid markers) for rotational speeds between 70,000 and 105,000 rpm, providing validation of the compressor model used in the closed-loop test rig.

Figure 2 shows the pressure ratio variation with mass flow rate, where both datasets exhibit the expected compressor behavior with pressure ratio increasing toward surge and decreasing toward choke. The Dymola results follow the CFD reference closely, confirming that the implemented map interpolation and scaling were correctly realized within Modelica environment. Minor deviations near low mass flow conditions are attributed to transient stabilization during dynamic operation.

Figure 3 presents the isentropic efficiency characteristics. The Dymola model successfully reproduces both the magnitude and position of the efficiency peaks, maintaining the typical parabolic trend observed in the CFD results. The strong correlation in both pressure ratio and efficiency distributions indicates that the compressor model is robust and faithfully represents the underlying CFD-derived data.

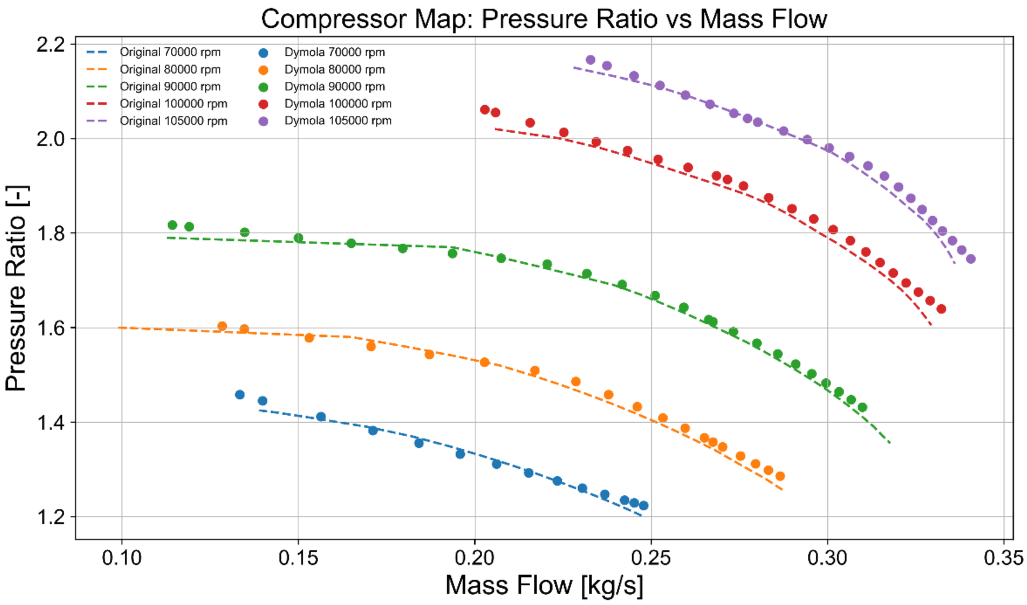

Figure 2. Compressor pressure ratio map: comparison between original and simulated data

This consistency assessment provides confidence in the compressor's predictive capability within the close-loop dynamic model. Consequently, the subsequent stability and transient analyses of the steam compression test rig are basedon a physically consistent compressor representation. It also confirms that the implemented compressor model can be confidently used to analyze rig transients, surge avoidance, and control performance under realistic operating conditions.

