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Real-Time Optimization of CO2 Heat Pumps for Industrial Dishwasher Applications

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Abstract

Transcritical CO_2 heat pumps, due to their non-isothermal heat-rejection characteristics, are well suited for water-heating applications where high temperature lifts are required. However, maximizing the cycle performance while satisfying the thermal demands of real applications remains challenging, since the optimal high-side pressure depends on the sink temperature and operating conditions. In this work, a transcritical CO_2 heat pump serving a professional dishwasher is modelled using a dynamic lumped parameters model. The dynamic model is used to verify that the required outlet water temperatures for the washing (55 °C) and rinsing (85 °C) phases are met, and to generate steady-state performance maps of the COP as a function of discharge pressure for different sink-side conditions.

Analysis of these maps shows that, for a given outlet temperature, the optimal discharge pressure maximizing the COP is largely independent of the inlet sink temperature, making the high-side pressure an effective manipulated variable for supervisory optimization. A dither-free Least-Squares Extremum Seeking Control (LS-ESC) scheme is then implemented in MATLAB/Simulink and applied directly to the steady-state COP maps, operating on a 1-D lookup table without requiring an analytical model of the cycle. For each operating condition, the LS-ESC iteratively updates the discharge pressure and converges to the COP-maximizing value starting from non-optimal initial guesses.

The results demonstrate that LS-ESC can reliably recover the optimum of realistic performance maps obtained from a detailed thermodynamic model, confirming its suitability as a supervisory optimizer for CO_2 heat pumps during operation, adapting the operating conditions to achieve the best performance while satisfying the process constraints. The integration of the LS-ESC layer with the full dynamic dishwasher model for true real-time optimization is identified as promising future work.

Keywords:Real Time Optimizer, dither-free extremum seeking control, Heat Pump, Dishwasher, CO_2 ,Static Performance Map;

1. Introduction

Improving the performance of thermal systems such as CO_2 heat pumps requires optimization strategies capable of adapting to uncertain and time-varying operating conditions. In many cases, the underlying system model is difficult to identify with sufficient accuracy, motivating the use of model-free optimization and control approaches. Recent advances in feedback-based optimization have shown that optimization algorithms can be embedded into closed-loop architectures, enabling robust adaptation under uncertainty [1, 2]. This challenge is intensified in thermal and energy systems, where strong nonlinearities, component interactions, and varying boundary conditions often make it difficult to derive accurate low-order control-oriented models.

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Furthermore, real systems may experience performance drift over time due to factors such as aging, fouling, or variations in operating conditions, reinforcing the need for model-free approaches

Professional dishwashers represent significantly energy-intensive appliances, with a large fraction of their energy consumption associated with water heating for the washing and rinsing phases, which must be also realized in short amount of time to guarantee adequate productivity and sufficient hourly washing cycles in professional kitchens. Since the standard technology currently employed for heating the process water in these kind of systems consists on electrical heaters, the integration of heat-pump technology can offer a practical route to improve energy efficiency. Transcritical CO_2 (R744) heat pumps are well suited for this purpose thanks to their low environmental impact of the refrigerant fluid (ODP = 0, GWP = 1), chemical stability (it is non-flammable and does not decompose into substances harmful to health), high temperature lift and strong heat-transfer characteristics [3].

Their non-isothermal heat rejection also enables close temperature matching with the process water, which is advantageous for dishwasher applications. However, the optimal operating pressure of a transcritical CO_2 cycle strongly depends on boundary conditions. As a result, fixed-pressure operation or pre-calibrated lookup tables may yield suboptimal performance under realistic and varying dishwasher conditions. The task of adjusting system inputs to maximize a performance metric such as COP can be formulated within the framework of Extremum Seeking Control (ESC). ESC is a model-free real-time optimization technique that adapts a manipulated variable to drive a system toward the extremum of an unknown cost function. Its origin dates back to the pioneering work of Leblanc (1922) [4], and a rigorous stability foundation was later provided by Krstić and Wang using averaging theory [5, 6]. Over the years, ESC has evolved from classical dither-based schemes to more advanced approaches, including input–output correlation-based methods [7], dither-free gradient estimation [8], swarm-based ESC [9] and sensitivity-aware techniques [10]. ESC has been successfully applied in several thermal and energy systems, including CO_2 inverse cycles [11], vapor-injected CO_2 heat pumps [9], dedicated subcooling transcritical CO_2 water heaters [12, 13], and organic Rankine cycle units [14].

Among recent developments, dither-free Least-Squares ESC (LS-ESC) is particularly attractive for systems where perturbation-based excitation is undesirable. LS-ESC estimates the local gradient from historical input–output data using a least-squares fit, enabling smooth and noise-robust convergence without the need for artificial dithering [8].

In this work, a CO_2 heat pump integrated into a professional dishwasher is modelled in the commercial software Simcenter Amesim, based on the discretization of real components in a system of lumped parameters elements connected to describe the entire system through a set of differential equations, using real component data [15, 16, 17] to assess the performance of each element in the unit. The dynamic model is used to verify that the required outlet temperatures for the washing (55 °C) and rinsing (85 °C) phases are met, and to generate steady-state performance maps of the COP as a function of discharge pressure for different inlet sink temperatures.

