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Virtual test bench for the design of control strategies for water heaters

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ABSTRACT

An innovative methodology and a virtual test bench are proposed to support the design of water heaters' control strategies. This platform allows to speed up the development and evaluation of control systems

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even before the existence of prototypes or real test environments. By simulating the environmental conditions and the state of the different device components, it will be possible to detect and correct possible initial errors in the control system design which can be time consuming and costly due to subsequent modifications to the system or equipment components.

The architecture of the proposed system establishes four operating modes, open loop data acquisition, real time simulation, hardware-in-the-loop simulation, and test of the complete real system, the incorporation of these functionalities in the same platform is not reported in the literature for domestic water heaters. The virtual test bench was designed to accommodate different water heaters including, but not limited to, gas, electric and heat pumps, for instantaneous hot water production or including hot water storage. The prototype of the virtual test bench is described emphasizing the hardware-in-the-loop methodologies and embedded control. The particular case study of a tankless gas water heater is presented implementing the different operation modes in the virtual test bench. The water heater models, control strategies, simulation and experimental data are presented and discussed.

Keywords: virtual test bench, water heaters, hardware-in-the-loop simulation, embedded control, tankless gas water heater

1 INTRODUCTION

There is a growing awareness and concern with the scarceness of natural resources, associated with the noticeable energy consumption increases and associated harmful emissions, causing adverse effects to the environment and society. Water heating represents significant part of the total buildings energy consumption, domestic hot water production accounting for approximately 18% of total energy consumption in the residential sector in the USA [1] and 14.5% in the EU [2]. Regulations set increasingly exigent requirements on energy efficiency, nitrogen oxide emission levels, volume for

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water heaters storage, and heat losses from hot water storage tanks, [3], bringing new challenges to the manufactures.

The purpose of this work is to develop tools and methodologies to support the implementation and evaluation of advanced control strategies for water heaters with improved comfort, by reducing temperature undershoots and overshoots, in addition to higher sustainability and lower environmental impact, by energy and water consumption and gaseous emissions reductions.

Control strategies of water heaters have become increasingly complex, namely with combined feedforward feedback [4,5], artificial neural networks [6,7], adaptive [8,9] and predictive control [10–12], as well as the increased number of sensors and actuators involved. The time available for the development and testing of new control strategies in the real environment has diminished, demanding shortening of the development, implementation, and test phases [13,14]. Moreover, it is necessary to detect and correct possible errors in the design of the control system as earlier as possible, as they become more time consuming and costly as they are only later detected and corrected.

The development of new water heaters components, configurations, and control strategies could be supported by simulation techniques such as hardware-in-the-loop-simulation (HILS), without the need of the physical system (that sometimes is not yet available). By simulating real conditions or even extreme conditions beyond the physical limits of some of the elements, it is possible to evaluate the performance at reduced

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costs and time, and additionally avoiding possible safety problems as, for example, with combustion systems.

The first successful approaches of HILS were developed for flight simulation [15], where the early objectives were to simulate the instruments in a secure and stable cockpit. HILS systems are somehow embedded in the simulation loop, aiming to get more accurate results. In HILS, part of the simulation loop is composed of computer simulation, while the rest consists of hardware systems [16]. The hardware components can include physical actuators and sensors and/or embedded controllers [17]. There is an increasing interest in the application of HILS to improve the control of heating systems [18], advanced servo pneumatic valves [19],steam plants [20], large energy production facilities as thermal powerplants [21] or large hydro-power plants [22], and even satellites [23]. In literature there are some previous works concerning the development of test benches based on hardware-in-the-loop-simulation methodologies for water heater systems. In [18], an implementation of a HILS test bench is presented for heat pumps, considering space heating and tank based domestic hot water production. A real heat pump is tested under real weather conditions, imposed by a simulated building and emulation of a thermostat. A software-in-the-loop method is implemented for test and optimize control strategies of a solar thermal system [24]. A real controller of a solar thermal appliance is connected to a building simulation model on Dymola environment. A test bed to improve controller's performance of ground-source heat pumps is presented [25,26]. Whitin this system the simulated components are the controller and build model. The hardware components consist of a brine water

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heat pump and a test bed composed by heat sink, heat storage, and heat source modules to emulate dynamics of external conditions and domestic hot water consumption. In [27] an HILS emulation method is presented to evaluate the control strategies of a hydronic radiant heating system. The authors replaced the model of a hydronic network with real hardware, and the building physics is analyzed by a simulation, to minimize the results uncertainties. A test bench has been realized to create an interface between hardware heat pump and a TRNSYS build [28], offering the possibility to simulate real ambient conditions for comparison of embedded devices performance under reproducible laboratory conditions.

Methodologies based on HILS are state-of-the-art procedures for the evaluation of embedded systems, aiming to shorten the time of the product development process. However, similar works identified in the literature are mainly focused on heat pump systems, applied for combined space heating and domestic hot water. Some of the systems are based on simulated controllers other on simulated plant models, but none incorporate in the same platform all the functionalities proposed in this work.

The manuscript is structured as follows, in section two the development of a virtual test bench (VTB), as well as its modes of operation, is described. The proposed VTB supports and accelerates the development of control strategies and algorithms for thermal systems. In particular, the presented VTB prototype is designed to accommodate different technologies for domestic hot water production, such as gas, electric and solar water heaters and heat pumps, both for instantaneous water heating or including a hot water storage tank. In section three, the particular case of a tankless

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gas water heater (TGWH) is taken as an example, considering the VTB different operating modes. It includes a presentation of the development and validation of the water heater models; the design and implementation of control strategies; and the implementation of HILS methodologies. In section four, simulated and experimental data are presented and discussed. For validation of VTB concept, and evaluation of the controller's performance, tests in all operating modes are analyzed and compared. The conclusion is the fifth and final section.

2 VIRTUAL TEST BENCH

This section describes the definition of a framework and the developments for the implementation of a platform to help the design of control strategies for water heaters, referred to as virtual test bench. This platform enables the assessment of advanced control strategies at the earlier stages recurring to real-time simulation techniques, and in subsequent stages with the increasing introduction of hardware components, until the test of the complete physical system.

The central components of the proposed VTB are dynamic models of water heaters, compatible with real-time simulation. VTB users select which components are to be tested from the model's simulation library, and which are real hardware. Water heaters' models need to be able to reproduce both fast and slow dynamics of thermal and fluidic components, bringing additional complexity to the implementation in real-time and HILS scenarios. Some of the detailed and complex models need to be simplified, and reduced models are derived for inclusion in the platform.

