MODELING AND SIMULATION OF TANKLESS GAS WATER HEATERS TO REDUCE TEMPERATURE OVERSHOOTS AND UNDERSHOOTS

Costa, V.A.F.[1]*, Ferreira, J.A.F.[1], Guilherme, D.C.[2]
*Author for correspondence
[1]Centro de Tecnologia Mecânica e Automação, Departamento de Engenharia Mecânica
Universidade de Aveiro
Campus Universitário de Santiago, 3810-193 Aveiro Portugal
[2]Bosch Termotecnologia
Estrada Nacional 16, km 3,7, Cacia, 3800-533 Aveiro Portugal
E-mail: v.costa@ua.pt

ABSTRACT

The hot water user's comfort perception is severely affected by sudden water temperature changes above a certain magnitude. Sudden temperature changes, with overshoots or undershoots, could occur in hot water systems based on domestic tankless gas water heaters (TGWH). These are mainly due to sudden changes on the overall hot water flow rate demand and to the response delays inherent to the heating system, which cannot be anticipated by the equipment controller.

This work presents the modeling and simulation of a proposed solution to reduce the temperature undershoots or overshoots to small acceptable values, not perceptible by the users. The proposed solution includes a tank acting as a thermal capacitance, a mixing valve to mix the tank and heat cell water flows and a bypass valve, connected to the output, the latter to eliminate the outlet temperature overshoots.

Typical situations originating temperature undershoots and/or overshoots are simulated for validation of the proposed solution, showing that it is able to: a) Substantially reduce the waiting time for hot water in the cold start of the water heater; b) Respond to sudden increases of the hot water flow with only a small acceptable decrease in the outlet water temperature (for hot water flow rates varying from 2 to 14 L/min the temperature undershoots are lower than 0.5 °C); and c) Complete elimination of temperature overshoots for sudden decreases of the hot water flow rate.

INTRODUCTION

Hot water can be produced in many ways, TGWH being usually more efficient than heaters with an associated accumulation reservoir [1]. However, they have their own drawbacks. One of the most relevant drawbacks is the difficulty to control the outlet hot water temperature as changes in hot water flow rate of a domestic water heating system can be very fast and unpredictable, the system has its own thermal inertia, the temperature changes travel at the water flow velocity, and the thermal and fluid dynamics are linked and inherently non-linear.

Several strategies were proposed in the last years, to minimize these undesirable situations. The solution proposals involve: a) Additional hardware components installed in the hot water circuit, such as accumulation reservoirs, recirculation pumps and bypass or mixing valves; and b) Evolution of feedback control strategies of classical PID controllers to more robust ones, such as optimal, predictive or intelligent controllers [2-3].

Even if some studies can be found concerning transient modeling and simulation of TGWH [4-6], mainly using TRNSYS, and the best management practices of TGWH [7], to the authors' best knowledge, there are no published studies on modeling and simulation of TGWH including proposals to reduce the overshoots and undershoots of the outlet hot water temperature, what is the main objective of the present work.

Once set the problem, a solution is proposed to be included in the TGWH, but the effectiveness of the proposed solution needs to be assessed, what is made through modeling and simulation. Semi-empirical time dependent models, including the thermal, mechanical and fluid dynamics issues of the components forming the proposed solution are presented and parameterized using experimental data. The proposed control strategy to drive the components (power delivery to the heat cell, and mixing and bypass valves actuation) is also modeled and simulated to control the simulated model of the whole water heater.

The whole water heater and controller are fully modeled and simulated with Matlab&Simulink platform, using solvers able to deal with the continuous and discrete model equations.