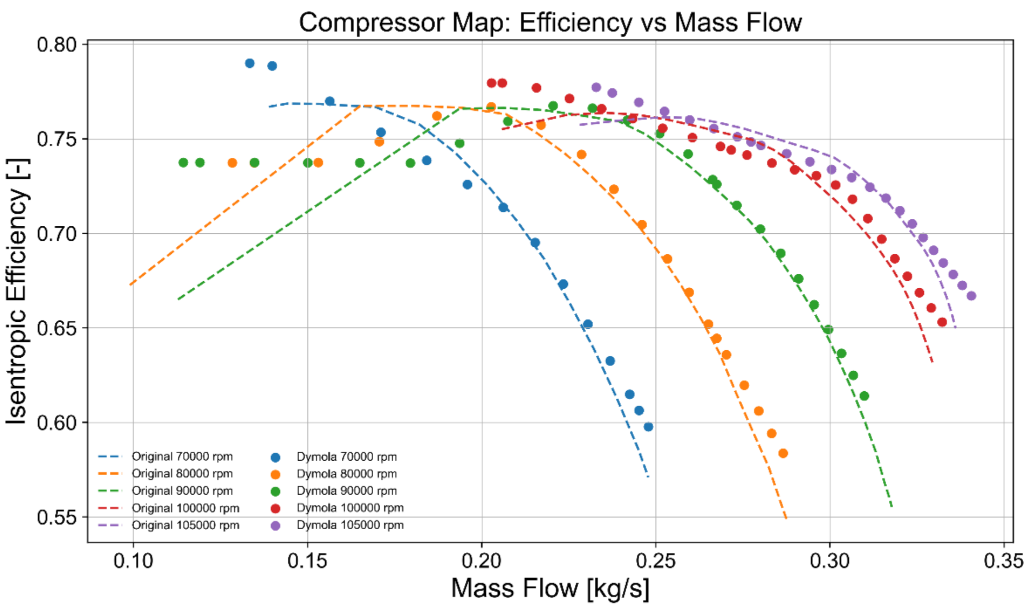

Figure 3. Compressor isentropic efficiency map: comparison between original and simulated data

2.5. Simulation objectives and analysis approach

The simulation campaign aimed to investigate the dynamic behavior, stability, and control performance of the compressor test rig. Key objectives included evaluating the startup behavior assessing how the system transitions from rest to stable operation through time-dependent monitoring of compressor outlet temperature, pressure ratio, and mass flow rate. Recirculation dynamics, analyzing the reversal and stabilization of steam flow in the recirculation loop to confirm autonomous operation without continuous steam generator input. Control performance and stability, verifying the PI controller's ability to maintain the target vapor fraction and pressure during transient compressor speed variations. Compressor map validation, ensuring that all operating points remained within the compressor's performance envelope and matched the original manufacturer data.

The dynamic simulation captured the full startup and stabilization of the compressor test rig. Figure 4 illustrates the prescribed rotational speed profile applied to the compressor during the dynamic simulation. The speed variation serves as a boundary condition to assess the model's transient response to changes in operating conditions. The simulation begins with the compressor operating at low speed increases linearly up to 90,000 rpm within the first 1000 s. After reaching this operating speed, the system maintains a steady-state period to evaluate the stability of mass and energy balances under constant-speed operation. A step decrease to 80,000 rpm is then introduced to emulate a load reduction event, followed by a recovery phase where the speed ramps up to 100,000 rpm and remains constant until the end of the simulation.

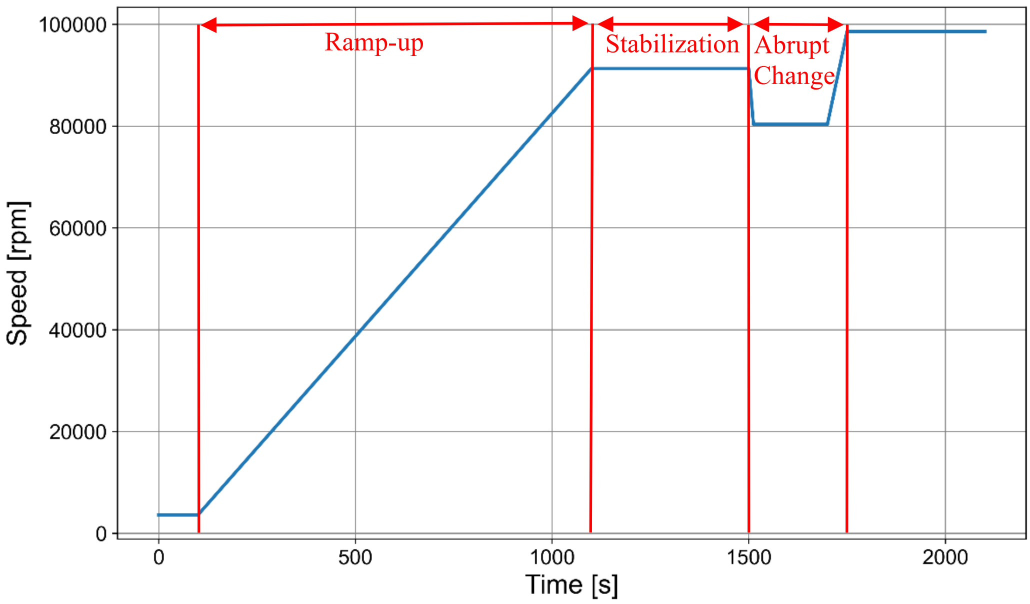

Figure 4. Compressor speed variation in rpm

This speed profile was chosen to represent a realistic operating sequence typically encountered in experimental compressor tests, including start-up, steady operation, and transient load variation.

