Universidade de Aveiro
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Intelligent module to promote water-savings and thermal comfort in domestic water heating equipment

Módulo inteligente para promover a poupança de água e o conforto térmico em equipamentos domésticos de aquecimento de água

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob orientação científica de Jorge Augusto Fernandes Ferreira, Professor Associado do Departamento de Engenharia Mecânica da Universidade de Aveiro, e de Vítor António Ferreira da Costa, Professor Catedrático do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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keywords Thermal systems, water heating devices, tankless gas water heaters, thermal comfort, domestic hot water, dynamic models, modelling, simulation, design, mechanical project

abstract There is a growing concern about to the scarceness of natural resources such as water, which portrait an essential role in domestic water heating applications. Although tankless gas water heaters (TGWH) are widely used, some models present challenges related to sudden and unexpected variations in the demanded hot water flowrate that cannot be anticipated by the equipment controller. These undesired output temperature variations are commonly referred as temperature undershoots and overshoots. Furthermore, there is a high waste of water associated with the long waiting time in cold starts of this household appliance. All of these factors affect the users' thermal comfort. Modern models are already designed and engineered to overcome these problems.

The present dissertation proposes to develop an intelligent module to install in existing or new TGWH devices in order to promote the user thermal comfort as well as promote water savings. The proof of concept of the proposed solution depends on modeling and simulation (in a simulated environment) in order to minimize temperature undershoot and overshoot to values not perceived by users. The mechanical project includes the selection of the components included and the design layout in the proposed solution for an easy to install device.

palavras-chave Sistemas témicos; equipamentos de aquecimento de água; esquentadores; conforto térmico; modelos dinâmicos; modelação; simulação; design; projecto mecânico

resumo

A preocupação com a escassez de recursos naturais como a água tem vido a aumentar, recurso este que protagoniza um papel essencial nos sistemas de aquecimento de água domésticos. Embora os esquentadores de água a gás sem tanque (TGWH) sejam amplamente utilizados, alguns modelos apresentam desafios relacionados com variações repentinas e inesperadas de caudal de água quente, que não podem ser previstas pelo controlador do equipamento. Essas variações indesejadas de temperatura de saída são denominadas de *undershoots* e *overshoots* de temperatura. Além disso, existe um elevado desperdício de água associado ao longo tempo de resposta no arranque a frio. Todos esses fatores afetam o conforto térmico do utilizador. Alguns equipamentos mais modernos foram desenhados de modo a incluir estratégias para melhorar estes aspetos.

A presente dissertação propõe o desenvolvimento de um módulo inteligente para instalação em dispositivos de aquecimento de água novos ou já instalados com o objetivo de promover o conforto térmico do utilizador, bem como a poupança de água associada ao tempo de espera no arranque a frio. A prova de conceito da solução proposta depende da modelação e simulação (em ambiente simulado) procurando minimizar os *undershoots* e *overshoots* de temperatura a valores não perceptíveis pelo utilizador. O projeto mecânico inclui a seleção dos componentes e o layout da solução proposta para um dispositivo de fácil instalação.

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Chapter 1

Introduction

1.1 Motivation

A thermal system is a complex assembly of interacting components to achieve a certain goal, where mass and energy exchanges occur. These systems emerge in various engineering fields such as in energy production, HVAC (Heating, Ventilation and Air Conditioning), water heating, automobile and aerospace engineering. As these areas grow so does the need to design and optimize thermal systems [1].

The design and optimization of a thermal system evolve towards efficiency, regarding the wanted useful effect and the required resources for its operation (e.g. water, gas, electricity).

In the system addressed in this dissertation, water is one of the required resources. According to the "Vulnerability of Portugal to Drought and Scarcity" report from ANP (Portugal Nature Association) and WWF for Nature (Word Wide Fund), Portugal may face a water shortage in a near future. As a consequence, in the Summer, the temperature is predicted to rise 3 °C or 7 °C (depending on the region), a precipitation reduction during Spring, Summer and Autumn, and a major contrast between wet and dry seasons (seasonal duality) [2].

One of the guidelines proposed by the experts is to reduce water consumption and increase water efficiency before that becomes an emergency situation. More specifically, for citizens, they suggest reducing their domestic water consumption permanently and choose to consume low water footprint products and equipment. There are various ways to address this problem. One is to reduce the amount of water wasted while the user is waiting for hot water to reach the faucet. Furthermore, the thermal comfort of the user is affected when there are sudden variations in the requested hot water flow, due to the lack of rapid response by the tankless water heaters. This dissertation intends to develop a low cost solution that helps to mitigate these problems, described in detail in the next section, which can be installed in a new equipment or to be an upgrade of a previous existing equipment.

1.2 Identifying the problem

Domestic hot water is requested on a daily basis for several purposes such as baths, dish-washing or clothes washing. There are distinct means to do so, tankless gas water heaters (TGWH) being more efficient when compared to heaters with an accumulation reservoir [3].

The outlet temperature dynamics of a TGWH depend on several factors as the inlet water temperature, flow rate, thermal power released by the heat cell, thermal inertia of the system and ducts' lengths, among many others which have smaller contributions to the outlet temperature changes. A critical problem of TGWH appears when sudden hot water flow rate changes occur, which can be essentially due to the following reasons: changes in the number of users demanding hot water, changes in the hot water flow rate 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 unable 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 that strongly depend on the hot water flow rate and on the length of the ducts where it is flowing [3]. This problem is referred to as temperature overshoot if the output temperature is higher than the desired one, whereas if the opposite occurs it is referred to as temperature undershoot. Furthermore, another drawback identified in these systems is a significant waste of water associated with the response time during the cold start of the TGWH.

1.3 Objectives

As to answer the common deficiencies that have been identified in domestic water heating devices, this dissertation aims to develop an intelligent module to install in those devices to promote thermal comfort, as well as to promote water savings associated with the waiting time during the cold starts. For that purpose, it is mandatory to research alternative strategies used on the domestic water heating devices industry in order to improve thermal comfort and promote water savings. To achieve these goals, a methodology has been followed: briefly studying thermal systems, proposing different solutions to solve the identified problems and select the most appropriate one. Then, modelling the selected device in a simulated environment (MATLAB/Simulink platform [4]) to prove the concept. Lastly, designing an easy to install device in an existing or new TGWH, based on the previously developed mathematical models for TGWH that, subsequently, will be translated in the device design. The design includes the mechanical, hydraulic, thermal and electric device components.

1.4 Dissertation organization

The present dissertation is organized in 6 chapters, being this section included in the Introduction. In addition, this first chapter contains the motivation, the problem this dissertation tries to answer and the objectives of the proposed work. The fundamental concepts and state of the art, as well as related work, comprise the second chapter. On Chapter 3 is presented the methodology used in the development of models to describe the dynamic behavior of the thermal, fluidic and mechanical components relevant to the study of the device's behavior. The model's implementation in a simulated environment along with the control stratergy are presented on Chapter 4. Chapter 5 includes the study and analysis of different solutions modelled in a simulated environment. Chapter 6 includes the information regarding the device's design, starting from several architectures proposals and selecting the most appropriate ones to solve the TGWH problem. Then, the mechanical design of the device is developed as well as all the hydraulic, thermal and electrical components. The last chapter includes the conclusions and future works.