NOMENCLATURE

A	[m^2]	Cross-sectional area
c	[J/(kg.ºC)]	Specific heat
C_d	[-]	Discharge coefficient
g	[m^3/(Pa..s]	Orifice conductance
m	[kg]	Mass
$\dot{m}$	[kg/s]	Mass flow rate
P	[Pa]	Pressure
$\dot{q}$	[m^3/s]	Volumetric flow rate
$\dot{Q}$	[W]	Heating power
t	[s]	Time
T	[ºC]	Temperature
V	[m^3]	Volume

Special characters

α	[K^{-1}]	Volumetric expansion coefficient
β	[Pa]	Bulk modulus
Δ	[ºC; s]	Difference value
η	[-]	Efficiency
ρ	[kg/m^3]	Density

Subscripts

amb	Ambient
c	Cell
in	Inlet
out	Outlet
0	Reference state

THE PROBLEM, AND THE PROPOSED SOLUTION

The outlet temperature dynamics of a TGWH depends on several factors as the inlet water temperature, flow rate, thermal power released to the heat cell, thermal inertia of the system and ducts' lengths, between many others which have smaller contributions to the outlet temperature changes. One critical problem of TGWH appears when sudden hot water flow rate changes occur, which can be essentially due to changes on the number of users demanding hot water, to changes on the hot water flow rete demand of one user, and during the starting periods of hot water production. Even TGWH with feedback control of the outlet hot water temperature are not able to reduce the changes on the outlet temperature to acceptable values when fast hot water flow rate changes occur. This happens due to the relatively slow dynamics of the heat cell, and to the time delays on the outlet hot water temperature changes which strongly depend on the hot water flow rate and on the length of the ducts where it is flowing. The above-described problem can be visualized in Figure 1, which shows the temperature overshoots and undershoots of a 58 kW nominal power TGWH for sudden changes on the hot water flow rate. The controller implemented in this equipment intends to stabilize the outlet hot water temperature as 60ºC but, with the unpredictable changes in the hot water flow rate the temperature overshoots and undershoots achieve magnitudes which are not acceptable and comfortable for the users.

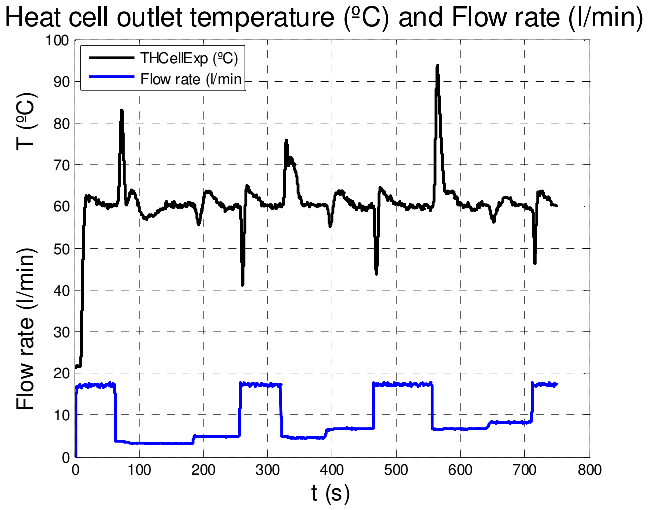

Figure 1 Experimental data of the hot water outlet temperature and flow rate for a heat cell in a TGWH.

Maintaining the basic characteristics of the TGWH, it is proposed to design and develop a new water heater which efficiently solves the temperature undershoot and overshoot problems occurring due to sudden hot water flow rate changes, with acceptable costs and satisfying the user's comfort requirements.

The proposed solution involves the incorporation of other hardware components and a control strategy. Regarding the hardware components, the proposed solution (in Figure 2) includes:

- A motorized three ways bypass valve (x_{by}), to minimize the temperature overshoots by mixing the hot water leaving the heat cell with some cold water coming from the water heater inlet;
- An accumulation reservoir (*Tank*), mounted in parallel with the hot water line, to minimize the outlet temperature undershoots and overshoots (using the inertia and the thermal mixing effect of the water inside it). The tank is mounted in parallel with the hot water line also to: (*i*) Allow the implementation of strategies to reduce: the waiting time for hot water, in the cold start of the water heater; and (*ii*) Reduce the waste water that usually occurs when the hot water faucet is maintained open as the user waits for hot water above an acceptable minimum temperature for use. The tank is used only to avoid undershoots and overshoots on the outlet hot water temperature, and not for hot water (energy) accumulation, and the system continues being considered a TGWH;
- A motorized three ways mixing valve (x_{mix}), to minimize the temperature overshoots and/or promoting the mixture of the outlet hot water leaving the heat cell with the water coming from the *Tank*.