By combining detailed thermodynamic modeling with realistic control implementation, the simulation results enable comprehensive assessment of the system's transient behavior and confirm its potential for stable operation under varying conditions.

The following section presents and discusses the results of the dynamic simulations, including the startup sequence, control response, and overall system stability. The analysis focuses on how the compressor and auxiliary components interact during transient operation, dem onstrating the model's capability to predict the physical behavior of the closed-loop compressor test rig with high fidelity.

3. Results

3.1. Start-up and dynmamic behavior

The dynamic simulation captured the full startup and stabilization of the compressor test rig. The system was initiated at low compressor speed, which was gradually increased over the first 1000 seconds as shown in Figure 4. During the initial phase, the compressor acted as a turbine, circulating vapor without producing a significant pressure rise. Effective compression began at approximately 500 seconds, corresponding to a speed of around 42,000 rpm. This transition is evident in the sharp increase in compressor outlet temperature and pressure ratio as visually presented in Figure 5 and Figure 6.

As the compressor speed ramped up, the outlet temperature increased from approximately 60°C to 180°C, while the pressure ratio rose from unity to about 1.9. The compressor pressure ratio exhibits an initial transient decrease during startup effects, this short transient where outlet pressures are still stabilizing. It is then followed

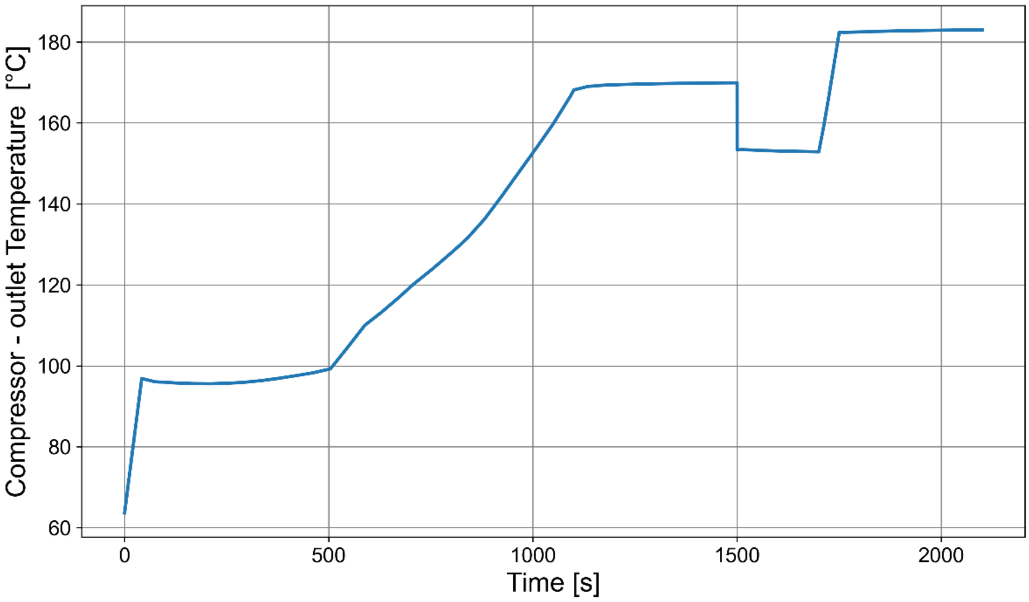

Figure 5. Compressor outlet temperature

by a gradual rise as the system accelerates and load increases. After reaching a quasi-steady state, a short disturbance causes a temporary drop in pressure ratio before the compressor stabilizes at a higher final operating point (PR ≈ 1.9). This dynamic evolution reflects the system's response to sequential speed or load adjustments during the test sequence. Simultaneously, Figure 7 showed that the mass flow rate exhibited a rapid rise followed by stabilization, indicating the establishment of steady flow conditions through the compressor. The startup process was smooth, with no signs of oscillatory or unstable behavior.