Firstly, dynamic simulations of the CO_2 heat pump are realized to assess the capability of such solution to satisfy the water temperature profiles within the short cycle time required for this specific application, with high efficiency compared to standard electric boilers. Secondly, a dither-free Least-Squares Extremum Seeking Control (LS-ESC) scheme is developed and evaluated as a supervisory optimizer on steady-state COP – pressure maps to identify the optimal high pressure level. LS-ESC is implemented as a single-parameter optimizer, where the compressor discharge pressure is the manipulated variable, and the gradient of the COP–pressure relationship is estimated through a first-order least-squares fit over a sliding data window. By avoiding dither-based excitation, the method achieves smooth and robust convergence on realistic COP maps. The results show that LS-ESC reliably recovers the optimal discharge pressure for each operating condition, demonstrating its suitability as a lightweight supervisory tool.

A key motivation for adopting ESC is that, while model-based methods such as model predictive control could in principle predict system behavior and optimize control, in heat pump applications dynamic models are difficult to develop and maintain due to incomplete parameter knowledge, nonlinearities, and time-varying characteristics. For this reason, ESC represents a practical model free alternative that can perform real-time optimization without requiring a detailed system model. It is important to note that simplified thermodynamic and numerical models are still very useful for system analysis, understanding operating limits, and testing ESC in simulation. However, they are not sufficiently accurate or robust to serve as the basis for real-time model-based control. This distinction reinforces the choice of ESC as the most appropriate strategy for HP control.

By estimating the local performance gradients directly from input-output data, LS-ESC enables real-time with a dither free option. the system operates in a plug-and-play, model free manner, without imposing additional stress on the system, underlining the significance of this research work for heat pump applications.

The originality of this work therefore consists in providing an initial demonstration of dither free LS-ESC applied to steady state performance maps of a transcritical CO_2 (R744) heat pump, highlighting its possible use as a model-free and minimally stressful optimization.

2. Numerical Modelling Framework

2.1. System Description

A transcritical CO_2 heat pump system has been modeled and controlled to achieve optimal energy efficiency through a hierarchical control strategy. The objective is to maximize the COP while ensuring that the outlet water temperature of the process meets the desired setpoint under various boundaries (e.g., cycle time, ambient conditions, sink inlet temperature).

A lumped-parameter numerical model of the heat pump has been developed in Simcenter Amesim, where all system components are discretized in lumped parameters elements, connected together to describe the entire system through a set of differential equations solved over time, based on real component data and manufacturer-provided characteristics. This detailed numerical model enables the evaluation of heat pump performance and control strategy under multiple operating conditions, including variable compressor speeds and expansion valve openings.

The system is designed for water-heating applications and operates on a transcritical CO_2 vapor compression cycle, realized through the simplified schematic presented in Fig. 1.

The main components and their models in Amesim are as follows:

- **Compressor:**
  A variable-speed semi-hermetic CO_2 compressor whose volumetric efficiency and overall compression efficiency are interpolated from manufacturer performance maps. The compressor speed N_c is assumed to be controlled by an inverter and is the main actuator for thermal power control, to guarantee the water temperature values necessary for the washing phase (55 °C) and for the subsequent rinsing phase (85 °C).
- **Gas Cooler (GC) and Internal Heat Exchanger (IHX):**
  Modeled as brazed-plate heat exchangers operating in counterflow configuration. The gas cooler transfers heat from the CO_2 realizing the vapor compression cycle to the process water loop, which needs to be heated from a supply temperature variable between 10 °C and 25 °C to the above-mentioned process temperatures for the two phases of each full washing cycle. The internal heat exchanger is used to provide refrigerant superheating at compressor suction and to improve cycle efficiency, allowing flooded evaporation operation. It is worth pointing out that the evaporator is not included in the model, since evaporation at a fixed pressure, corresponding to a saturation temperature of 10 °C, is assumed, consistently with the assumption that the dishwasher will be placed in indoor kitchen environments, with air temperature (corresponding to the source temperature for the CO_2 vapor compression cycle) always around 20 °C.
- **Expansion Valve (EV):**
  An electronic expansion valve regulates the high-pressure level of the heat pump. A PI controller adjusts the valve opening to maintain the desired discharge pressure of the compressor, which defines the system's high-pressure operating point.
- **Sensors:**
  Temperature and pressure sensors are placed at all key thermodynamic state points for monitoring, control feedback, and performance evaluation.