Along with the hardware referred above, a control strategy involving different operation modes is also proposed.

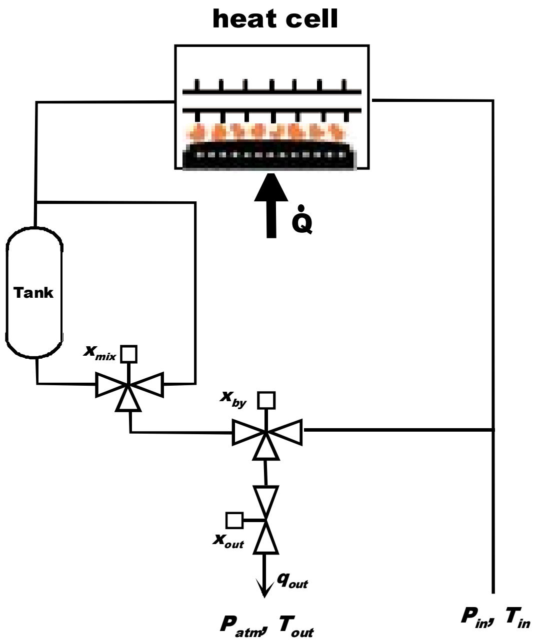

Figure 2 Configuration and connections of the proposed solution.

MODELING

This section presents the models considered to describe the dynamics of flow (pressure and flow rate), mechanical components and temperature. Such models must capture the relevant thermal and fluidic dynamics as they are to be used on the design of feedback controllers.

The system's components are modelled using a lumped space approach, taking the time as the independent variable; the spatial variations, if necessary, are implemented through series assemblies of lumped models.

Considering that water has the effective bulk modulus β, and the volumetric expansion coefficient α, its density is related with pressure and temperature as

$$\rho(P,T) = \rho_0 \left[1 + \frac{1}{\beta}(P - P_0) - \alpha(T - T_0) \right] \qquad (1)$$

Mass conservation equation, in its transient form, can be written as

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

for control volumes of constant volume V, $\dot{q}$ being the water volumetric flow rate, and P is the water pressure inside the control volume.

The volumetric flow rate $\dot{q}$, corresponding to a turbulent flow throughout an orifice, is defined as

$$\dot{q} = sign(\Delta P)\, C_d A_0 \sqrt{2\Delta P/\rho} \qquad (3)$$

where C_d is the discharge coefficient, A_0 is the orifice area, ΔP is the pressure drop between the orifice inlet and outlet, and $sign(\Delta P)$ is the sign of ΔP. If the flow in the orifice is laminar, the relationship between the volume flow rate and the pressure drop is considered to be linear

$$\dot{q} = g\Delta P \qquad (4)$$

where g is the orifice conductance that varies, naturally, with the orifice area.

The fluid dynamic part of the problem is detached from the thermal part by assuming that the variations on the fluid density are neglected in the energy conservation equation.

Setting the energy conservation equation for a control volume, assuming negligible changes on the kinetic and gravitational potential energy, and that the enthalpy changes of water can be expresses as the product of its specific heat by the corresponding temperature changes, leads to

$$mc\frac{dT}{dt} = \dot{Q} + \sum_{in} \dot{m}cT - \sum_{out} \dot{m}cT \qquad (5)$$

For energy conservation formulation purposes, the mass contained in each control volume can be considered constant, and only the time changes in internal energy of the system are relevant, which can be set as $mc(dT/dt)$.