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Hardware and software components were defined for the VTB, with a dedicated real-time board, acquisition and interface software, instrumentation sensors, and actuators for imposing environmental test conditions. An embedded control platform, based on a microcontroller, with similar capabilities to the electronic control units (ECU) used in appliances, is selected for the evaluation of control strategies with HILS methodologies.

2.1 Operating modes

To assess the proposed concept and its features, the VTB must be tested through different types of experiments and controllers. The design of a controller can start in a fully simulated environment, afterwards, the controller is implemented in a hardware-controlled device and finally, it is tested with the physical system's prototype.

Design of control processes requires substantial investments in time and resources, which can be substantially reduced if the controllers' behavior can be predicted and tested even before programming the microcontroller [29,30].

For accomplishing the different functionalities of the VTB, four operating modes are defined as presented in Fig. 1:

The first operating method (open-loop data acquisition) enables the capability to acquire and record data from the equipment, with data acquisition software and hardware, in open-loop experiments. The equipment and the virtual model do not have any type of controller, except the ones to ensure safety measures, ensuring that the temperature and pressure limits are not exceeded. This operating mode is intended for real-time data acquisition, with the main objective of enabling parameters estimation

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and models' validation. By executing different experiments, in different scenarios, it is possible to collect experimental data that allow models parameterization and verification.

The second operating mode (real-time simulation) allows performing virtual simulation in real-time, without any hardware for water heater or controller. The dynamic model of the thermal system is controlled by a virtual model of the controller while the simulation is executed in real-time. At an early stage of development, this operating mode proves to be useful since it is possible to rapidly test the controllers and tune their parameters.

In the third operating method (hardware-in-the-loop simulation), the VTB is capable of performing HILS that can be either a real water heater appliance controlled by a virtual model of the controller or a microcontroller platform with embedded code controlling a virtual model of the system. As the main focus of this work is to support control design, an embedded controller in a hardware platform is used, as the virtual controller is preferred for the experimental validation of the water heater hardware components. The VTB must comprise the hardware and software to simulate external conditions perceived by the controller, by emulating electric signals of sensors and actuators and interacting with a real-time simulation of the water heater. This mode allows evaluating the controller in closer conditions of the ECU used in mass production water heating appliances. Extreme environmental conditions, that are difficult or even impossible to test in the real appliance, can be simulated and imposed on the controller implemented in the hardware devices.

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Finally, in the fourth operating mode (complete real system), it is possible to test the actual controller in the complete real/physical system. This feature is beneficial at the final phases of the test and optimization, with all components physically implemented in hardware components. This is a common functionality of the conventional test benches used in different engineering areas. In this operating mode, the user may impose some of the environmental variables to implement automated and repeated tests.

2.2 Virtual test bench prototype

A prototype of the VTB was developed, to test and validate the proposed concept and its functionalities. This prototype was designed to accommodate different domestic hot water technologies, such as gas, electric and solar water heaters, and heat pumps, both for instantaneous hot water production or including a hot water storage tank.

Besides the water heating appliance, several types of equipment were used to measure and control the system's parameters. Table 1 presents the main equipment used in the VTB prototype. This includes sensors for water and gas flow rates, probes for multi-point water and environment temperature measurement, water pressure sensors, and actuators that allow different hot water consumption regimes to be imposed in an automated and replicable way.

Regarding the dynamic models and their parametrization, these will be quite different due to the complexity and specificity of each system. The software selected for

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modelling and simulation is based on the MATLAB/Simulink platforms and toolboxes from MathWorks.

For the implementation of real-time simulation and HILS, a commercial digital signal processing (DSP) controller board DS1104 from dSPACE was chosen. This controller board supports MathWorks Simulink Coder, so the Simulink models can be easily compiled to C code and optimized for real-time execution on the board. The dSPACE Real-Time interface connects the Matlab, Simulink, and C code generator Simulink Coder with dSPACE real-time system to form an integrated ready-to-use development environment for real-time applications. The dSPACE ControlDesk software is used as an interface with real-time simulation on the DS1104 board, allowing data acquisition, graphic visualization and interaction with model parameters.

For the real discrete controller, implemented in a hardware platform, an Arduino Mega is used as a low-cost controller board, to implement the functionalities of a commercial ECU unit. At present time, the Arduino microcontroller is a popular low-cost and highly portable solution for many engineering problems and research, so it becomes a valuable resource for hardware-in-the-loop applications [31].

The equipment listed in Table 1 were assembled in a structure with the appropriate attachments to support different water heaters. The water connections, with respective instrumentation, assure the adequate supply line and allow the definition of the hot water demand. The necessary electrical connections were implemented for appliances power supply, instrumentation and emulation of sensors signals on HILS mode. For safety reasons, when performing tests with gas water heaters

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a carbon monoxide detector was used to prevent carbon monoxide poisoning. Fig. 2 presents the CAD model of the VTB, and a photo of the VTB prototype and Fig. 3 presents the details of the water pipe connections and some of the used sensors.

3 CASE STUDY

A case study was conducted for the VTB assessment. The residential and commercial instantaneous gas water heater Bosch TGWH Junkers Hydro 4600 F WTD10-4 KME 23 JU was selected. This non-condensation model has 22 kW thermal power, 86% thermal efficiency, 8 L/min maximum water flow rate, a forced-air ventilation system, and a temperature feed-forward control strategy implemented in an ECU.

3.1 Modelling

The central elements of the proposed VTB are mathematical models compatible with real-time simulation, that describe the thermal, fluidic, and mechanical dynamics of the water heater appliances.

The TGWH system is modeled as a lumped model in which each component is implemented as a lumped element. This modelling strategy is widely used in thermal systems, for example in [32,33]. Bond graphs is other popular methodology for modelling thermal systems as a modular collection of reusable sub-models [34,35]. Bond graphs were invented by Paynte [36] and become popular with Karnoop [37].

Previous work [38], based on a different TGWH, was used for the development and parameterization of this appliance model. In the present work, the model has been simplified, with special emphasis on the energy balance equation of the control volume

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that is the heat cell. The heat cell involves the gas burner and the heat transfer to the water in the heat exchanger. In the previous work, the heat cell also includes a second heat exchanger for condensation of the steam in the flue gases. The water and the metal (copper alloy) were assumed to be at the same temperature *T*, and their densities *ρ* are kept constant. The TGWH model is a semi-empirical nonlinear model, the energy balance equation is expressed as:

$$\frac{dT}{dt} = \frac{1}{m_w c_w + m_m c_m}\left(\dot{Q} + \dot{m} c_w (T_{in} - T)\right) \quad (1)$$

Indices *w* and *m* are used for water and metal respectively, and symbols *m* and *c* for mass and specific heat, respectively. The heating power ($\dot{Q}$) is prescribed through the flow of air+gas mixture, controlled by an electrically actuated gas valve and atmospheric or fan-forced air inlet, considering a heating efficiency *η*.