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Chapter 2

Fundamental concepts and state of the art

The aim of this chapter is to present some fundamental concepts in order to have a better understanding of the developed work. For that purpose, the fundamental concepts that define the development of the dissertation are explained in this chapter. Some solutions to the problem that this work tries to solve are also presented in this chapter. This compilation is not only based on what solutions, products or devices are available on the market, but also on scientific research.

2.1 Thermal systems

A thermal system can be composed by one or more units that interact with each other. For example, a heat exchanger or a heat pump can be represented by a thermal system, as well as more complex arrangements as a blast furnace or a cooling tower. Furthermore, integration is made leading to a complete system, such as a power plant or a manufacturing assembly line. A system can be distinguished by identifying its main characteristics, the components that interact with each other and how the entire entity for analysis and design is considered [1].

The analysis of thermal systems is often complex due to the intricate nature of fluid flow and heat and mass transfer processes occurring in these systems. As a result, typical thermal systems have to be simplified to make it possible to analyze them and therefore obtain the inputs required for the idealized design. Some characteristics as time-dependence, energy losses and irreversibilities, turbulent flow, influence of ambient conditions, complex geometries, multidimensionality, change of phase, material structure, variety of energy sources, coupled transport phenomena, variable material properties, nonlinear mechanisms, and complex boundary conditions are commonly encountered in thermal systems and processes. As a result of the time-dependent, multidimensional nature of typical thermal systems, the governing equations are generally a set of partial differential equations, nonlinearity arising due to momentum transfer, variable properties and radiative heat transfer. However, approximations and idealizations are used to simplify these equations, resulting in a simple set of algebraic and ordinary differential equations that satisfactorily describe many practical situations [1].

2.2 Thermal systems modeling

Modeling is one of the most crucial elements in the design and optimization of thermal systems. Practical systems that involve processes are generally complex and must, therefore, be simplified based on idealizations and approximations to make a problem amenable to solve. Modelling can be described as the process of simplifying a given problem, allowing its representation by a system of equations, for analysis or for experimentation. It is required for understanding and predicting the behavior and characteristics of thermal systems. After a model is set, it is subjected to a variety of operating conditions and design options. If the model is a good representation of the real system under consideration, the outputs obtained from the model satisfactorily characterize the behavior of the specified system [1].

2.3 Related work

It is intended to develop and design a system that efficiently satisfies the comfort conditions of the user both from the energy and cost-efficient points of view. Additionally, solving the problem of temperature undershoots and overshoots when a sudden change of flow occurs, by means of the users action.

On one hand, TGWH have been proved to be usually more efficient when compared with those including an (associated) accumulation reservoir [5]. Additionally, they are smaller, have a longer life time, are capable of providing a continuous stream of heated water, and do not present the energy associated to hot water storage, known as standby losses [6].

As explained in the previous chapter, more precisely in Section 1.2, TGWH present some disadvantages regarding temperature undershoot or overshoot when sudden flow changes occur. These effects arise due to the lack of a fast response of the implemented system. After an extensive research of a solution for this problem, some approaches where found.

The difficulty to control the outlet temperature regarding the comfort and safety of the user has been reviewed by some authors. Among them, Henze [6] points out the traditional approach to control TWH based on PI or PID feedback control, in which the manipulated variable (in this case the control output) is adjusted in response to the error sensed by the outlet temperature sensor. In addition, several patents have been filled concerning alternative strategies to improve the control of the TWH device's, including heating a number of chambers connected in series separately [7], including a small water tank to add thermal capacitance to the system [8], and using an adaptive fuzzy control [9]. In 2006, Kubik [10] proposed an approach of mixing heated water with cold water. The system heats cold water in a heat exchanger to produce overheated water. Furthermore, a blending valve is used to mix the overheated and the cold waters to obtain the required temperature.

Concerning the operating modes, previously developed work only addressed control strategies like adaptive control, robust control, and model predictive control (MPC) [6].

In order to ensure thermal comfort, some companies (like WATTS) propose a digital water mixing system, that can be integrated into a building automation system to allow facilities' managers to remotely monitor and control water temperatures. Although this seems to be a good solution, it is appropriate to commercial and institutional facilities, but not to be implemented in domestic water heating devices. Despite all the efforts made (both at the scientific level and available on the market) an ideal solution is yet to be found.

Costa et al. [3] proposed a solution to reduce temperature overshoots and undershoots that occur 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, as the temperature changes travel at the hot water flow velocity. That solution allows the reduction of temperature overshoots and undershoots to small acceptable values, not perceptible by the users. Besides the implemented control strategy, this solution includes a small tank, a motorized three way mixing valve and a motorized three way bypass valve. Figure 2.1 shows the configuration of that proposed solution [3].

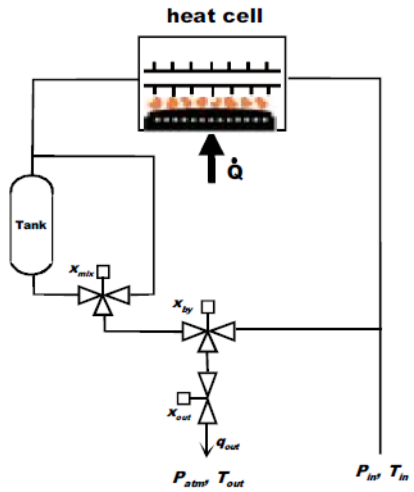

Figure 2.1: Configuration of the proposed solution by Costa et al. [3]

The small tank serves as a thermal capacitance, connected in parallel with the heat cell output pipe to minimize the outlet temperature undershoots and overshoots. This type of setup allows the implementation of strategies to reduce the waiting time for hot water (in the cold start of the water heater) and reduce the water waste (while the faucet is open as the user waits for hot water above a minimum temperature for use). This small tank, is only used to avoid undershoots and overshoots on the outlet hot water temperature and not for hot water accumulation and for use, thus the system continues to be considered a TGWH. Both motorized three way mixing and bypass valves attempt to minimize the temperature overshoots and undershoot. The mixing valve promotes the mixture of the outlet hot water from the heat cell with the water coming from the small tank essentially for preventing undershoots. The bypass valve mixes the heated water with some cold water coming from the water heater inlet, thus preventing overshoots. Regarding the implemented control strategy, in a simplified way, the water is heated in the heat cell above the desired temperature set point (this temperature increment depends on the tank volume, the estimated maximum undershoot peaks and the permissible undershoots, among other factors). The mixing valve is used to reduce the waiting time for hot water and to minimize undershoots. The bypass valve prevents the temperature overshoots by mixing the overheated water coming from the heat cell with cold main water.

The proposed solution was simulated and proved to be able to:

- Substantially reduce the waiting time for hot water in the cold start of the TGWH;
- Respond to sudden increases on the hot water flow rate with only a small acceptable decrease on the outlet hot water temperature (for hot water flow rates suddenly changing from 2 to 14 L/min the temperature undershoots are lower than 0.5 °C);
- Complete elimination of temperature overshoots for sudden decreases on the hot water flow rate.