The components of the proposed solution are modeled and implemented separately as Simulink blocks, and connected to achieve the whole circuit shown in Figure 1. Modeled components are: pipe, tank, flow split, mixing valve, bypass valve and output valve.

The heat cell involves complex systems from several domains such as combustion and conduction, convection and radiation heat exchange. A semi-empirical model is used to reduce the model complexity, where some of the dynamics observed in real heat cells (burners + heat exchangers) are described using empirical models. Thus: a) It is assumed a lumped model for the heat cell, by using Equations (2 and 5) for the flow and thermal dynamics b) Time delays are considered for temperature changes at the heat cell output and also for the thermal power delivering; c) Flow rate dependent time delays are considered for the inlet and outlet fluid temperatures of the heat cell; and d) An efficiency in thermal powered delivery to the heat cell is considered.

The thermal power effectively applied to the heat cell is

$$\dot{Q}_{in} = \eta \dot{Q}(t - \Delta t) \qquad (6)$$

where $\eta \le 1$ is the efficiency, Δt represents the time delay between the order to deliver a certain thermal power to the heat cell and its real effect in the water temperature (represents the delays in the information processing, valves actuation, gas circuits, combustions air fan, etc.).

In what concerns the outlet temperature of the heat cell it is evaluated as

$$T_{out} = T(t - \Delta t_c) + \Delta T_{out} \qquad (7)$$

where $\Delta t_c = \pi R_i^2 L_t / |\dot{q}_{in}|$ is the time delay due the flow rate, L_t is the length of the heat exchanger pipe, R_i is the internal pipe radius and ΔT_{out} represents the temperature increment at the heat cell outlet. By its own turn,

$$T_{in} = T_{amb} + \Delta T_{in} \qquad (8)$$

where ΔT_{in} represents the temperature increment at the heat cell inlet.

The heat cell model was parameterized with experimental data. Figure 3 shows the comparison between the experimental temperature data, obtained at the heat cell outlet, and the simulated temperature with the same inputs (flow rate, temperature of the inlet water and thermal power applied in the experimental tests). It can be concluded that the semi-empirical model proposed for the heat cell captures the essential of the heat cell dynamics, namely the magnitude and time instants of the temperature overshoots and undershoots, to be used to simulate the overall proposed solution in the search of temperature overshoots and undershoots minimization to acceptable levels.

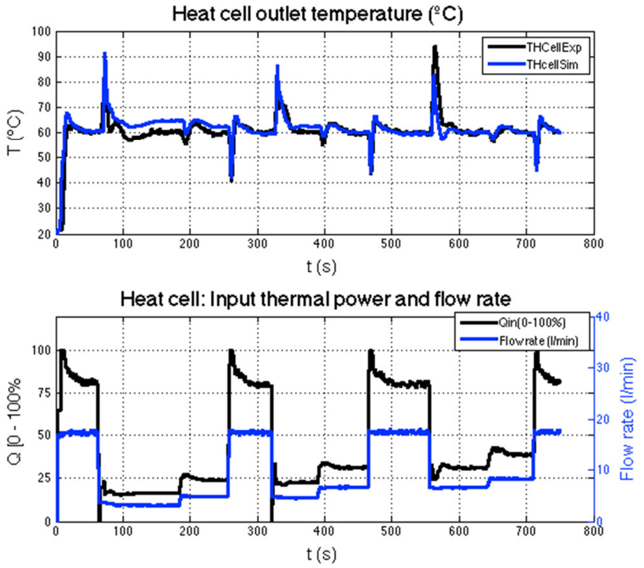

Figure 3 Comparison between experimental and simulated (with the parametrized model) results for the heat cell outlet temperature.

SIMULATION

All the models referred in the Modeling section were implemented in Matlab&Simulink framework from Mathworks. All the models were implemented separately and then connected in accordance with Figure 1. The connection between models transports temperature and pressure values from upstream block to its downstream block. To solve energy and continuity equations in a block the inlet flows are calculated in actual block and outlet flows are calculated in downstream blocks, and then introduced through an input in the current block, as shown in Figure 4.