The fluidic component is described by the continuity equation in the form of Eq. (2), where *P* is the water pressure, *β* is the bulk modulus, *V* is the volume of the control volume and $\dot{q}$ is the volumetric water flow rate.

$$\frac{dP}{dt} = \frac{\beta}{V}(\dot{q}_{in} - \dot{q}_{out}) \quad (2)$$

The Reynolds number Re is used to determine the water flow regime. The pressure drop was estimated by using the orifice equation with turbulent flow in inlet of each component. For turbulent flow, the water volumetric flow rate through an orifice is expressed by Eq. (3), where A_0 is the orifice area and C_d the discharge coefficient.

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$$\dot{q} = sign(\Delta P) C_d A_0 \sqrt{\frac{2}{\rho} \Delta P} \quad (3)$$

The heat cell involves processes of greater complexity associated with combustion. As a semi-empirical model has been adopted, it requires parameterization using experimental results to reasonably reproduce the static and dynamic relationships between the water flow rate, the thermal power delivered to the heating cell, and the temperature of the water at the exit of the heat cell.

The time delay (Δt) of changes in the outlet water temperature due to the water flow is determined by the average water velocity; regarding the definition of the water mass flow rate $\dot{m}$, for a circular cross section pipe of radius R_i and length L it is defined as:

$$\Delta t = \frac{L \rho \pi {R_i}^2}{\dot{m}} \quad (4)$$

This time delay depends on the water flow rate. When the system is subjected to fast changes or disturbances on the water flow rate the delays vary accordingly, causing additional difficulties on the temperature controller.

To maintain the model's complexity within the limits required for its implementation in real-time control methodologies, these processes were empirically modelled and parameterized using laboratory experimental data. A time delay for the thermal power delivery (t_{Pdelay}) and water temperature increments at the heat cell inlet (ΔT_{in}) and outlet (ΔT_{out}) were also considered.

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Fig. 4 presents the MATLAB/Simulink implementation of the semi-empirical model for the heat cell.

The model of a two-way proportional flow control valve was used to implement different water flow rates patterns, simulating changes in the hot water user demand. The orifice area of the valve is determined by the spool position *x* and the radius *R* of the circular cross-section water inlet, by means of common trigonometric functions Fig. 5.

$$A = R^2 cos^{-1}\left(\frac{R-x}{R}\right) - (R-x)\sqrt{2Rx - x^2} \quad (5)$$

The fluidic component of the model is defined by the mass conservation equation in the form of Eq. (2) for the control volume of a valve with one inlet and one outlet. Heat losses from the valve to the environment are neglected due to its small surface area. The model for the two-way proportional valve was implemented in MATLAB in a similar way as for the heat cell model.

The complete TGWH model was achieved by connecting the heat cell and valve Simulink blocks, as well as the controller block, which is illustrated in Fig. 6 The connections between the components of the model link their temperatures, pressures, and flow rates. The temperature and pressure values are transported from the upstream heat cell block to the downstream valve block. The outlet flow rate for the heat cell is calculated in the valve block, as a function of the spool position, and is transported to the heat cell block through an input. The controller model defines the

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thermal power to apply, based on the temperature setpoint defined by the user, and on the water inlet and outlet temperatures and flow rate.

3.2 Control strategy

There is a great potential to improve water heaters efficiencies and user comfort by optimizing controllers' performance, and by implementing advanced control strategies [39]. Combined feedforward with feedback control can significantly improve the heating systems' performance over classic feedback PID control, whenever there is a major disturbance that can be assessed before it impacts the process. Combined feedforward feedback techniques are typically used by TGWH manufactures, and so it was selected as the controller strategy for validation of the VTB prototype.

The TGWH appliance implements thermostatic discrete control and safety functions, embedded in an ECU, based on the temperature setpoint defined by the user, feedback by water temperature sensors placed at the inlet and outlet pipes, and influencing the combustion air+gas mixture by actuating the electrically actuated gas valve and air fan.

A model was developed for implementing the combined feedforward feedback thermal power control as schematically represented in Fig. 7.

The feedforward component is based on the heat exchanger energy balance equation, to calculate the predicted power required to heat water from the inlet temperature up to the required setpoint temperature in steady-state conditions, for the measured water flow rate, that is:

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$$\dot{Q}_{FF} = \dot{m}_{in} c_w (T_{set} - T_{in}) \quad (6)$$

For the PID component, the feedback power is calculated based on the measured heat cell outlet water temperature. The PID parameters are empirically adjusted and not fully optimized.

3.3 Model parametrization

To enable the full use of the VTB, the water heater model must be parameterized and validated with experimental data. Since several of the model's parameters are unknown, the initial approach was to use the parameters from another TGWH appliance [38] to parameterize the new model. A Bosch Greentherm T9800 SE 199 water heater, with thermal power of 58.3 kW and thermal efficiency of 99%, was used for that purpose. This appliance has gas modulation, water flow regulation valves (with a water bypass circuit), condensation heat exchanger, burner power segmentation and forced air ventilation. This information and the provided data are summarized in Table 2, which shows the parameters used in the initial simulations. It should be noted that the model used in this case study has a smaller thermal capacity than the one used as a reference for initial parametrization, and it is thus expected that the calibrated model performs with slower dynamics.

Several parameters of the TGWH heat cell model were unidentified, namely the mass of water (m_w) and metal (m_m) for the heat exchanger and the length (L) of the internal pipes. Experimental tests were performed in the VTB to identify the unknown parameters. Based on the energy balance equation, in the form of Eq. (1), and focusing

366 on the constant terms, for simplification these parameters were considered together as
367 one single undetermined term C_1.

$$C_1 = m_w c_w + m_m c_m \tag{7}$$

368 In addition to the unknown dimensional parameters, there are parameters from
369 the empirical model component, namely the time delay for the thermal power delivery
370 (t_{Pdelay}) and water temperature increments at the heat cell inlet (ΔT_{in}) and outlet (ΔT_{out}),
371 which are assumed to be equal.

372 For collecting experimental data in open-loop tests, the thermostatic closed-loop
373 controller was disabled, and constant thermal power was forced by parameterization of
374 the ECU microcontroller. Only routines for limits monitorization remained active for
375 safety reasons.

376 Two types of tests were conducted. Steady-state regime tests were performed
377 for a combination of different constant values of thermal power and hot water flow
378 rate. Transient regime tests were made including fast changes on the water flow rate
379 under constant thermal power.