This proposal is very consistent and presents a good solution to the identified problem. Despite being a more complex system, when compared with other proposals listed above, this one stands out for allowing to solve efficiently several problems simultaneously. This work aims to propose a solution with essentially the same features as the solution proposed by Costa et al. [3], set in a form of a kit, allowing its ease integration in both existing and new TGWH.

Chapter 3

Modeling the dynamic behavior of the TGWH

The aim of this chapter is to present the methodology used in the development of models to describe the dynamic behavior of the thermal, fluidic and mechanical components in order to study the device behavior regarding its thermal and fluidic aspects.

In a first stage, it is necessary to simplify the model expressed in the form of an equations' system. Then, the resulting models are used to predict the dynamic behavior for each main component of the system.

3.1 Thermal components modeling

Regarding the thermal components, the system must be modeled using its energy analysis. This is made based on both mass and energy balance equations for each unit [3]. The general mass conservation equation is

$$\frac{d\dot{m}_{cv}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}, \tag{3.1}$$

where m_{cv} is the mass in every instant inside the control volume coinciding with the system. In this specific analysis, the mass contained in each module is constant.

The general equation for energy conservation is

$$\frac{dE_{cv}}{dt} = \dot{Q} + \dot{W}_{cv} + \sum_{in} \dot{m}(h + \frac{1}{2}V^2 + gz) - \sum_{out} \dot{m}(h + \frac{1}{2}V^2 + gz), \tag{3.2}$$

where E_{cv} is the energy inside the control volume coinciding with the system in every instant, evaluated as the sum of the different forms of energy (internal energy, kinetic energy and gravitational potential energy among others), that is, $E = U + 1/2mV^2 + mgz + m(...)$. The terms of the previous equation related with kinetic energy and gravitational potential energy can be neglected, while the specific enthalpy can be taken as depending only on the temperature. The term relating to work transfer, $\dot{W}_{cv}$, is zero for the case in question. Thus, the energy balance equation can be rewritten as

$$mc_p\frac{dT}{dt} = \dot{Q} + \dot{W}_{cv} + \sum_{in}\dot{m}c_pT - \sum_{out}\dot{m}c_pT. \tag{3.3}$$

Shown on Figure 3.1 is the schematics of the model used for a preliminary analysis. Applying the energy conservation equation to the heating cell, it gives

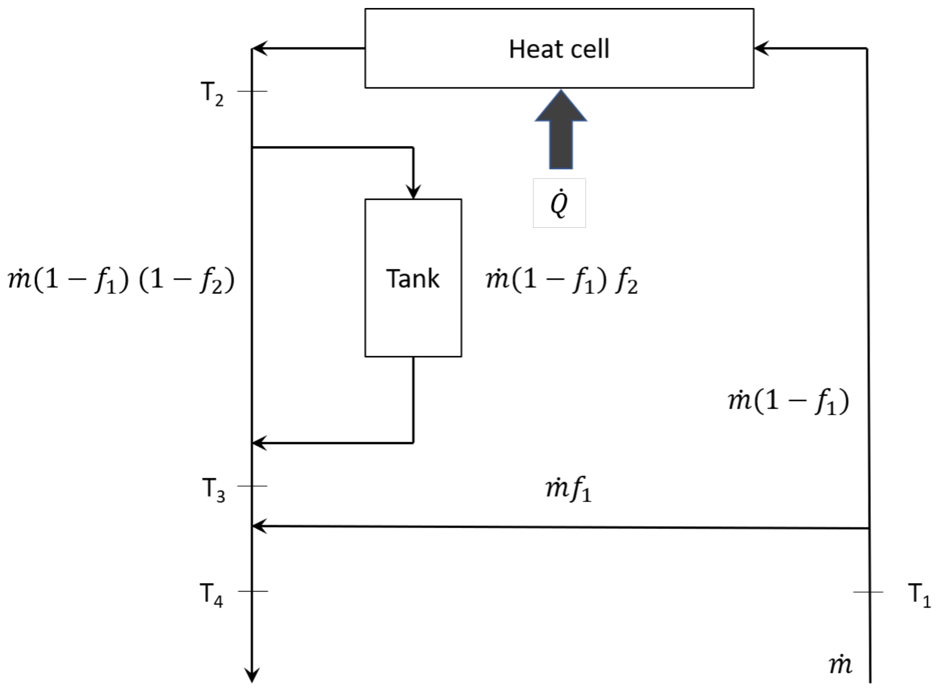

Figure 3.1: Preliminary schematics of the model

$$\left(m_ac_{P,a} + m_mc_{P,m}\right)\frac{dT_2}{dt} = \dot{G} + \dot{m}(1-f_1)c_{p,a}(T_1 - T_2), \tag{3.4}$$

joining together the thermal capacities of water and metal,

$$m_cc_{P,c}\frac{dT_2}{dt} = \dot{G} + \dot{m}(1-f_1)c_{p,a}(T_1 - T_2). \tag{3.5}$$

Energy conservation equation for the tank, assuming that the water is perfectly mixed in its interior, that is, has an uniform temperature at each instant,

$$\left(m_ac_{P,a} + m_mc_{P,m}\right)\frac{dT_r}{dt} = -UA_s(T_r - T_{amb}) + \dot{m}(1-f_1)f_2c_{P,a}(T_2 - T_r). \tag{3.6}$$

The spacial variation of the water temperature is considered through the connections between different modules, and is characterized by the specific conditions of each connection, while each module is treated through with a concentrated parameters approach.

A time delay between different modules need to be taken in consideration as temperature changes travel with the flow velocity along the ducts connecting the system components. In the heating cell, the output temperature delay depends on the sum of two therms. The first one is constant and relies to the heating cell. The second term depends on the water velocity within the pipes of the heating cell as well as of their lengths. Considering $\dot{m}(1 - f_1)$ as the mass flow rate in the heating cell, the time delay associated with the water velocity can be calculated as

$$\Delta t = \frac{L}{V} = \frac{L\rho A_c}{\dot{m}(1 - f_1)}. \tag{3.7}$$

The pipe length connecting two consecutive modules is L and A_c as the cross-section area of the connecting pipe. The previous equation can be generalized for the connection between two consecutive modules as

$$\Delta t = \frac{L\rho A_c}{\dot{m}}. \tag{3.8}$$

Regarding the schematics of the pipe module as shown in Figure 3.2, it allows the simplification of its mass and energy balance equations. Even so, the pipe modules are assumed to be perfectly thermally insulated, that is, no relevant heat losses occur from the pipe modules.