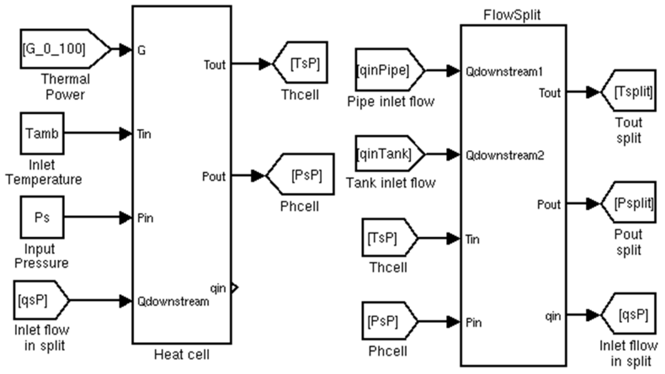

Figure 4 – Heat cell and flow split Simulink blocks, and their connections.

The proposed control strategy implements three operating modes for the TGWH: stop mode, cold start mode and normal operation mode. These modes of operation implement different controllers for the mixing and bypass valves, and for the thermal power calculation to deliver to the heat cell. Figure 5 represents a Grafcet explaining the overall behavior of the implemented controller.

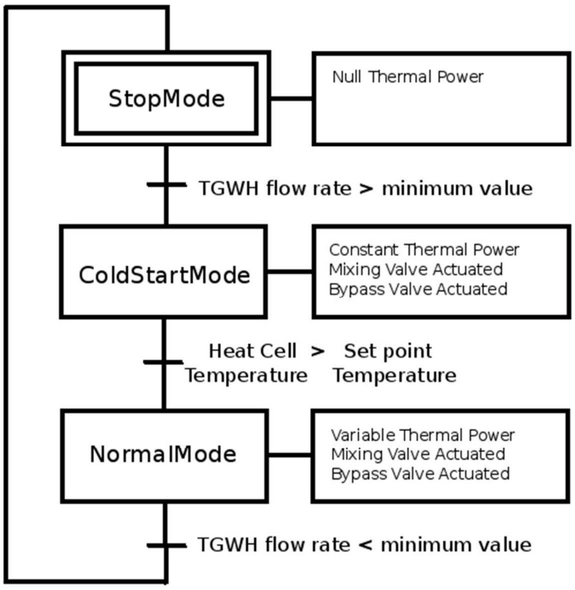

Figure 5 Grafcet for the implementation of the control strategy.

In the first state (StopMode), the controller waits for an event triggered by the TGWH flow rate and the ColdStartMode state is activated.

In the cold start mode, the thermal power delivered to the heat cell may be constant and higher than needed (to reduce the waiting time) until the temperature reaches a value near the set point outlet temperature (mixing valve positioned in the pipe zone). The mixing valve progressively mixes pipe water with water from the tank, until its temperature reaches the set point

In the NormalMode, the thermal power delivered to the heat cell is calculated in accordance with: the inlet water temperature, the temperature at the outlet of the heat cell, the temperature set point, and the water flow rate in the heat cell. The mixing and the bypass valves are actuated to minimize the magnitude of temperature overshoots and undershoots at the output of the TGWH.

Both TGWH and controller models were implemented in Simulink as shown in Figure 6.

RESULTS AND DISCUSSION

Potential, and typical, situations originating temperature undershoots and/or overshoots are simulated for validation of the proposed solution. The output valve, simulating the user´s valve (faucet) for hot water flow rate control, was actuated to set a hot water flow rate pattern ($\dot{q}_{out}$ in the top of Figure 8), thus imposing sudden changes of different magnitudes on the hot water flow rate to the TGWH model. The heat cell input power (Figure 8, middle) was calculated by the controller using a simple feed forward strategy (power is calculated taking in consideration the set point temperature, the inlet temperature and heat cell water flow rate), and a close loop proportional controller to achieve the set point temperature at heat cell outlet. Figure 7 shows the dynamics of temperature, and Figure

8 shows the dynamics of, pressure, flow rate and delivered thermal power variables obtained by simulation of the TGWH and controller models. Time in abscissas of Figures 7 and 8 is the same.