380 A multi-objective optimization method was implemented for the parameters'
381 estimation, based on the MATLAB *fminsearch* function. The cost function is based on
382 the root mean square error of a vector of experimental and simulated values that are
383 calculated in each iteration for new parameters estimations. A Simulink model of the
384 nonlinear TGWH model was used for obtaining the simulation values.

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$$J = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Tsim_i - Texp_i)^2} \quad (8)$$

Using the optimization method, with experimental and simulated values, it was possible to estimate the parameters of the semi-empirical heat cell model that are presented in Table 3.

As the water heater used in this work is a non-condensing appliance, the temperature increments were found negligible and removed from the model. However, as the appliance used to obtain the initial parameters has a condensation heat exchanger, the temperature increments revealed to be relevant and cannot be ignored.

3.4 Hardware-in-the-loop simulation

The previously described calibrated TGWH model was implemented in Simulink and compiled for real-time simulation in the dSPACE DS1104 board. For performing closed-loop simulation in real-time, the combined feedforward feedback control strategy was also implemented in Simulink and connected to the TGWH model blocks. For the implementation of HILS methodologies, a low-cost Arduino based platform was used for the application of the embedded controller. The Arduino MEGA was selected to replace, in a more realistic way, the microcontroller used in the ECU of commercial TGWH appliances. The ECU implemented in the TGWH used in this work is based on a Renesas 16-bit microcontroller, with approximately 250 ms program cycle time, which

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implies a significant time delay in the controller reaction. The hardware and software implemented for the HILS framework are schematically presented in Fig. 8.

The integration of the water heater model (implemented in the dSPACE board) with the embedded controller (implemented in the Arduino board) was achieved with analogue voltage electric signals. The dSPACE DS1104 controller board is built with the embedded 64-bit MPC8240 processor, a sampling frequency of 1 kHz was used for real time simulations. This board has eight analogue inputs, four with 12 bits and four with 16 bits, with ± 10 V single-ended range and eight 16 bits voltage analogic outputs, also with ± 10 V. For the Arduino, the analogue inputs are in the 0 to 5V range, so not the full range of the dSPACE signals is used, but as the Arduino ADC resolution is only 10-bit, this is not a problem. The Arduino PWM outputs are converted to analogue voltages by using discrete RC low pass filters.

The values for the inlet and outlet water temperatures and water flow rate are sent from the virtual model, as dSPACE output signals, connected to the Arduino inputs. The output of the controller is the thermal power to apply to the system, defined as Arduino output connected to the dSPACE input. The calibration of the electric signals was performed in steady-state for the minimum and maximum input and output values, for compensating RC voltage drop and acquisition errors. The diagnostic of the Arduino program was implemented with serial communication to the PC.

The action control signal is determined in the Arduino embedded program, by implementing the combined feedforward feedback control strategy. First, water temperature and flow rate values are read from the analogue inputs and converted to

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an appropriate scale. Second, mathematical expressions are applied to determine the theoretical and effective thermal power including saturation functions. Third, the thermal power error is determined as the difference between theoretical and effective thermal powers, this error is the PID controller input. The fourth step consists of calculating the PID terms, which are summed and saturation is implemented. Finally, the PID term is added to the result obtained from the theoretical thermal power, saturated, and converted to the scale of the output signal.

4 RESULTS AND DISCUSSION

Following the defined methodology, tests were carried out in the VTB four modes of operation to evaluate its capabilities for the TGWH case study. The experimental and simulated results are presented and discussed in this section.

4.1 Data acquisition and model parameterization

As previously referred, experimental tests were conducted in an open-loop, both in steady and in unsteady regimes, to collect data for the parameterization of the heat cell model. A multi-objective optimization routine was used to obtain the calibrated model. For model validation purposes, a separate set of laboratory tests was performed, to gather experimental data, different from the data used for parameterization purposes. To evaluate the model's performance, several simulations were performed under different scenarios, and the predicted values compared with the measured data.

Steady-state experiments were performed with constant inputs for the inlet temperature, water flow rate and thermal power, and after stabilization, the average

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outlet water temperature was recorded. For a scenario of constant minimum thermal power, without extinguishing the burner, experimental and simulated steady-state outlet water temperatures were recorded for different values of constant water flow rate (Fig. 9). The experimental and simulated results are in very good agreement, with just a small discrepancy for the smaller flow rates.

Fig. 10, presents the comparison between experimental and simulated results for open-loop tests in a scenario of constant water flow rate, and a sequence of fast changes in the applied thermal power (32%, 50% and 100%). The simulation results are in very good agreement, even if overlapping the experimental results in most cases. In what concerns the steady-state values, they are essentially coincident, even if small differences are observed during the transient segments.

The calibrated TGWH model was considered reliable for this work, as the observed differences between simulated and experimental results fall between acceptable limits. A script was used to obtain the steady-state simulated values, for the full range of water flow rate and thermal powers. Fig. 11 presents the simulated outlet water temperature for the combination of inputs. The observable upper plane on the left of Fig. 11 is due to a temperature saturation in the model, with values higher than the safety appliance limits.

4.2 Real-time simulation

After the calibration and validation of the TGWH model is possible to go some steps forward and perform close loop tests with thermostatic control. In this VTB

operating mode, it is possible to perform tunning tasks and evaluation of controller performance by executing the real-time simulation.

One of the disadvantages of instantaneous water heaters is the difficulty to maintain a constant hot water temperature as sudden changes occur in the hot water demand. One way to access the controller's performance is to measure water temperature overshoots and undershoots when the hot water flow rate suddenly changes.

Fig. 12 presents the simulation results for a sequence of fast changes in the hot water flow rate demand. Even though the controller can respond and return to the setpoint temperature after the disturbance, some significant overshoots and undershoots are still noticed, which is a handicap for the user comfort.

4.3 HILS with microcontroller

After tunning the controller parameters, it is possible to implement and assess the control strategy in an embedded controller, in a closer way as implemented in the real ECU microcontroller.

In Fig. 13 is possible to observe the controller performance in the embedded controller, with HILS, versus the real-time simulation, for fast changes on the hot water demand. Both temperature and thermal power are almost perfectly overlapping. A slight discrepancy in the outlet temperature is observed after the 500 s time mark and an almost imperceptible oscillation due to the noise in the acquisition process.

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4.4 Tests with the complete system

After validation of the controller in an embedded environment it is possible to advance to the last VTB operating mode, which corresponds to conduct tests with the complete system. The control strategy and tunning parameters can be integrated into the source code of the appliance ECU. This task needs to be performed and validated by the manufacturer for safety reasons, and to assure that the appliance fully complies with the required standards. For the fourth operating mode of the VTB, tests were performed with the complete real system, without any simulated component, yet without the updated ECU code.