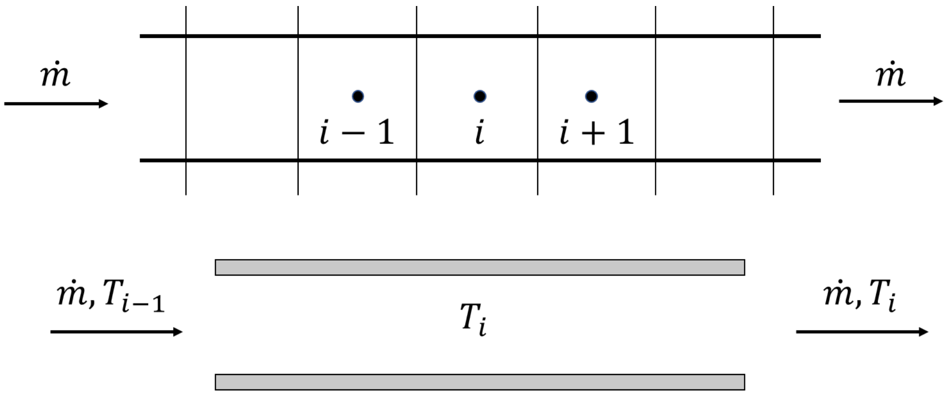

Figure 3.2: Schematics of the pipe module

The energy conservation equation applied to the section of pipe in Figure 3.2 gives:

$$\pi L_i \left[\rho R_i^2 c_{p,a} + \rho_m \left(R_e^2 - R_i^2 \right) c_{P,m} \left(1 - \frac{U_i}{h_i} \right) \right] \frac{dT_i}{dt} = -2\pi R_i L_i U_i (T_i - T_{amb}) + \dot{m} c_{P,a} (T_{i-1} - T_i). \tag{3.9}$$

The overall heat transfer coefficient referred to the inner area of the pipe module is calculated as

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{R_i}{k_m} \ln \frac{R_e}{R_i} + \frac{R_i}{R_e} \frac{1}{h_e}}. \tag{3.10}$$

The heat transfer by external convection coefficient, h_e, can be taken as constant, and assume a value close to 5 W/(m^2 °C). The internal convection heat transfer coefficient,

h_i, is calculated as depending on the water flow inside the pipe. This starts calculating the flow Reynolds number as

$$Re_i = \frac{\rho V D_i}{\mu} = \frac{2\dot{m}}{\pi R_i \mu}. \tag{3.11}$$

If $Re_i <\approx 3000$ the fluid flows in laminar regime and $Nu_i = 3.660$; (assuming that a uniform heat flux condition exists at the tube wall).

If $Re_i >\approx 3000$ the fluid flows in turbulent regime, and the Nusselt number is calculated as

$$Nu_i = \frac{\left(\frac{f}{8}\right)(Re_i - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5} \times (Pr^{2/3} - 1)}. \tag{3.12}$$

where the friction factor is evaluated as $f = (0.79 \ln Re_i - 1.64)^{-2}$.

Once known the Nusselt number, Nu_i, the internal convection heat transfer coefficient is calculated as

$$h_i = \frac{kNu_i}{D_i}. \tag{3.13}$$

A preliminary analysis has shown that the cooling of water when traveling through the pipes, due to heat exchange between the pipes and the outside environment, is not relevant, even if the water flow rates are low.

3.2 Fluidic component modeling

From the mass conservation equation 3.1, assuming the linearized equation of a fluid, that expresses its density as depending linearly on pressure and temperature,

$$\rho(P,T) = \rho_0\left(1 + \frac{1}{\beta_e}(P - P_0) - \alpha(T - T_0)\right) \tag{3.14}$$

where $m = \rho V$, α is the volumetric thermal expansion coefficient, β_e is the effective compressibility module and V as the volume.

Assuming that the effects of compressibility on the specific volume are much more significant than those of temperature, it is:

$$\rho(P) = \rho_0\left(1 + \frac{1}{\beta_e}(P - P_0)\right). \tag{3.15}$$

Thus, the mass conservation equation 3.1 can be rewritten to obtain the continuity equation that applies to the fluidic component of the problem:

$$\sum_{in} q - \sum_{out} q = \frac{dV}{dt} + \frac{V}{\beta_e}\frac{dP}{dt} \tag{3.16}$$

where q is the volumetric flow rate, V the volume of the control volume and P the pressure inside the control volume.

Equation 3.16 can be further simplified to the case of no volume change of the control volume to:

$$\sum_{in} q - \sum_{out} q = \frac{V}{\beta_e}\frac{dP}{dt}. \quad (3.17)$$

The Reynolds number is used to determine if the water flows in a laminar or a turbulent regime. For a turbulent flow, the volumetric flow rate through an orifice can be expressed as:

$$q = sign(\Delta P) C_d A_0 \sqrt{\frac{2}{\rho}|\Delta P|} \quad (3.18)$$

where C_d is the discharge coefficient, A_0 is the orifice area, ΔP is the pressure difference between the inlet and outlet of the orifice, $sign(\Delta P)$ is the signal of ΔP and ρ is the fluid density.

For a laminar flow, the following expression can be used to express the volumetric flow rate as a linear function of the pressure difference through the orifice:

$$q = g\Delta P \quad (3.19)$$

where g is the conductance of the orifice which, as expected, varies with the orifice cross section.

Thus, to determine the pressure evolution within a given control volume, as well as to determine the volume flow rates entering and leaving the control volume, Equations (3.16) to (3.19) are used. In this model it is considered that the head pressure losses are located in the orifices and that the pressure evolution in the control volume is determined by the continuity Equations (3.17) to (3.18).

3.3 Configuration proposals

The first proposal represents the simplest one and includes a bypass valve. This motorized two way valve mixes the cold water and the overheated water that comes from the heat cell. A control strategy is implemented to control the power of the heating cell along with temperature sensors placed in strategic places. This structure allows to eliminate the temperature overshoots when a sudden decrease of hot water flow rate occurs. However, the temperature undershoot situations are not accounted for, neither is the waiting time for hot water in the cold start of the water heater.

On one hand, this system has the advantage of being simple, consisting of a bypass valve and three temperature sensors, the arrangement shown in Figure 3.3. On the other hand, as mentioned before, this proposal is unable to satisfy all the requirements to solve the TGWH problem.

This type of configuration is commonly adopted as a solution in the context of the hotel industry given the high water flow rate required throughout the establishment. As such this configuration is not suitable for domestic water heating applications.

In order to eliminate the water waste while waiting for hot water, proposal 2 is based on a recirculating pump, as shown in Figure 3.4. Until the temperature in sensor T is equal to the desired temperature, the pump recirculates the output water from the heat cell to the inlet of the equipment. In the meantime, although the faucet is opened for hot water usage, the user has no access to water (or has access just to a very little flow

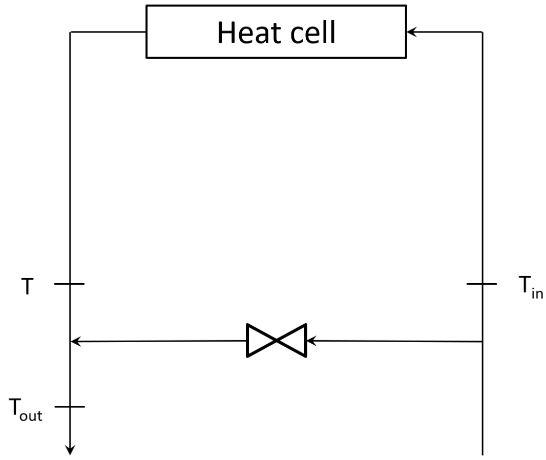

Figure 3.3: Configuration proposal 1

rate), and this valuable resource is not wasted. The waiting time is the same as if the system would be without the recirculating pump. Also, the temperature overshoots and undershoots are also unaccounted for. Furthermore, the amount of energy required to keep the water circulating represents another disadvantage of this configuration. Low complexity is one of the main advantages of this architecture.