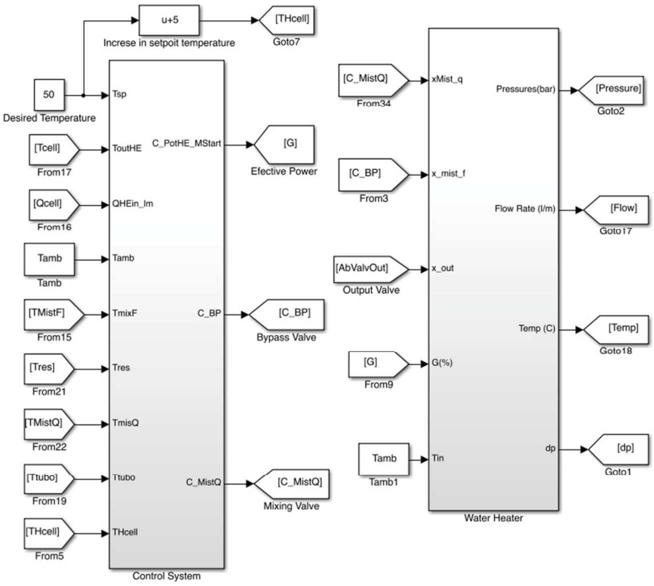

Figure 6 Simulink blocks implementing the models for the proposed solution (controller + TGWH).

The simulation results, and especially the temperature dynamics results in Figure 7, as the outlet hot water temperature is the main variable under analysis, show that the whole proposed solution:

a) Substantially reduces the waiting time for hot water in the cold start of the TGWH. This is because in the ColdStartMode the input thermal power is higher than the one necessary to achieve the set point temperature. In this case, the mixing valve *uses* the cold water inside Tank to avoid temperature overshoots due to such increased input thermal power. Reduction of the waiting time has two positive effects: reduces the time needed to the user to have sufficiently hot water, and promotes water savings, as during the waiting time the hot water is not sufficiently hot, is not used and is directly discharged to the sewage system;

b) Responds to sudden increases on the hot water flow rate with only a minor acceptable decrease on the outlet water temperature (for hot water flow rates changing from 2 to 14 L/min, the temperature undershoot is less than 0.5 °C), thus preventing the occurrence of undesirable undershoots; and

c) Adequately eliminates temperature overshoots for sudden decreases of the hot water flow rate. In Figure 8, top, it can be seen the bypass water flow rate mixed by the bypass valve at time instants with potential conditions for overshoots occurrence. As the heat cell outlet temperature set point is higher than the desired temperature at the TGWH outlet, to reduce the temperature undershoots, the bypass valve is always injecting some cold water to mix with the previously heated water when passing through the heat cell.

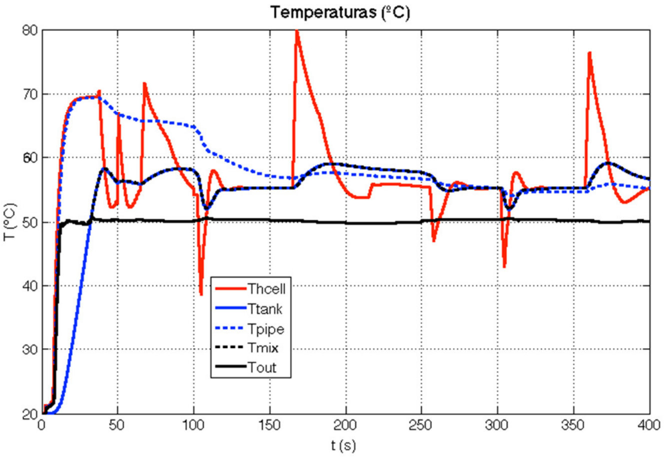

Figure 7 Temperature dynamics: Thcell – temperature at the outlet of heat cell; Ttank – temperature inside the tank; Tpipe – temperature inside the pipe (connected in paralell with the tank); Tmix – temperature at the outlet of mixing valve; Tout – temperature at the outlet of bypass valve (outlet of TGWH).