Fig. 14, presents the experimental results for a test of the TGWH a in close loop under a very demanding sequence of fast changes in the hot water flow rate. For smaller water flow changes the observed temperature overshoots and undershoots are acceptable. However, when submitted to a more demanding situation, after the 530 s time mark, the controller is not able of providing suitable temperatures for the user's comfort and becomes unstable after 600 s. The high-water temperatures of 55 °C for a setpoint of 40°C are not acceptable and can even become a safety issue. This is due to the relatively slow dynamics of the heat exchanger, and to the system varying time delays, causing temperature changes on the outlet hot water that depend heavily on the hot water flow rate and on the length of the pipes where it is flowing. The registered data confirm that more research is needed to develop and validate advanced control strategies and support tools, as the proposed VTB, for improved control design and validation.

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5 CONCLUSIONS

The methodology and the virtual test bench presented in this work are important achievements enabling faster development of control strategies for water heaters. To the best of the authors' knowledge, there are no successful implementations of test benches with similar methodology and capabilities for this field in the literature.

A prototype of the VTB was developed and validated, through experimental and simulated tests in four operating modes, using a TGWH as a case study. By applying HILS methodologies, the performance of a combined feedforward feedback control strategy was evaluated in an embedded controller, using both simulation and the real water heater appliance.

Laboratory tests revealed some limitations of the present controller, reinforcing the importance of developing improved controllers. Accurate testing and validation of complex controllers are increasingly important for water heaters manufacturers. The presented concept supported the development and evaluation of new (predictive and adaptive) advanced control strategies for domestic hot water appliances under the scope of the Smart Green Homes project. This platform will be a major factor to shorten the development cycle and allow the development of increased performance controllers.

The proposed VTB also presents a great potential for use in the academic environment, namely in the fields of modelling, simulation and controllers design for thermal systems, as well as in the experimental application of HILS concepts.

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FUNDING

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NOMENCLATURE

A	area
c_p	specific heat
C_1	auxiliar constant for calculation
C_d	discharge coefficient
L	length
m	mass
$\dot{m}$	mass flow rate
P	pressure
$\dot{q}$	volumetric flow rate
$\dot{Q}$	heating power
R	radius
Re	Reynolds number
t	time
T	temperature
V	volume
x	position
β	bulk modulus
ρ	density

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η efficiency

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727 **Figure Captions List**
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Fig. 5 Valve orifice area schematic

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730 **Table Caption List**
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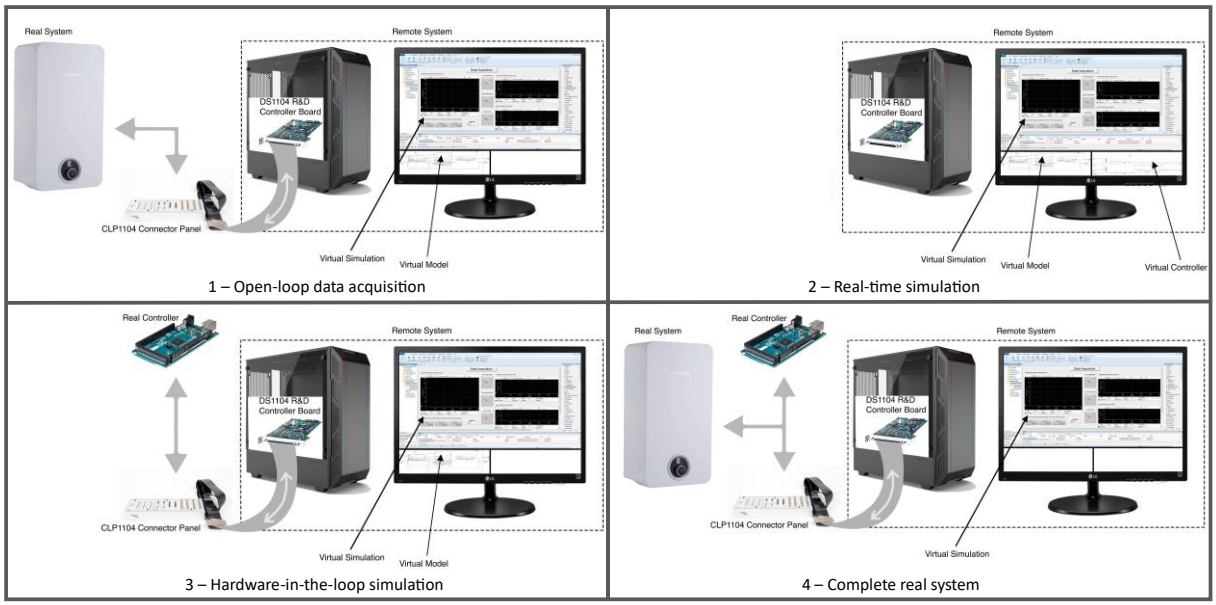

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734 **Fig. 1 Layout of the virtual test bench for the four different operating modes**

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736 **Fig. 2 VTB CAD model and prototype's photo**