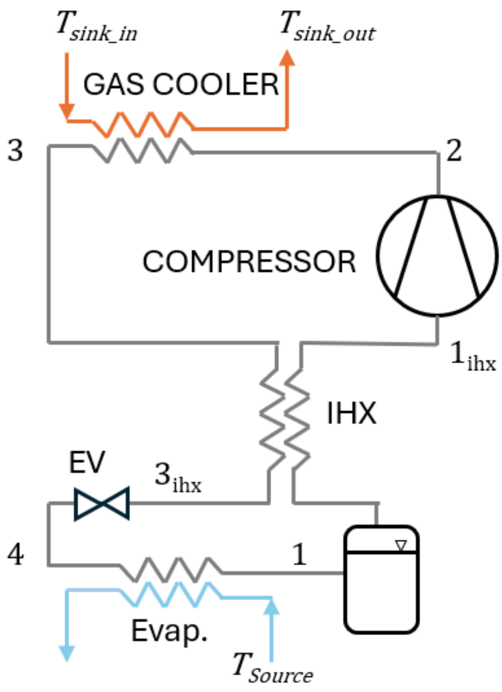

Figure 1. The HTHP simplified cycle schematic.

The thermodynamic states (enthalpies h_{1ihx}, h_2, h_3) are used to compute the COP as:

$$\text{COP} = \frac{h_2 - h_3}{h_2 - h_{1ihx}} \tag{1}$$

The numerical model of the CO2 heat pump developed in Simcenter Amesim is presented in Fig. 2, where the main cycle elements mentioned above can be identified, as well as the two PI control loops which will be described in the next section.

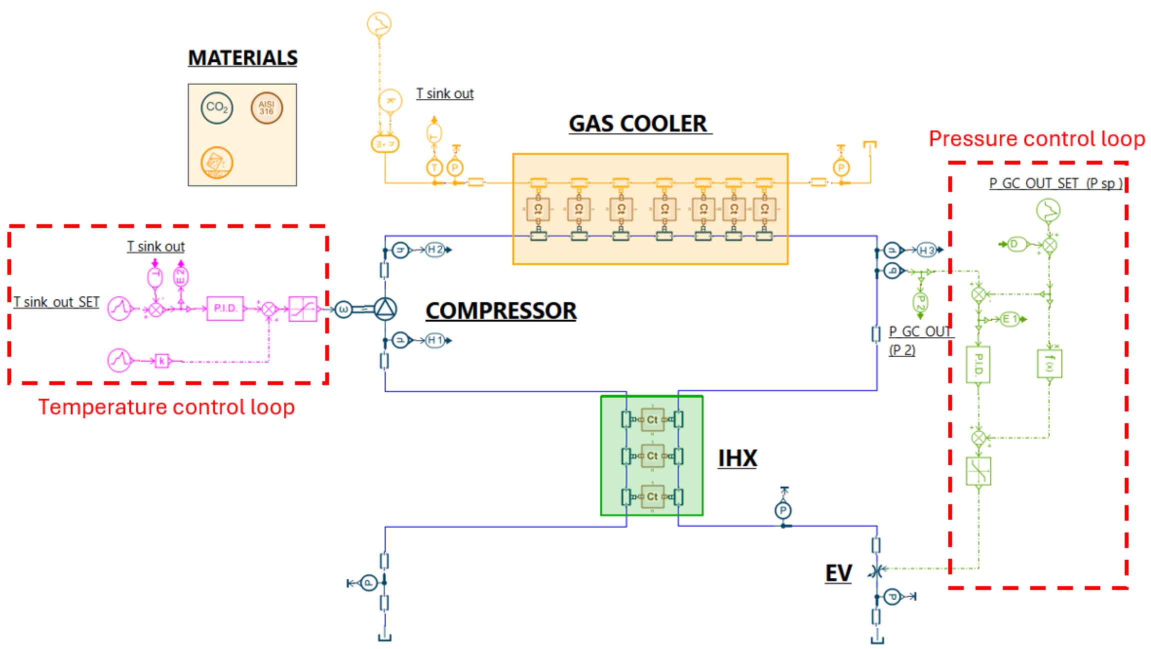

Figure 2. CO2 heat pump numerical model.

2.2. Control Architecture

The proposed control structure combines two low-level PI control loops for regulation and one upper-level ESC loop for optimization. Each PI controller is supported by a Forward control signal, based on a-priori knowledge of the system. This hierarchical design ensures both stability and optimal efficiency.

2.2.1. Temperature Control Loop (Compressor Speed Loop)

- Controlled variable: Outlet water temperature $T_{sink,out}$
- Manipulated variable: Compressor rotational speed N_c
- Setpoint: Desired outlet temperature $T_{sink,out,SET}$
- Controller type: PI controller
- Purpose: Maintain $T_{sink,out}$ at the desired setpoint despite external disturbances or thermal load variations.

$$N_c(t) = N_{c,0} + K_p^T e_T(t) + K_i^T \int e_T(t)dt \tag{2}$$

where: $e_T(t) = T_{sink,out,SET} - T_{sink,out}$.

2.2.2. Pressure Control Loop (Expansion Valve Loop)

- Controlled variable: Discharge pressure P_2
- Manipulated variable: Expansion valve opening position α_v
- Setpoint: Pressure reference P_{sp} (determined by the ESC)
- Controller type: PI controller
- Purpose: Maintain the discharge pressure around its target to ensure correct refrigerant mass flow and proper superheat.

$$\alpha_v(t) = \alpha_{v,0} + K_p^P e_P(t) + K_i^P \int e_P(t)dt \tag{3}$$

where: $e_P(t) = P_{sp} - P_2$.