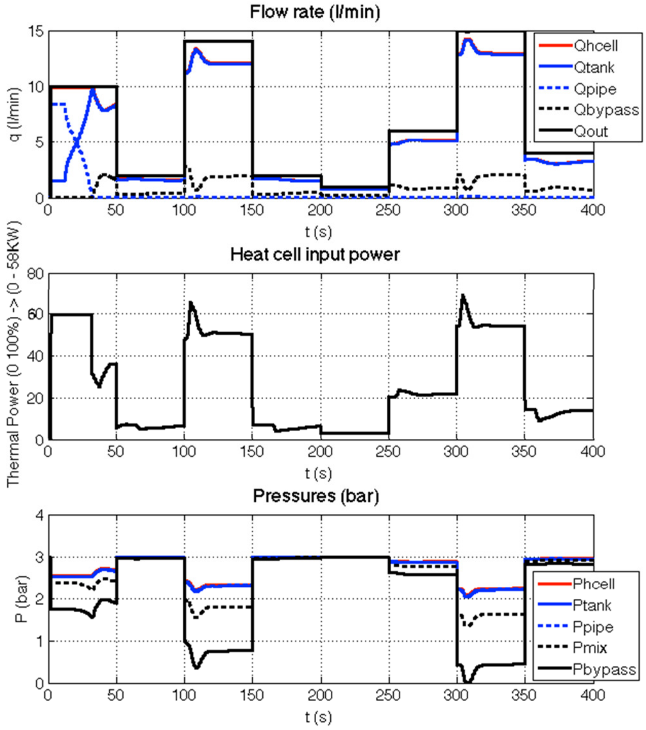

Figure 8 Dynamics of other variables: Flow rates through the components; delivered thermal power; and water pressure.

CONCLUSIONS

The present work proposes a solution to reduce the undesirable temperature overshoots and undershoots occurring in TGWH due to sudden, and unpredictable, changes in the hot water flow rate, to the delay of the gas burner system, to the thermal inertia of the water heater elements, and to the delay of temperature information which travels with the hot water flow velocity.

The proposed solution uses a small tank to serve as a thermal capacitance, connected in parallel with the heat cell output pipe, and two three-way mixing valves to be used as mixing and bypass valves, respectively. The tank, of reduced capacity, is used only to avoid undershoots and overshoots on the outlet hot water temperature, and not for hot water (energy) accumulation, the system continuing being considered a TGWH Together with this hardware increased solution, a control strategy is also proposed. In simple words, the control strategy is the following: a) The water is heated in the heat cell above the desired temperature set point (the increment of heating depends on the tank volume, the estimated maximum undershoot peaks and the permissible undershoots, among other factors); b) The mixing valve is used to reduce the waiting time for hot water and to minimize the undershoots; and c) The bypass valve prevents the temperature overshoots by mixing the hotter water coming from the heat cell with cold water.

The whole proposed solution was modeled and simulated for a set of potential, and typical, situations inducing temperature overshoots and undershoots in TGWH, in order to be assessed given its main purpose. Heat cell was modeled through a semi-empirical model, parametrized using experimental data.

Results show that the whole proposed solution effectively prevents the occurrence of hot water temperature overshoots and overshoots, which are thus maintained within acceptable levels for the users' comfort, even for strong and sudden changes on the hot water flow rate. Additionally, it reduces the waiting time for hot water, thus also reducing wasted water during the waiting period. Future work will include the bypass and mixing valves design, considering information obtained from simulation results, and the experimental validation of the whole proposed solution.

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