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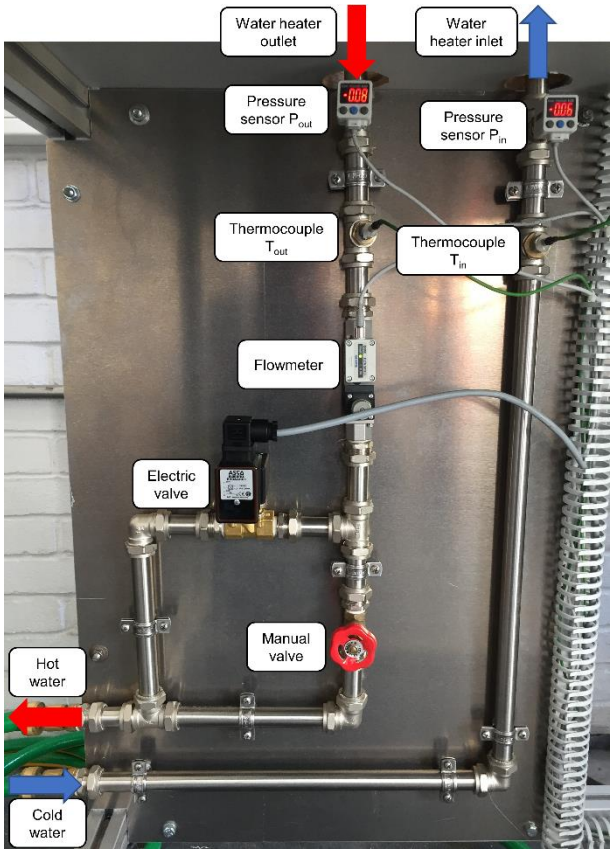
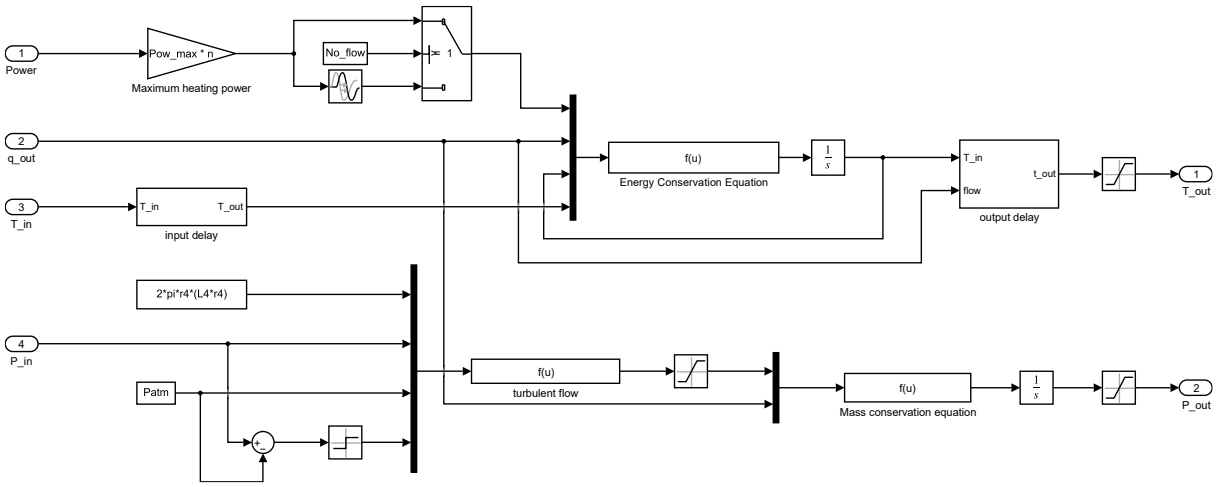


Fig. 3 Details of VTB water connections and sensors



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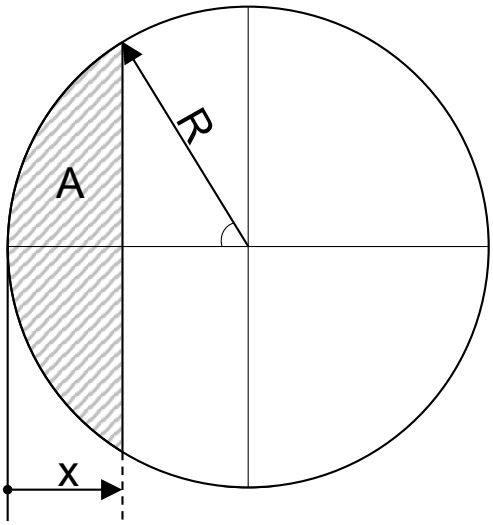
740 **Fig. 4 MATLAB/Simulink model diagram for heat cell**



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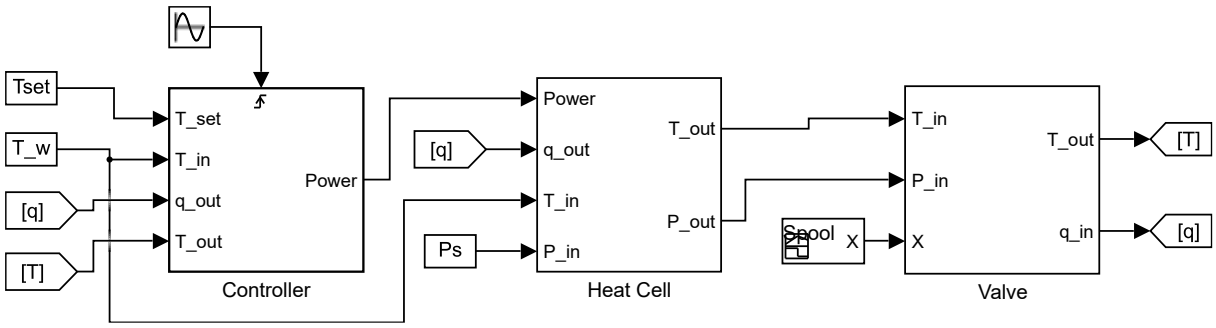
742 **Fig. 5 Valve orifice area schematic**



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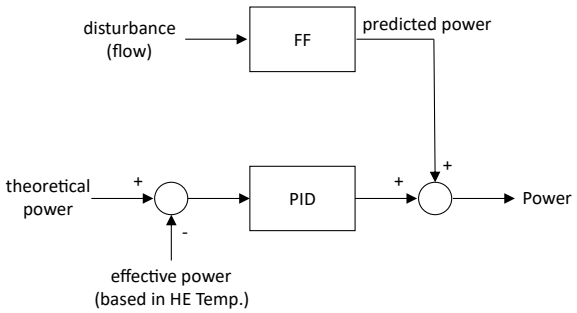
744 **Fig. 6 Simulink model diagram of TGWH**



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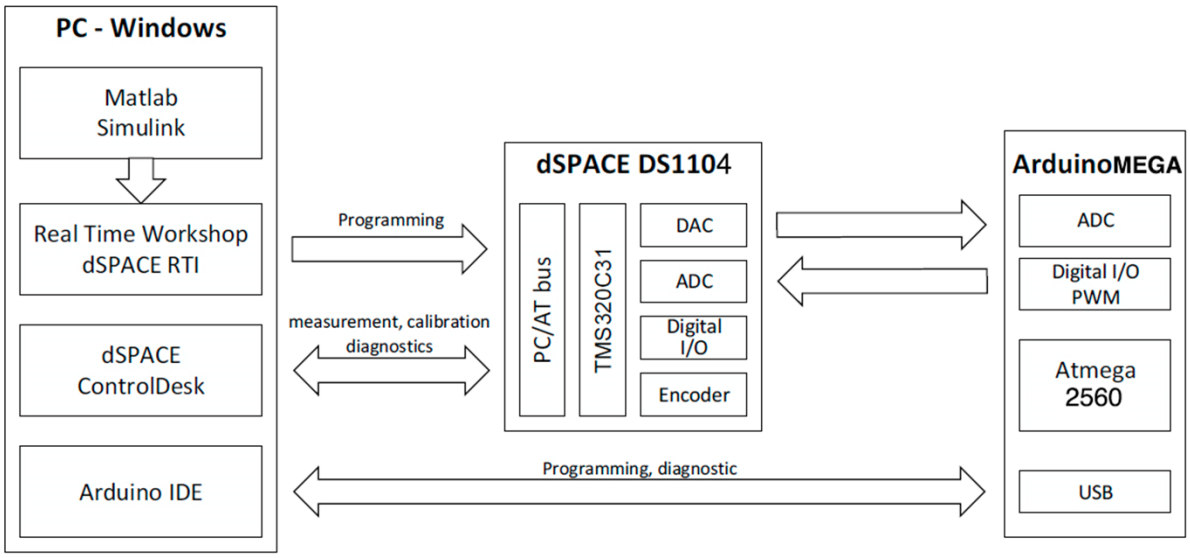
746 **Fig. 7 Schematic of the combined feedforward feedback thermal power controller** [40]