2.2.3. Dither-Free LS-ESC

The LS-ESC acts as a supervisory real-time optimizer (RTO) layer that continuously updates the discharge-pressure setpoint P_{sp} to maximize the system's COP while ensuring the outlet-temperature constraint.
The RTO problem can be formulated as follows:

$$\underset{P_{sp}}{\text{argmax}} \; J(P_{sp})$$

where J is a suitable objective function, that is measurable/ calculable in real-time.
It is defined as follows:

$$J(P_{sp}) = \text{COP}$$

At each sampling instant $t = k\tau$, the most recent N samples of (P_{sp}, J) are stored:

$$J_t = [J(t-(N-1)\tau) \;\cdots\; J(t)], P_t = [P_{sp}(t-(N-1)\tau) \;\cdots\; P_{sp}(t)] \tag{4}$$

A first-order least-squares fit is applied to this data to estimate the performance gradient:

$$\hat{g} = \widehat{\frac{\partial J}{\partial P_{sp}}} = \frac{cov(P_{sp}, J)}{var(P_{sp})} \tag{5}$$

The discharge-pressure setpoint is updated as:

$$P_{sp}(t) = P_{sp}(0) + \int_0^t \hat{\dot{P}}_{sp}(\tau)\, d\tau \tag{6}$$

$$P_{sp}(t) = P_{sp}(0) + \int_0^t K\hat{g}(\tau)\, d\tau \tag{7}$$

where:

K: ESC adaptation gain (controls convergence rate)
$P_{sp}(0)$: initial discharge pressure setpoint (integrator initial condition)
P_{sp}: discharge pressure setpoint which is bounded within a safety range $[P_{\min}, P_{\max}]$.

Unlike traditional perturbation-based ESCs, this dither-free LS-ESC uses historical data for gradient estimation, eliminating artificial oscillations and improving convergence stability. The approach guarantees smooth tracking of the optimal operating condition, maximizing the COP of a transcritical CO_2 heat-pump under industrial dishwasher load profiles.

A simplified flow chart of the LS-ESC optimization algorithm is presented in Fig. 3.

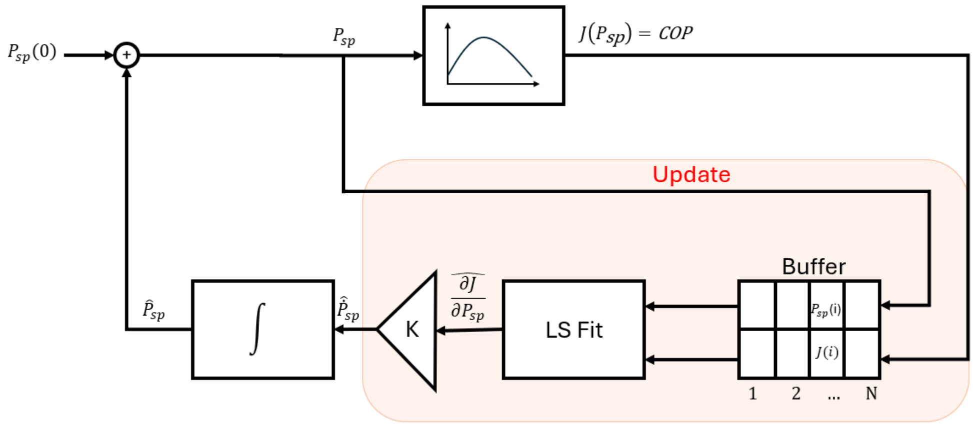

Figure 3. Flow chart of the LS-ESC dither free optimization algorithm.

2.2.4. Tuning of LS-ESC Parameters

The dynamic behaviour of the optimizer depends mainly on the adaptation gain K, the data window size N, and the sampling time τ, which together determine the trade-off between convergence speed and stability. Following the time-scale separation principle [5, 8], the product $KN\tau$ is kept small so that the optimization evolves slower than the inner PI loops. Increasing K accelerates convergence but may introduce oscillations, while enlarging N or τ improves noise rejection at the cost of slower adaptation. In practice, $T = N\tau$ is chosen several times larger than the dominant time constant of the pressure-control loop, τ is selected according to the system's sampling frequency, and K is tuned experimentally to achieve smooth convergence without steady oscillations [4, 6, 7].

3. Case Study: Dishwasher Heat Pump

The CO_2 heat pump dimensioning and the related numerical model were developed based on the requirements of a hood type professional dishwasher [15, 16, 17], whose objective is to realize washing cycles in a very short time (three cycle durations are possible, spanning from a minimum duration of 45 s to a maximum duration of 150 s), subdivided in two separate and subsequent phases (washing phase and rinsing phase), characterized by use of hot water heated at different temperature levels (55 °C and 85 °C, respectively).