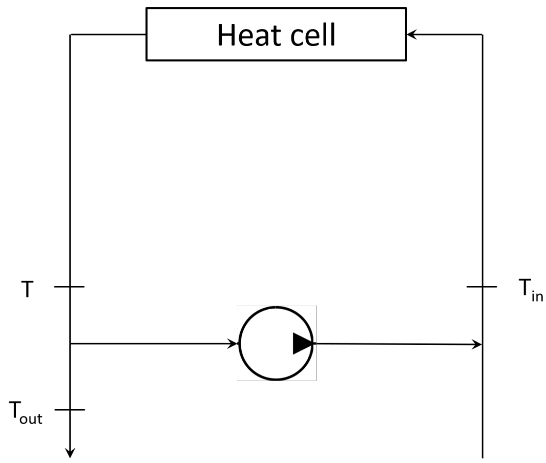

Figure 3.4: Configuration proposal 2

With the equivalent level of complexity, the third proposal is equipped with a small tank as shown in Figure 3.5. Serving as a thermal capacitance, the low capacity tank allows to decrease the temperature undershoots once the temperature of the water inside the tank is equal to the desired one. Otherwise, like in cold starts of the TGWH, the system is not capable of reducing temperature undershoots or overshoots by temperature. When a sudden change in the water flow occurs, the system may be unable to decrease temperature undershoots, depending if is in a cold start or not. The waiting time for hot water in cold starts of the TGWH is higher when compared with the situation where the small tank is absent. This architecture is by far the least effective when trying to overcome the identified problems. The disadvantages overcome the advantages because while simple, the proposed configuration does not solve all the problems identified in Section 1.2.

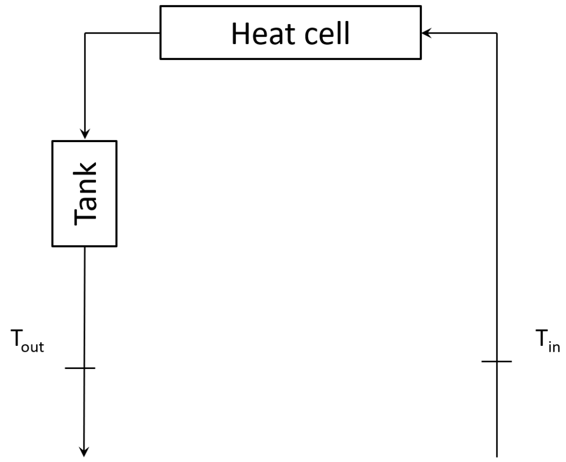

Figure 3.5: Configuration proposal 3

The previous architecture reveals a significant disadvantage regarding the waiting time for hot water and the water wasted during this period. In order to improve this aspect, in the architecture proposal 4 the tank is assembled in parallel with the outlet pipe from the heat cell. In the cold start of the TGWH, the overheated water from the heat cell flowing in the outlet tube is mixed in a mixing valve with the cold water from the small tank. This arrangement allows reducing the temperature overshoot as the water is being mixed to the desired temperature. Simultaneously, the tank is filled with overheated water and then serves as a thermal capacitance. After a period of time, the tank is capable of reducing the temperature undershoots as well as the waiting time. However, the waiting time for hot water is the same as if the TGWH would stand alone in cold starts. The temperature overshoot is only managed in cold starts of the TGWH. After the cold start and once the system has stabilized, this configuration is not able to control it. Because of the thermal capacitance granted from the small tank, the system can respond to a sudden increase of hot water flow but if there is a decrease this architecture has an inadequate response. The complexity of this proposal is higher than the previous ones, because apart from the temperature sensors it requires a small tank and a three-way valve. From the problems listed in Section 1.2 the temperature overshoots is the only situation this configuration does not solve.

Since the first proposal presents an effective strategy to answer the problem of temperature overshoot and the fourth proposal allow to solve the remaining deficiencies that have been identified in the majority of TGWHs, proposal 5 represents a combination of both.

With this configuration temperature overshoots may be eliminated as the bypass valve combines the overheated water from the heat cell with cold water from the main inlet to the desired temperature. When the small tank is filled with hot water, it acts like a thermal capacitance, allowing elimination of the outlet water temperature undershoots. In cold starts of the TGWH, the cold water inside the tank is mixed with the overheated water from the heat cell, thus eliminating the temperature overshoot. The waiting time for hot water and consequent waste of water can only be minimized if

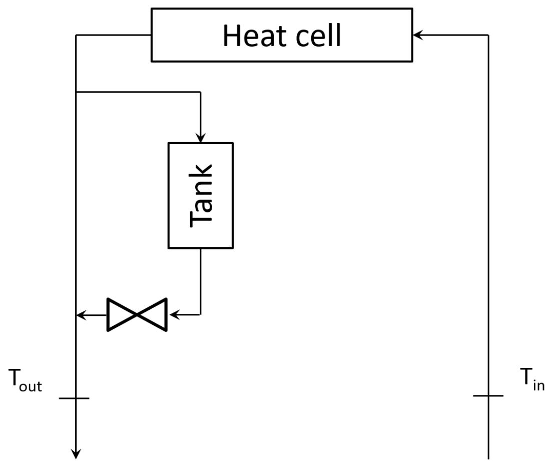

Figure 3.6: Configuration proposal 4

the tank water temperature is similar to the desired one. In addition, this configuration adequately provides a response to a sudden water flow increase. Therefore, this configuration proposal allows solving the problems presented in Section 1.2 effectively. However, it is more complex as it requires more components, in addition to an adequate control system.

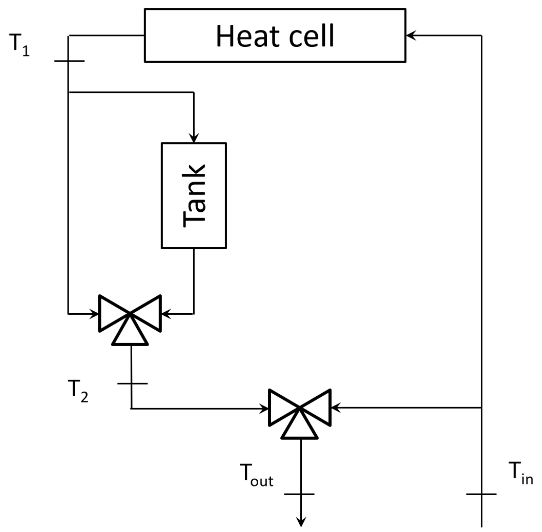

Figure 3.7: Configuration proposal 5

As shown in Figure 3.8, proposal 6 resembles the previous one (proposal 5) with the addition of a recirculation pump. Accordingly, temperature overshoots and undershoots are eliminated because of the configuration provided by the bypass valve, the mixing valve and the small tank. Additionally, it responds within acceptable range of temperatures when sudden increases of hot water flow occur. In cold starts, until the outlet temperature is at the desired level, the pump recirculates the water to the input of the heat cell. Consequently, saving water that otherwise would be waste. With this configuration, the water inside the tank is always at the desired temperature, almost completely eliminating the waiting time.