During startup, the steam generator supplied vapor to initiate the process. As the closed-loop recirculation developed, the generator contribution decreased gradually and was eventually reduced to zero once sufficient vapor was established within the loop. This confirms that the recirculation strategy allows self-sustaining operation after the initial warm-up phase.

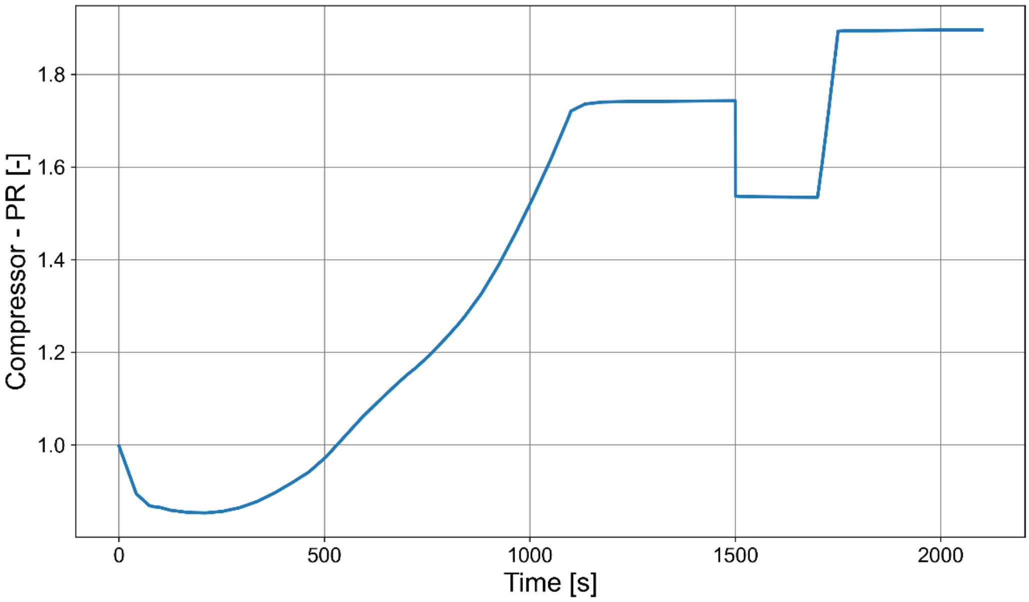

Figure 6. Compressor pressure ratio

3.2. System stability and controller performance

At 90,000 rpm, the system reached steady operation. To test stability and control response, intentional disturbances were introduced by varying the compressor speed first reducing it to 80,000 rpm and then rapidly increasing it to about 100,000 rpm after approximately 1500 seconds. The system returned to stable conditions within roughly 300 seconds following each change.