The operating conditions for each phase are summarized in Table 1. The reference unit consumes 2 L of supply water for each complete washing cycle and employs a 10 kW electric boiler for water heating.

Table 1. Dishwasher Cycle Description.

Phase	Start time	Ending time	Duration	$T_{sink,in}$	$T_{sink,out}$
[-]	t_s [s]	t_e [s]	[s]	[°C]	[°C]
Washing	0	80	80	10	55
Rinsing	80	150	70	10	85

3.1. Simulation setup and dynamic result of the cycle

Firstly, a dynamic simulation of a complete 150 s washing cycle is performed, to assess that the CO_2 heat pump is able to satisfy the process water temperature requirements within the limited time frame of the cycle duration and to assess its dynamic performance (heating power and COP) over the entire working cycle. In the simulation, the system is initialized at 20 °C, assuming thermal equilibrium with ambient air in indoor kitchen environment, and the two cycle phases (washing and rinsing) are consequently realized. Therefore, the dynamic simulation also takes into account the effect of thermal inertia in the heat exchangers in the evaluation of the dynamic system response.

At this stage, the RTO layer is inactive, and the system operates solely under the two PI control loops: the compressor-speed controller for temperature regulation and the expansion-valve controller for discharge-pressure regulation. The discharge pressure setpoints were selected according to high pressure correlations based on thermodynamic evaluation [3]: for the case of this simulation, the set values are 80 bar for washing phase and 125 bar for rinsing phase.

The dynamic dishwasher model simulation shows that the CO_2 heat pump is able to successfully increase the process water temperature from the supply value to the required setpoints for both operating phases in a reasonable amount of time (approximately 20 s for both washing and rinsing phases), while at the same time respecting the discharge pressure setpoints designed for the unit, as reported in Fig. 4.

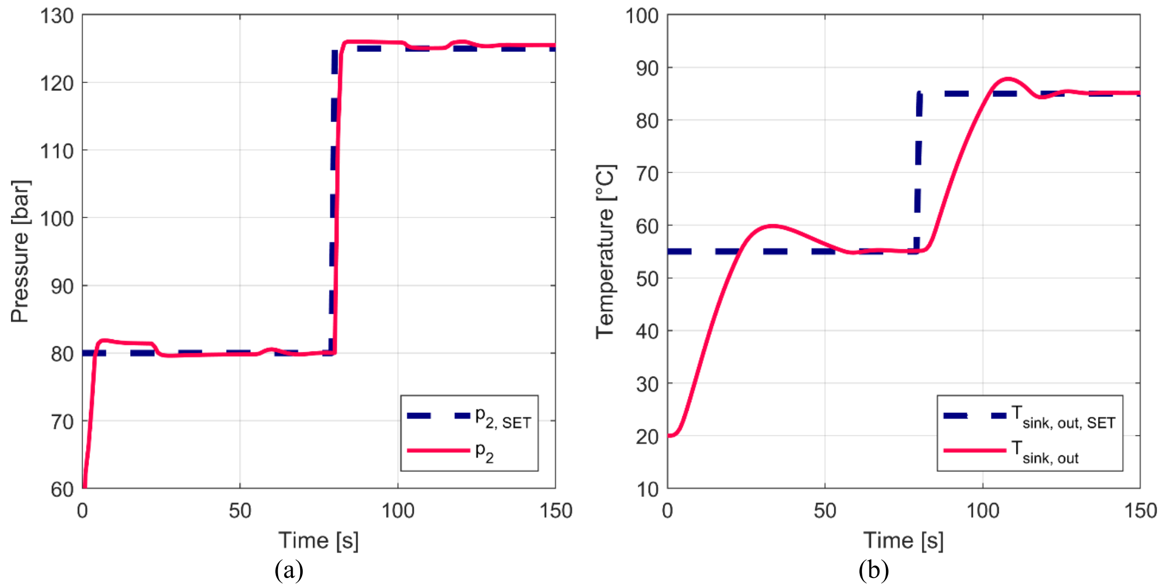

Figure 4. CO_2 heat pump operation in a complete washing cycle: (a) discharge pressure; (b) process water outlet temperature.

The dynamic thermal performance (COP and heating effect) is then presented in Fig. 5. At the beginning of each phase, the instantaneous COP (Eq. 1) presents significant fluctuations caused by the initial thermal imbalance. The use of an integral form for the COP allows to reduce instantaneous fluctuations and to better quantify the energy saving during the cycle:

$$COP^* = \frac{\int_{t_s}^{te} h_2 - h_3 \, dt}{\int_{t_s}^{te} h_2 - h_{1ihx} \, dt} \tag{8}$$

where t_s and e t_e are respectively the starting and the ending time of each phase of the cycle (see Tab. 1).

After stabilization, the integral COP settles at approximately 4.5 during the washing phase and 3.6 during the rinsing phase, which is significantly better than electric-resistance heating (COP = 1). The nominal heating power delivered by the heat pump is about 10 kW, consistent with the design target.