This configuration allows answering all the problems stated in Section 1.2. However, the user may not have access to water when the faucet is opened for a short period of time. In addition, this proposal is the most complex, needs more components, requires additional energy to drive the pump, and a more robust control system. All these aspects lead to an increased cost of the device.

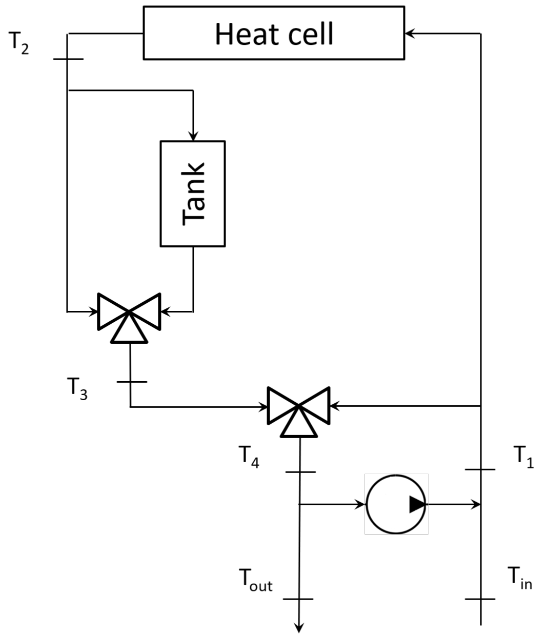

Figure 3.8: Configuration proposal 6

A three-way proportional solenoid mixing valve is more complex and therefore more expensive than a two-way proportional solenoid valve. For that reason, layout proposal 7 resembles the configuration of proposal 5; however, three 2-way proportional solenoid valves are required besides the temperature sensors and the small tank. These simpler 2-way valves are strategically located in order to control the water flow the same way as the 3-way proportional valves would. The design of the last intersection of pipes allows water at different temperatures to mix as a mixing valve would. As shown in Figure 3.9, the location of the temperature sensors allows to monitor the behavior of the proportional valves to achieve the desired output temperature.

Due to the layout similarities to proposal 5, this proposal presents the same advantages regarding the thermal comfort. It enables the device to eliminate the temperature overshoots and undershoots, reduces the waiting time, therefore minimizing water waste. Furthermore, the cost of the 2-way proportional solenoid valves is lower than the similar more complex 3-way bypass valves, consequently lowering the overall cost of the device.

After assessing the advantages and disadvantages of each configuration proposal, some have proven to be more effective in solving the problems identified in Section 1.2. Those configurations will be implemented and analysed in a simulated environment in order for the most suitable layout configuration to be identified.

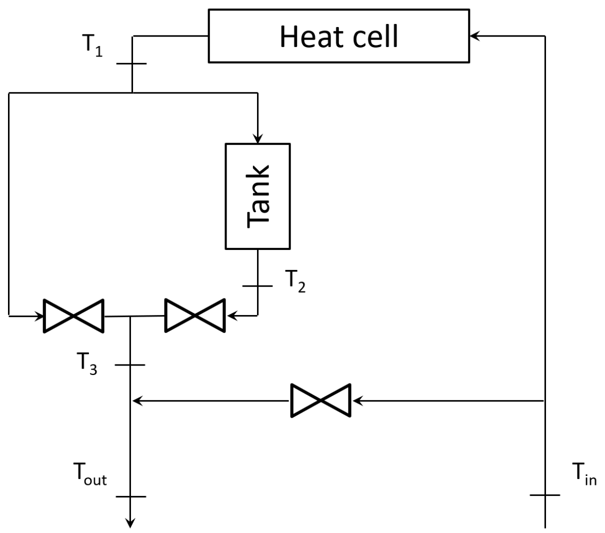

Figure 3.9: Configuration proposal 7

Chapter 4

Models' implementation

The purpose of this chapter is to analyze the models selected from the previous section in a simulated environment. For this purpose, the Matlab/Simulink platform [4] was used. These simulations help the decision regarding the choice of the components in the device with the essential required dynamic characteristics. In particular the valves, the reservoir, and the model layout as well as the control of the device itself. Finally, this tool will also allow foreseeing the dynamic response of the chosen system in order to minimize temperature overshoots and undershoots, which are contained within the admissible limits.

For the models' analysis the MATLAB/Simulink platform was selected. MATLAB is a programming and numeric computing platform, which provides a tool dedicated to making a block diagram environment for simulation of dynamic systems and model-based design named Simulink. The Matlab/Simulink platform features some benefits as to understand and analyse complex systems by simulating block diagrams, as well as allowing to configure the model according to the amount of detail for the task.

4.1 Methodology proposed to models' implementation in Matlab/Simulink

The following methodology was followed for the models' implementation in the selected platform. This approach started by considering a standard block with 3 inputs (P_{in}, T_{in}, q_{mount}) and 3 outputs (P_{out}, T_{out}, q_{in}).

The input flow of the block that models the component connected upstream is represented by q_{mont}, while q_{in} is the flow rate of the component transported to the outlet of the block in order to connect to the q_{mount} input of the next downstream component. P_{in} and T_{in} represent the input pressure and temperature, respectively, for the component. Similarly, P_{out} and T_{out} are the output pressure and temperature of the component, which are determined from the mass and energy conservation equations, and represent the pressure and temperature inside the control volume of the corresponding component.

Secondly, a pressure drop located at the entrance of each component was considered. This can be a function to calculate the volumetric flow rate depending on the pressure difference ($P_{in} - P$), where P is the fluid pressure inside the control volume.

4.2 Final solution implementation in Matlab/Simulink platform

The following solutions were modeled and simulated. A model with the reservoir assembled in two different layouts: in parallel to the output pipe from the heat cell and directly connected to it. Different models with a proportional valve assembled in different positions to control the flow rate from: the reservoir, the heat cell output, and the cold water input from the device main inlet (as a bypass). The final solution design was selected from the analysis of the results corresponding to the different possible combinations of solutions. In addition, the developed control strategy is included in this chapter.

Proposed model for the heat cell

A semi-empirical model was assumed, where some assumptions were made in order to describe the dynamic behavior of real heat exchangers or, in this case, the burners.

A concentrated parameters model of a heat exchanger is assumed, and time delays are foreseen for the evolution of the temperature at the heat cell outlet, for the delivered thermal power (also considering an efficiency), and also temperature increases at the entrance and at the heat exchanger output.

$$\dot{Q_{in}} = \eta \dot{Q}(t - \Delta t) \tag{4.1}$$

Equation 4.1 represents the thermal power, where $\eta < 1$ is the thermal efficiency, Δt represents the delay between the power delivery command to the burner and its effect (delays in the fan and gas circuit, among others), and $\dot{Q}$ is the thermal power applied to the heat cell.