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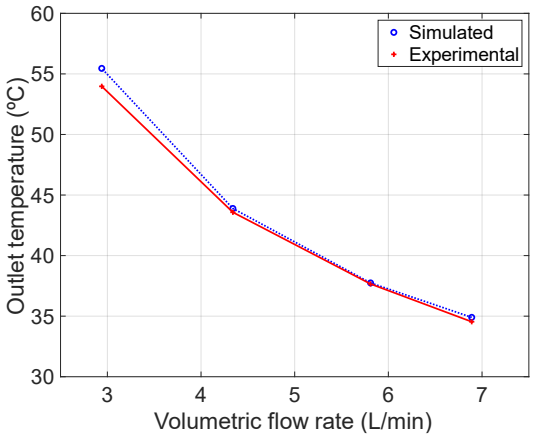
748 **Fig. 8 Hardware and software HILS framework**



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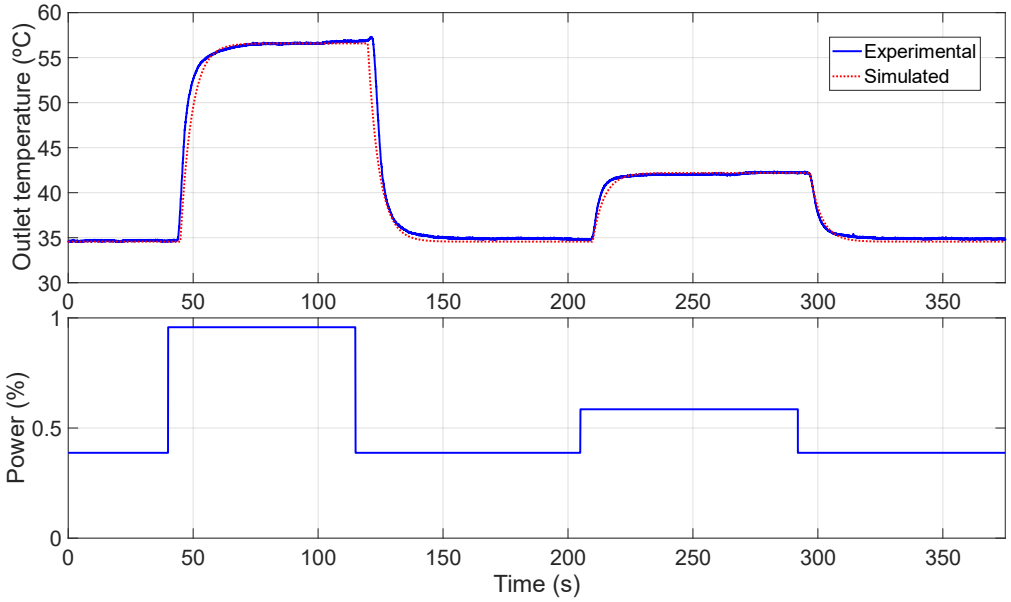
750 **Fig. 9 Experimental and simulated results (water temperature versus flow rate) for**

751 **minimum thermal power**



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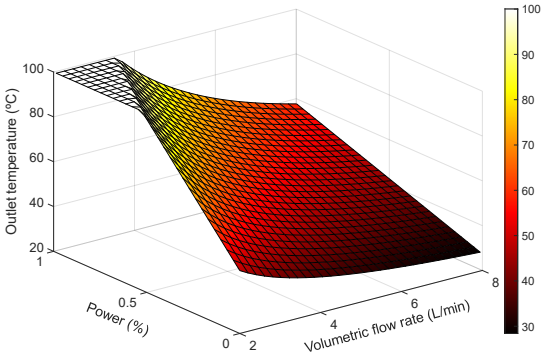
753 **Fig. 10 Experimental and simulated results (water temperature) for a sequence of**

754 **thermal power changes**



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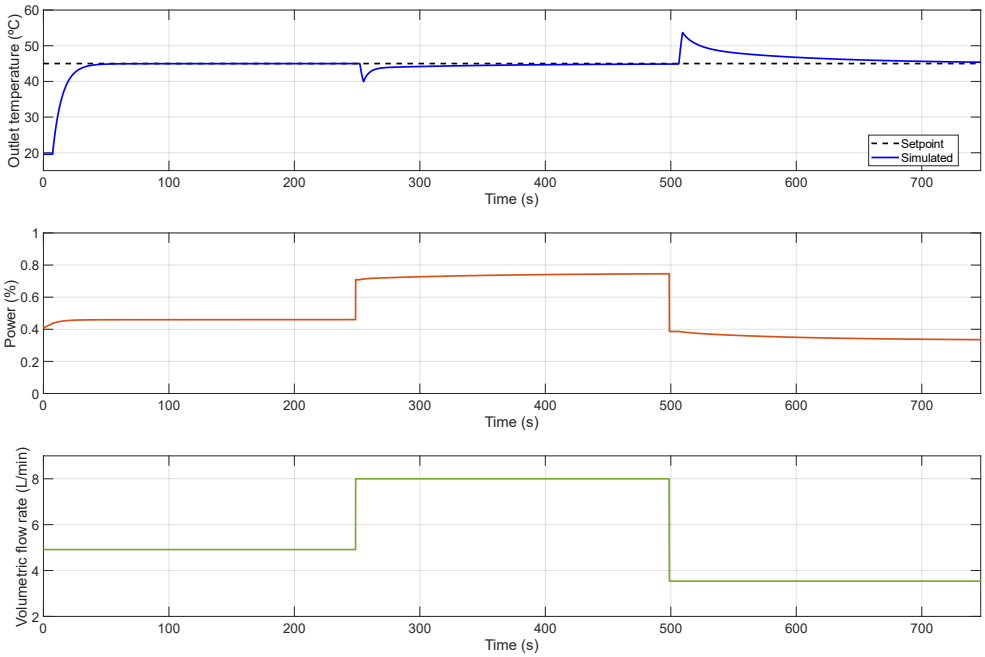
756 **Fig. 11 Simulated results (water temperature, water flow rate and thermal power)**