These results suggest that employing a CO_2 heat pump to replace electric boilers in industrial dishwashers, representative of current technology, could potentially allow to reduce the energy consumption up to 78% during the washing phase, and up to 72% during the rinsing phase, while still guaranteeing the process water temperature necessary for adequate washing operations and satisfying the short cycle times required in professional kitchen environments.

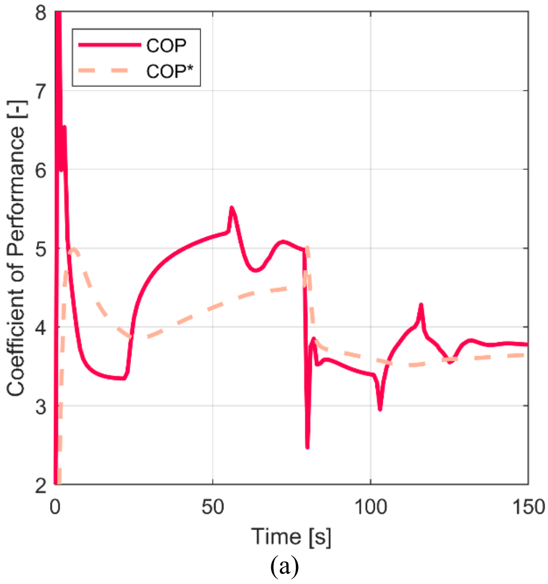

Figure 5. Dynamic performance of the CO2 heat pump over a complete washing cycle: (a) instantaneous COP; (b) heating power.

3.2. Steady state performance map

To support optimization, the heat pump numerical model is then employed to carry out steady-state simulations for two outlet temperatures, $T_{\text{sink,out}}$ = 55 °C and 85 °C, corresponding to the washing and rinsing phases, and for different inlet sink temperatures in the range $T_{\text{sink,in}} = 10\text{–}25$ °C. These conditions represent possible levels of process-water preheating via heat recovery. For all simulations, the source-side temperature is fixed at $T_{\text{source}} = 20$°C, for which an evaporating temperature of $T_{\text{evap}} = 10$°C is assumed, consistent with an indoor installation.

For each operating condition, the discharge pressure P_2 is varied over a suitable range and the corresponding steady-state COP is computed, obtaining COP–pressure maps. The results, presented in Fig. 6, show that, for both outlet-temperature levels, the maximum COP occurs within the pressure range that can be achieved by the existing PI controllers acting on compressor speed and expansion valve opening. Moreover, for a fixed $T_{\text{sink,out}}$, the discharge pressure that maximizes COP is almost independent of $T_{\text{sink,in}}$: different inlet temperatures lead to different peak COP values, with higher COP values reached with lower $T_{\text{sink,in}}$, as the CO_2 is cooled down to a lower temperature in the gas cooler, producing an increased useful effect for an approximately constant compressor power consumption, but the optimal P_2 remains essentially the same (with the only exception of the case with $T_{sink,in}$ = 25 °C and $T_{sink,in}$ = 55 °C). This behaviour confirms that the discharge pressure is a suitable scalar manipulated variable for supervisory optimization.