The temperature increment in the inlet of the heat exchanger can be calculated by:

$$T_{out} = T(t - \Delta t_c) + \Delta T_{out} \tag{4.2}$$

where $\Delta t_c = \frac{\pi (R_i)^2 L_t}{|q_{in}|}$ represents the time delay due to the flow, L_t is the length of the pipes inside the burner, R_i is the inner radius of the pipe and ΔT_{out} represents the increase in water temperature at the heat cell output.

The temperature increment in the outlet of the heat exchanger can be expressed as:

$$T_{in} = T_{amb} + \Delta T_m \tag{4.3}$$

where ΔT_{in} is the water temperature increase at the heat cell inlet. In order to simplify the problem, the temperature of the metal pipes of the heat exchanger was considered to be the same as that of the water, T_a, i.e, $T_a = T_m = T$.

This model was parameterized based on experimental data provided by BoschTT. The model implementation in the simulation platform is shown in Figure 4.1.

Proposed model for the tank

The model implemented for the tank is based on the assumption that the water temperature is constant throughout the entire volume of this component. The implementation of this model in the simulation platform is shown in Figure 4.2.

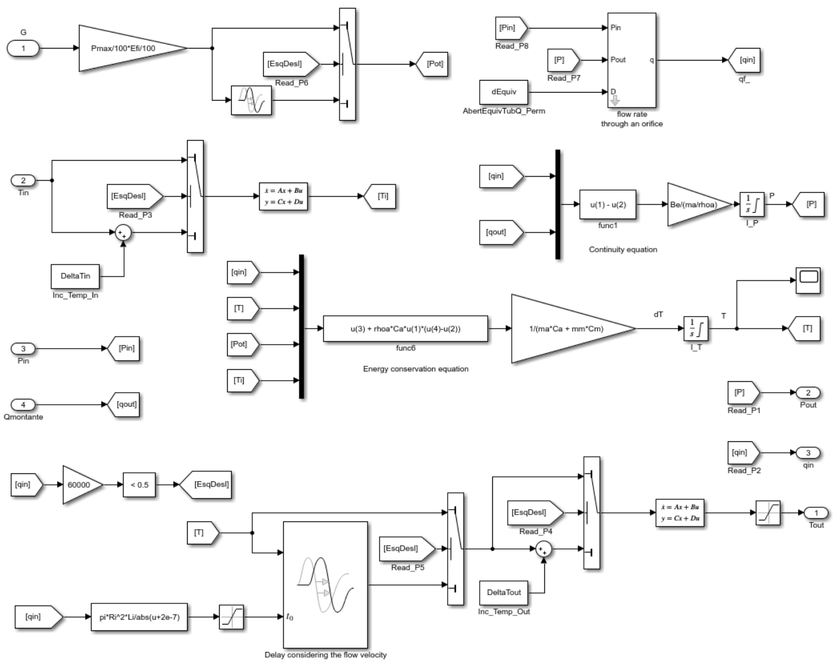

Figure 4.1: Implemented model of the heat cell

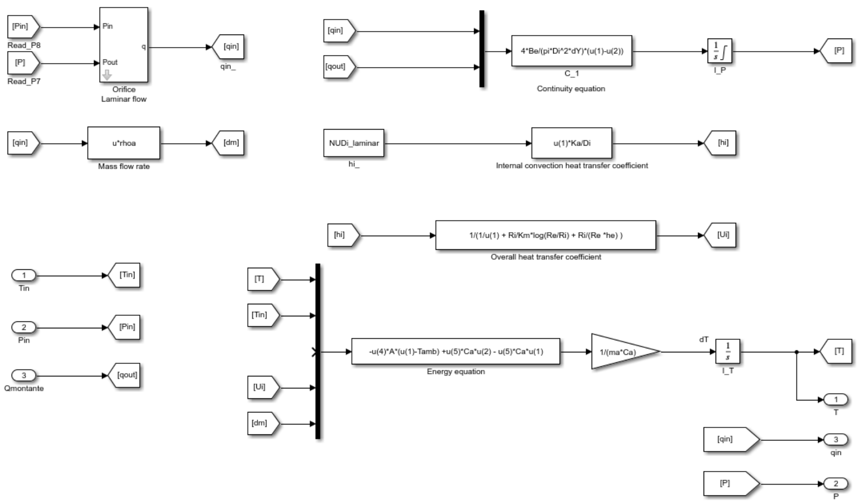

Figure 4.2: Implemented model of the reservoir

Proposed model for the pipes

A lumped model is used for the pipes, considering the possibility of turbulent or laminar flow depending on the Reynolds number. A time delay of the temperature is associated to the length of the pipe and the type of flow. A simulation to obtain the spatial evolution of temperature and pressure can be implemented through the series connection of short-length pipe models. This model also includes heat transfer from the surface to the outside. The block diagram for implementing the pipe model is shown in Figure 4.3.

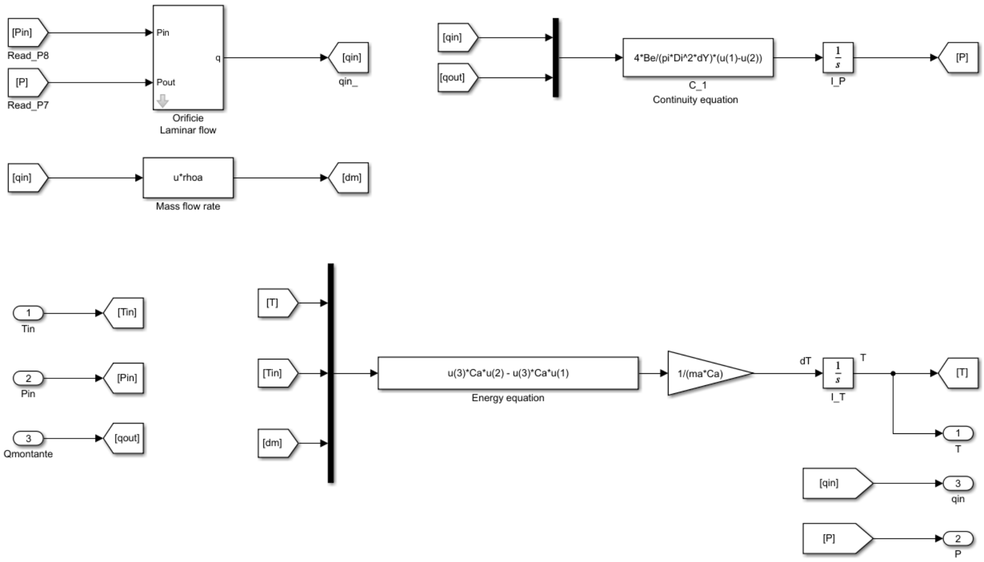

Figure 4.3: Implemented model for a pipe

Proposed model for the valves

To describe the fluidic and thermal behavior by the valve model, the mass and energy conservation equations were used. The orifice equation was used to characterize the pressure drop located at the valve inlet orifices. The block diagram corresponding to the implementation of the valve model is shown in Figure 4.4.