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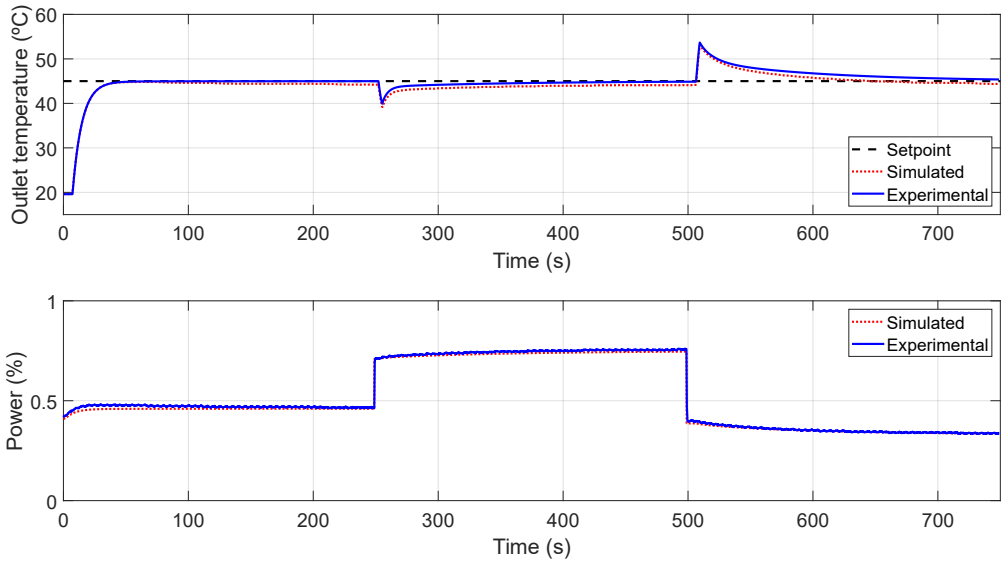
758 **Fig. 12 Closed-loop real-time simulation results**



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760 **Fig. 13 Embedded HILS vs real-time simulation results**

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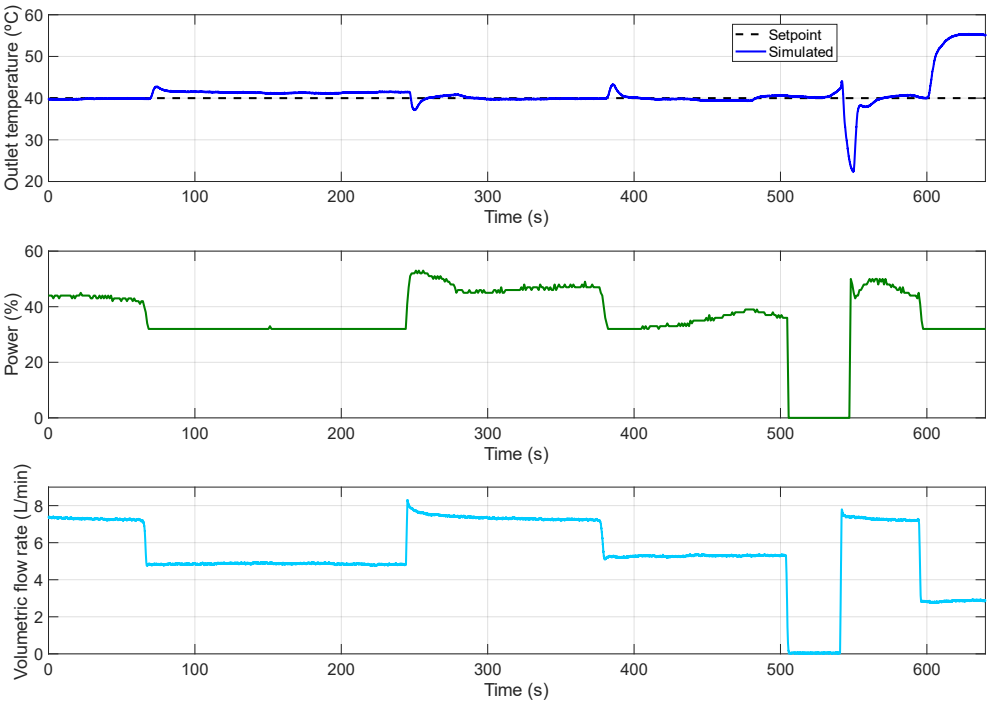

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763 **Fig. 14 TGWH controlled by the ECU implemented in the device experience**

764 **Table 1 Prototype instrumentation equipment**

Quantity	Components	Manufacturer part number
1	Carbon monoxide detector	Honeywell XC100
2	K-type thermocouple, ±2.5 °C	Tekon BT.MiK.1.2.1,5.50.PVC2,5.0
1	RTD PT100 sensor, class A, ±0.35 °C	Tekon BR.Pt1.1C.4.3.100.MFA2.0
2	Pressure sensor, 0-10 bar, ±2,5%	SMC ISE80-F02-T-X501
1	Water flow meter, 2 to 16 L/min, ±0,5%	SMC PF3W740S-F06-EN-M
1	Gas mass flow meter, 0-20 L_n/min, ±0,5%	Bronkhorst F-111AC
1	Proportional solenoid valve	ASCO SCG203B002
1	Manual flow control valve	

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766 **Table 2 TGWH initial parameters** [38]

Section	Parameters	Value
Water circuit	Inlet water temperature	16 °C
	Water supply pressure	$3x10^5$ Pa
	Effective bulk modulus (air+water mixture)	$5x10^8$ Pa
Valve	Orifice radius	$4x10^{-3}$ m
	Discharge coefficient	0.7
Heat cell	Power time delay	2.5 s
	Temperature increment at the input	1.25 °C
	Temperature increment at the output	1.25 °C
	Water mass	2 kg
	Cooper alloy mass	2 kg
	Orifice radius	$8x10^{-3}$ m
	Water circuit length	2.2 m

767

768 **Table 3 TGWH model parameters**

Parameter	Value	Description
C_1	2218.1 J/°C	Auxiliar constant for calculation
ΔT_{in}	0 °C	Inlet temperature increment
ΔT_{out}	0 °C	Outlet temperature increment
t_{Pdelay}	2.9 s	Power delivery time delay
L	2.2 m	Heat exchanger pipe length

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