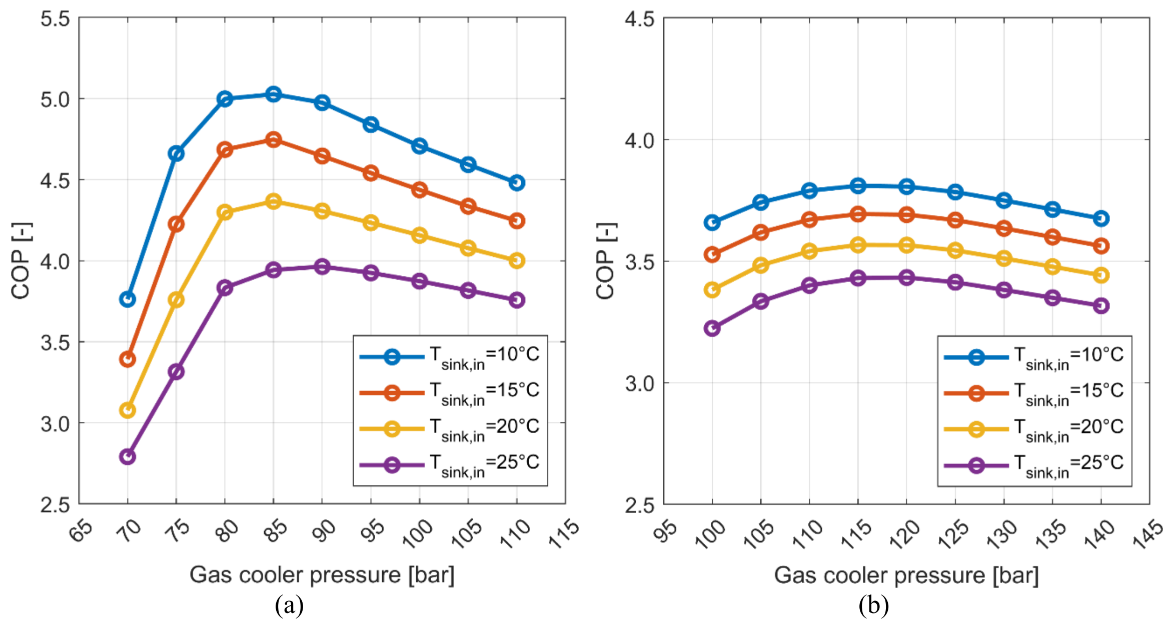

Figure 6. Steady-state performance of the CO2 heat pump, with evaporation temperature of 10 °C and different water inlet temperatures: (a) water outlet temperature setpoint of 55 °C (washing phase); (b) water outlet temperature setpoint of 85 °C (rinsing phase).

3.3. LS-ESC optimization algorithm implementation

Based on the steady-state simulations, an offline COP map is constructed, representing COP as a function of discharge pressure and operating condition (e.g. $T_{\text{sink,out}}$ and $T_{\text{sink,in}}$). This static map is used as the unit response model for the optimization layer, instead of embedding the ESC directly into the full dynamic Amesim model. In this way, the optimizer can be designed and tested with negligible computational cost, while still relying on realistic thermodynamic data.

The dither-free LS-ESC algorithm described in Section 2.2.3 is then applied to the COP map in MATLAB/Simulink. The ESC treats P_2 as the manipulated variable and COP as the performance index, and iteratively adjusts the pressure to maximize COP without requiring an analytical expression of the map. The optimizer is validated on a finite set of discrete operating conditions defined by the specific values of $T_{\text{sink,in}}$ and $T_{\text{sink,out}}$ considered in the COP maps and, in every case, it is initialized from a non-optimal pressure and converges reliably to the corresponding COP-maximizing P_2.

To illustrate the capability of LS-ESC to handle varying operating conditions, an additional test is performed in which the sink-side inlet temperature changes during the simulation, e.g. with a step from $T_{\text{sink,in}}$ = 25 °C to 10 °C after a given number of iterations (half of the total iterations in this case), while maintaining a constant setpoint for the $T_{\text{sink,out}}$ (55 °C).

Results of the optimization algorithm are shown in Fig. 7 and Fig. 8. The ESC trajectory shows that, despite starting from non-optimal initial conditions, the optimal gas cooler pressure value for $T_{\text{sink,in}}$ = 25 °C is found. After that, a rapid transition from the optimum of the first operating condition to the optimum of the new operating condition ($T_{\text{sink,in}}$ = 10 °C) occurs in correspondence of the step change, with a smooth adjustment of the discharge pressure and limited overshoot.

This behavior highlights the potential of the LS-ESC scheme as a supervisory optimizer for real-time operation, to be integrated with the dynamic dishwasher model in future work. In particular, as anticipated in Section 2.2.4, the tuning of the LS-ESC parameters (adaptation gain, data window size, sampling time) will represent a key calibration of the optimization algorithm when coupled with a real dynamic system, with characteristic response time which can influence the quickness and effectiveness in finding and implementing the optimal operating parameters of the heat pump within the boundaries of real operating cycle times.

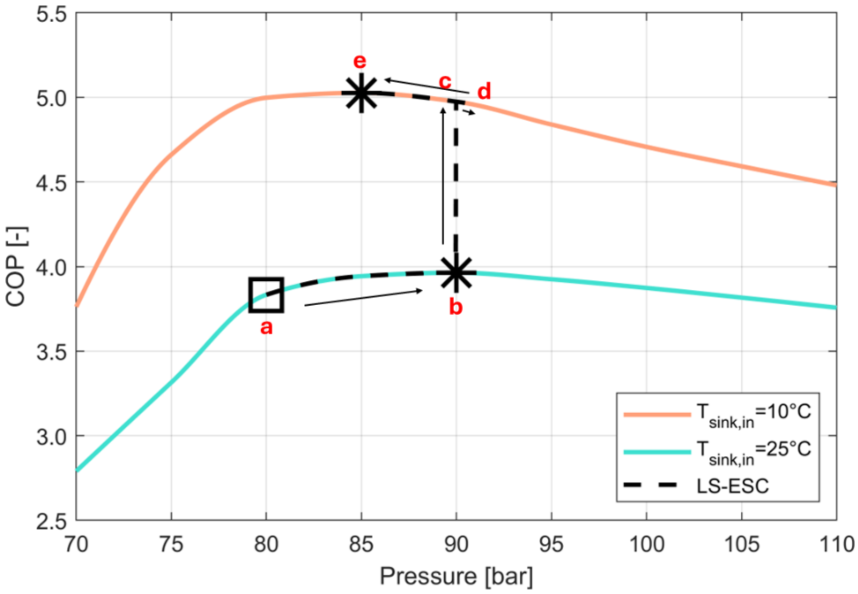

Figure 7. LS-ESC response at $T_{\text{sink,out}}$ = 55 °C for a step change in $T_{\text{sink,in}}$ from 25 °C to 10 °C: (a) starting point; (b) converged optimal pressure for $T_{sink,in}$ = 25 °C; (c) after the step change for $T_{\text{sink,in}}$; (d) pressure overshoot; (e) converged optimal pressure for $T_{sink,in}$ = 10 °C.