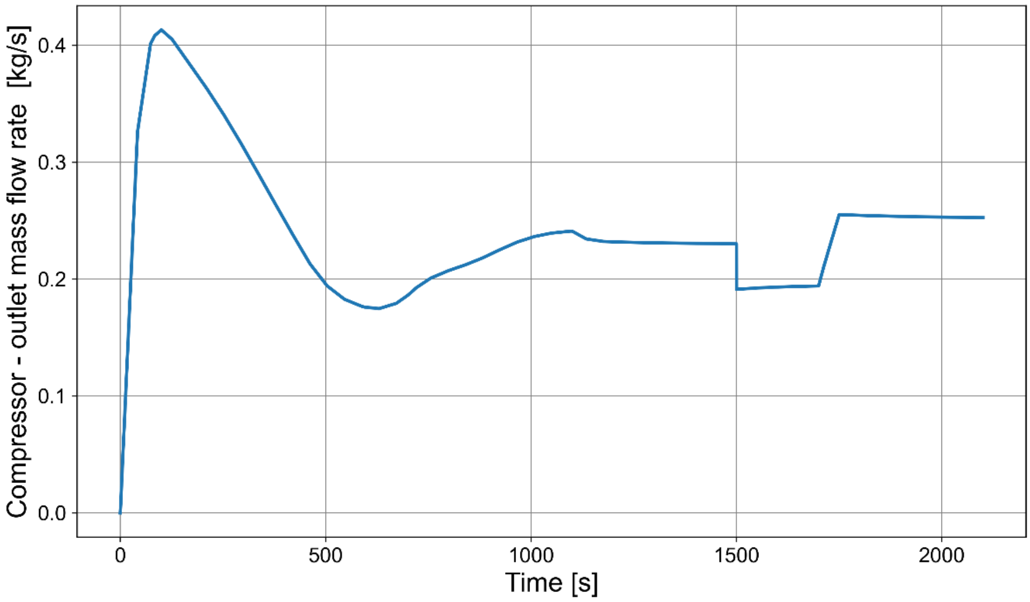

Figure 7. Compressor outlet mass flow rate

The compressor outlet temperature and pressure ratio responded proportionally to the imposed speed variations and recovered smoothly (Figure 5 and Figure 6). The PI controller maintained pressure and vapor fraction in the water bath cooler within limits by modulating the environmental bypass valve. This ensured that any excess vapor was discharged and replaced by feed water, keeping the mass and energy balance consistent. No overshoot or oscillation was observed, demonstrating the robustness of the control strategy.

The transient behavior of the water bath cooler provides critical insight into how the system stabilizes thermally and hydraulically during startup and subsequent operation. As shown in Figure 8, the vapor temperature initially fluctuates sharply, reaching a peak of approximately 110 °C before gradually decreasing and converging with the water temperature. This early fluctuation reflects the initial imbalance between the inflow of hot compressed steam and the relatively cold cooling water entering the bath. During this phase, condensation is not yet stabilized, and a portion of the steam directly heats the liquid phase, leading to rapid temperature rise and local vapor superheating.

As the system progresses beyond the initial transient (approximately the first 500 s), heat transfer between the vapor and the cooling water becomes more uniform. The water temperature rises steadily from about 30 °C to approximately 100 °C, while the vapor temperature gradually declines and stabilizes at a similar value. This convergence indicates that thermal equilibrium has been reached between the vapor and liquid phases inside the cooler, corresponding to the onset of steady condensation and vapor liquid coexistence at near saturation conditions.

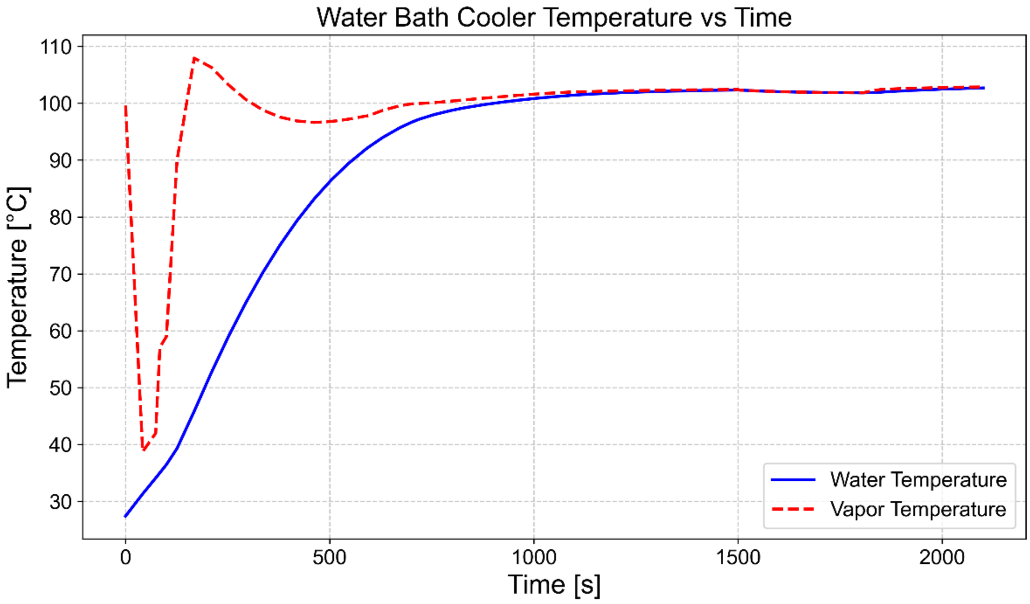

Figure 8. Water and vapor temperature evolution inside the water bath cooler during startup and stabilization.