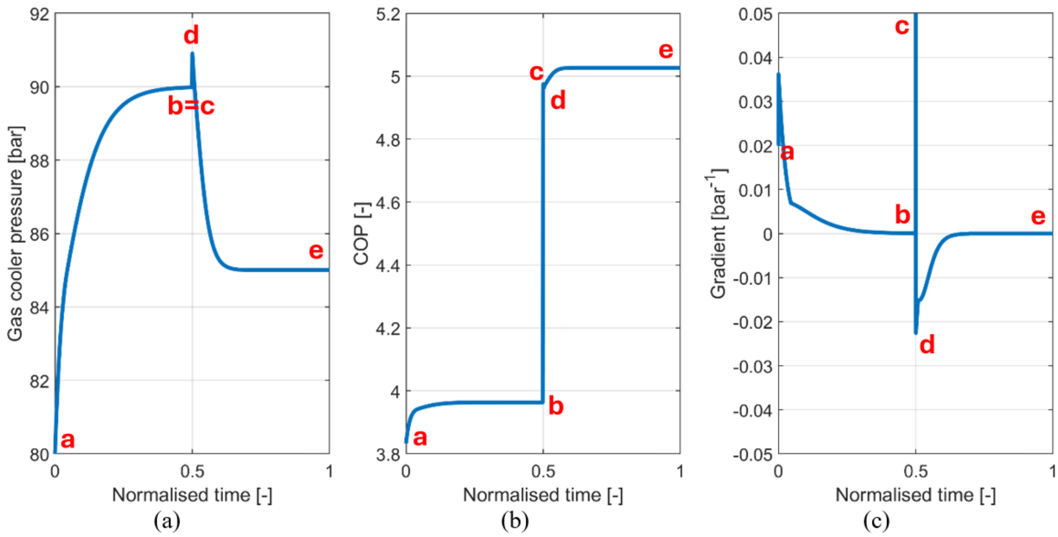

Figure 8. LS-ESC parameters response at $T_{\text{sink,out}}$ = 55 °C for a step change in $T_{\text{sink,in}}$from 25 °C to 10 °C: (a) Gas cooler pressure; (b) COP; (c) Gradient. Nomenclature for the points is the same as for Fig. 7.

4. Conclusions

This work developed and evaluated a transcritical CO_2 heat pump for a professional hood-type dishwasher, combining a detailed dynamic lumped-parameter model with steady-state performance mapping and an LS-ESC supervisory optimization strategy. The dynamic simulations confirmed that the system can reliably meet the strict thermal requirements of the washing and rinsing phases (55 °C and 85 °C, respectively) within the short cycle durations characteristic of professional applications. The heat pump successfully achieved the target temperatures in approximately 20 s for each phase, even when initialized from ambient conditions, demonstrating that thermal inertia does not hinder the rapid response required in real operation.

The dynamic performance analysis showed that the CO_2 heat pump delivers heating power close to the 10 kW design target, while achieving integral COP values of approximately 4.5 during washing and 3.6 during rinsing. Compared to conventional electric-resistance boilers, these values correspond to energy-consumption reductions of roughly 78 % and 72 %, highlighting the potential of CO_2 heat pumps to significantly improve energy efficiency in commercial dishwashing applications. These results validate the suitability of transcritical CO_2 systems for water heating under fast and thermally demanding operating cycles.

Steady-state simulations provided further insight into the optimal operation of the heat pump across a range of sink-side inlet temperatures. The resulting COP–pressure maps demonstrated that, for a specified outlet temperature, the discharge pressure that maximizes COP is nearly independent of the inlet water temperature. This property identifies discharge pressure as an effective scalar manipulated variable for supervisory optimization, simplifying the formulation of real-time performance-maximizing control strategies. The LS-ESC algorithm leveraged this characteristic by successfully converging to the optimal discharge pressure across all tested conditions, even when operating from non-optimal initial guesses or under step changes in inlet temperature.

Overall, the study demonstrates that LS-ESC is a robust and computationally efficient supervisory optimization method capable of navigating realistic CO_2 heat-pump performance landscapes. Its ability to track the optimal discharge pressure under changing conditions suggests a strong potential for real-time integration with the full dynamic dishwasher model. Future work will focus on embedding LS-ESC directly into the operational control structure, assessing the interplay between optimizer tuning and the system's inherent dynamic response, as the main challenge lies in coupling the proposed optimization algorithm with the dynamics of a real system and ensuring its reliable performance in real-time operation.

In this study only one operation condition ($T_{sink,out}$ or $T_{sink,in}$) at time was varied. Changing multiple operation conditions simultaneously and evaluating the system response will be considered in future work.

Acknowledgements

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