The pressure evolution inside the water bath cooler, shown in Figure 9, follows a similar trend. At the beginning of the startup, the pressure drops sharply from its initial value around 1 bar to below 0.1 bar, as the system experiences rapid condensation of steam due to the initially cold cooling water. This low-pressure period coincides with the early fluctuations in vapor temperature. As the water warms up, vapor generation within the bath increases, causing a gradual pressure rise. After approximately 1000 s, the pressure stabilizes around 1 bar, consistent with the temperature plateau near 100 °C, confirming that the system reaches saturated thermodynamic equilibrium.

The close alignment of the temperature and pressure stabilization points demonstrates that the PI-controlled bypass system effectively maintains the target operating conditions of the cooler. Once equilibrium is achieved, both the water and vapor temperatures remain stable, and no oscillations are observed, confirming that the cooler operates under stable two-phase conditions. This stability is essential to maintaining the required vapor quality and pressure at the compressor inlet, ensuring reliable operation of the closed-loop test rig.

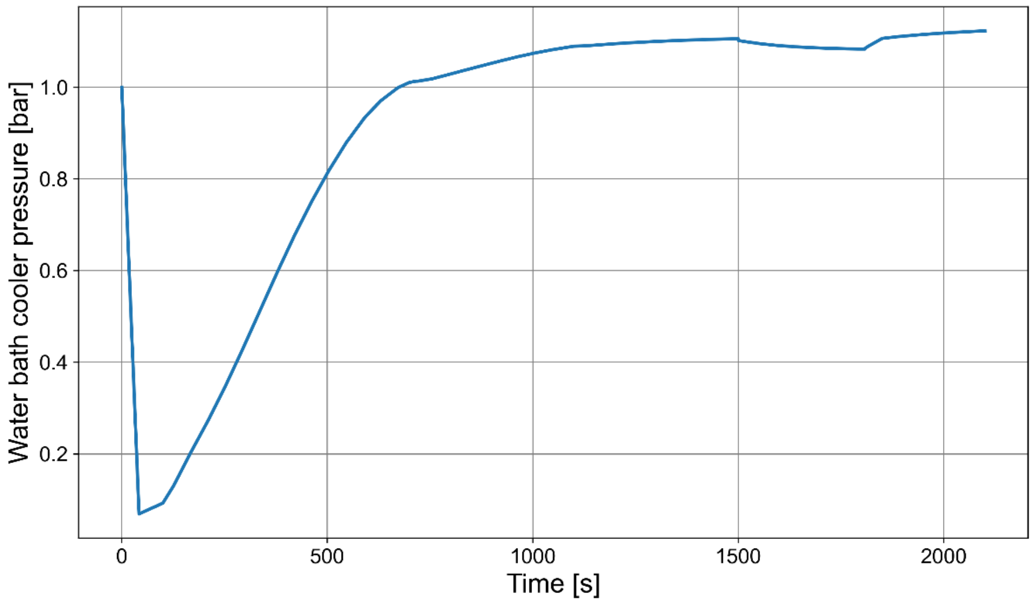

Figure 9. Pressure evolution inside the water bath cooler during startup and stabilization.

3.3. *Recirculated loop and flow behavior*

Figure 10 plotting the recirculated steam mass flow further confirms stable closed-loop operation. Initially, the flow was negative, indicating net vapor draw from the steam generator. As the compressor accelerated, the flow direction reversed and gradually reached a steady positive value of approximately 0.25 kg/s. Beyond this point, the loop operated independently of the steam generator, with the cooler and compressor maintaining a balanced vapor liquid cycle.

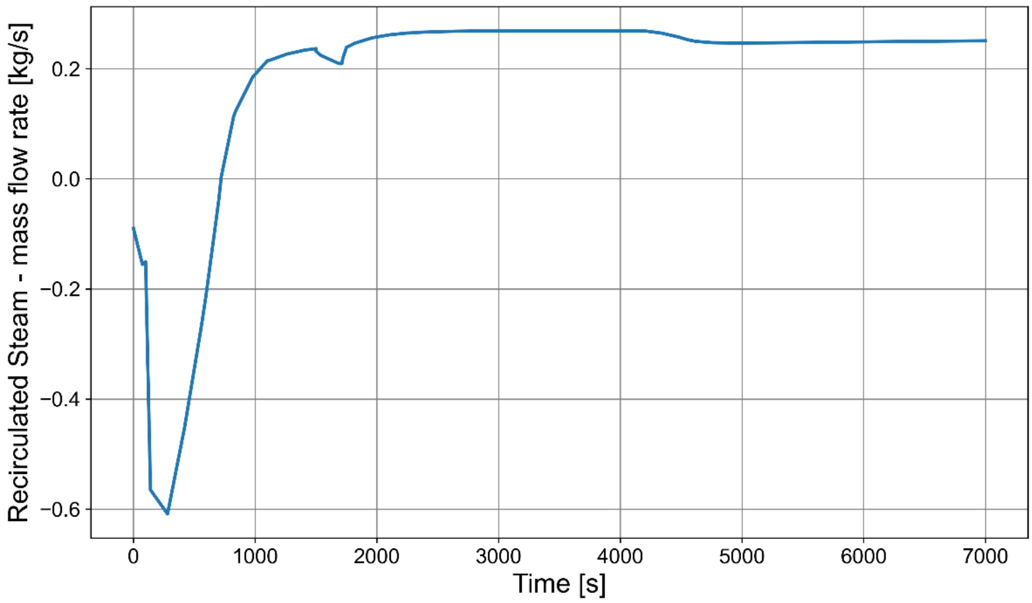

Figure 10. Recirculated steam mass flow rate

These results highlight that the proposed configuration can autonomously sustain vapor circulation after startup and effectively recover from perturbations, which is crucial for experimental flexibility in future compressor testing campaigns. The experimental validation of the complete test rig will be performed in future work to further confirm the overall model's accuracy under real operating conditions.

4. Conclusion

This study developed and analyzed a dynamic model of a closed-loop steam compressor test rig designed to evaluate compressor behavior under realistic operating conditions. The system integrates a steam generator, expansion valve, compressor, back-pressure valve, and water bath cooler arranged in a recirculating configuration that allows the steam generator to operate only during startup, significantly reducing steam consumption once the system reaches steady state.

Simulation results showed that the system achieved a smooth and stable startup, with the compressor beginning effective compression at approximately 42,000 rpm and the overall cycle stabilizing without oscillations. The PI controller effectively regulated the vapor fraction and pressure within the water bath cooler, maintaining operational stability during both steady-state and transient conditions. The cooler reached thermodynamic equilibrium as the vapor and water temperatures converged near 100 °C, while the pressure stabilized around 1 bar, confirming stable two-phase operation and reliable control of the vapor liquid interface.

The compressor model reproduced the CFD model's characteristic maps accurately, with all operating points remaining within the valid range of pressure ratio and efficiency. This validates the dynamic representation of the compressor and demonstrates that the closed-loop configuration can operate reliably under a range of speed and load variations.

Overall, the developed model provides a robust and flexible platform for studying the transient performance and stability of steam compression systems. It establishes a foundation for the design and virtual commissioning of experimental test rigs, enabling safe and efficient assessment of various compressor technologies. Future work will focus on the experimental validation of the system and on extending the model to include advanced control strategies, contributing to the broader development of electrified, high-temperature heat pump systems for industrial decarbonization.

Nomenclature

φ	Flow coefficient
η_{isen}	Isentropic efficiency
β	Dimensionless interpolation parameter
h_{suc}	Inlet specific enthalpy
h_{dis}	Actual discharge specific enthalpy
h_{isen}	Isentropic discharge specific enthalpy
p_{out}	Outlet compressor pressure
p_{in}	Inlet compressor pressure

Acronyms

PI	Propotional integral
PR	Pressure ratio
N_T	Corrected rotational speed
CFD	Computational fluid dynamics
MSL	The Modelica Standard Library
SGHPs	steam-generating heat pumps

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