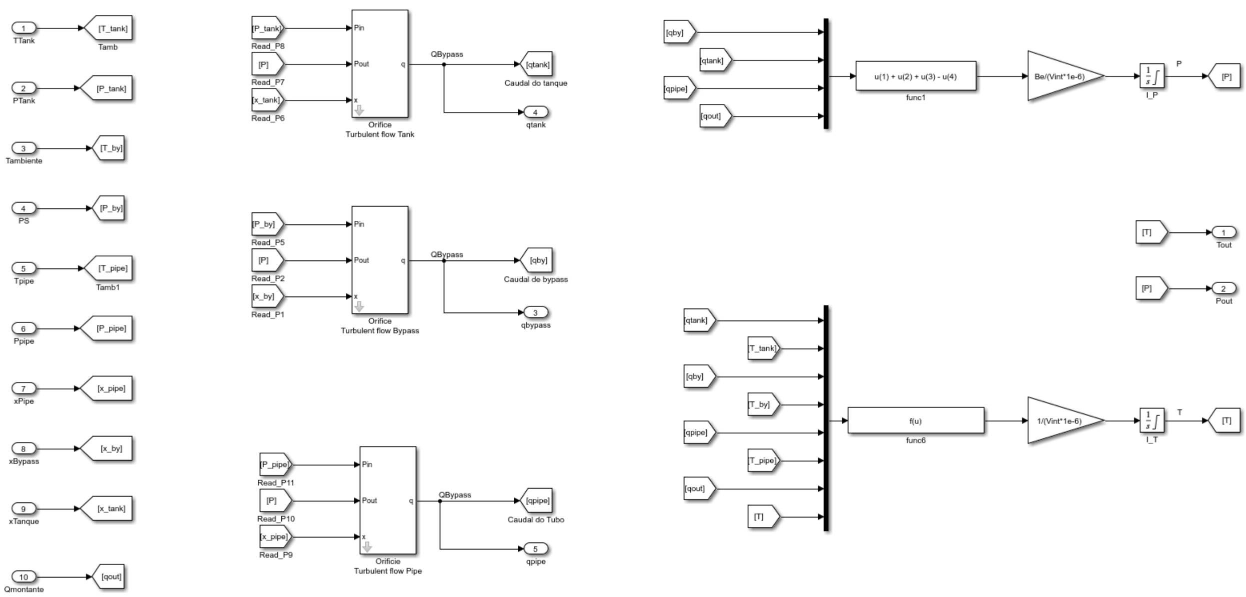

Figure 4.4: Implemented model of the proportional valves

4.3 Control strategy

The device control is managed by a micro-controller in this case, an Arduino board, that features a C/++ based program language [11]. For that reason a sequential control was designed instead of a block diagram, as usual in Simulink projects. Thus, writing a code in a language supporting structured programming allows the conversion of the code created in the simulated environment directly to the real controlling device. Structured programming relies on a structured control flow constructs of selection (if/then/else) and repetition (while/for) for a clear and less time consuming process of computer program development.

4.3.1 Operating modes

The proposed control strategy includes four operation modes: water heater off mode, cold start mode, reservoir reload mode and normal operation mode. These operation modes define the heat cell power control as well as the proportional valves positions. Shown in Figure 5.7 is a schematic representation of the proposed control strategy.

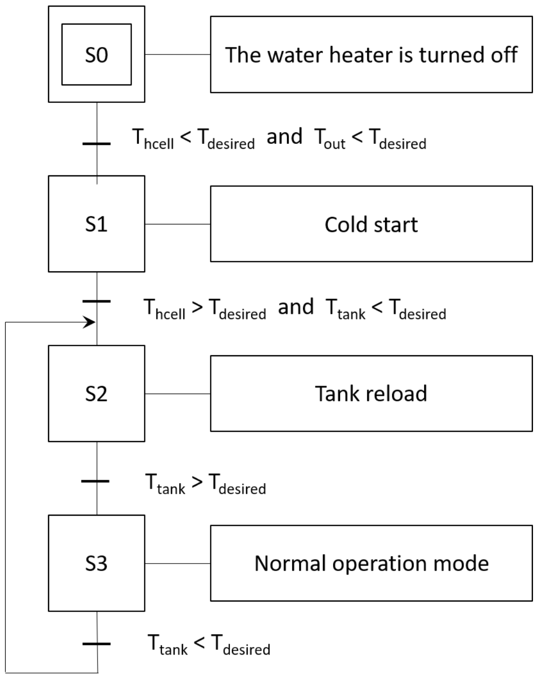

Figure 4.5: Implemented control described in a Grafcet

Each operation mode can thus be characterized as follows:

- Mode S0: the water heater is turned off. This is straightforward the simplest operation mode. This mode is activated when no hot water is required.
- Mode S1: cold start. As the name suggests, in this mode the water output temperature is lower than required and no hot water exists in the tank. The approach for this operating mode is as follows: heat the water in the heat cell up to a higher temperature than the setpoint temperature. Until the setpoint

temperature is reached, the hot water flows directly through the main pipe and no hot water is directed to the tank.

- Mode S2: tank reload. This operating mode is activated once the heat cell setpoint temperature is reached and the water inside the tank is colder than the desired temperature. From this moment forward, the water flows partially from the tank. In this stage, the output temperature is higher than desired, the proportional valves controlling the flow in order to achieve the desired output temperature. Both valves operate strategically in order to mix the overheated water from the main pipe and the cold water from the tank. As the temperature rises inside the tank the corresponding valve opens proportionally while the valve connected to the main pipe closes in the inverse proportion. The operation of both valves will be explained in detail later. Eventually, the water temperature inside the tank is higher than the desired temperature, triggering the control to change to the next operating mode.

- Mode S3: normal operation mode. In this stage, the water temperature in the tank as well as the water flowing from the main pipe leading from the heat cell is approximately equal to the setpoint temperature of the heat cell, so the proportional valve connected to the device's cold water input opens and acts as a bypass valve. Initially the bypass valve was to be controlled using a proportional–integral–derivative controller (PID controller). After testing and analyzing several control mechanisms, it was concluded that the integral and derivative parts did not have a significant effect. Therefore, the simplest proportional controller was chosen.

A better performance of minimizing the temperature overshoots and undershoots can be predicted while operating in the normal operation mode (S3). The temperature sensors placed in strategical locations of the device allow to the appropriate function of the control system. Different temperature measurements correspond to changes between operating modes. The implementation of the control strategy is represented in Figure 4.6.

4.3.2 Valve control strategy

This strategy applies if the water temperature in the tank is below the desired temperature. Thus, most frequently when mode S2, tank reload, is active. The incorporation of a tank in the device increases the waiting time in situations of cold start. The waiting time increases with the tank volume. However, the cold water stored inside it can be used to achieve the desired temperature when mixed with the overheated hot water flowing from the main pipe together with a suitable control strategy. This control strategy consists on estimating the fraction of total water flow rate that is necessary to be obtained at one of the segments as a function of the fluid temperatures in the two segments (the main pipe leading from the heat cell and the tank) to obtain the desired temperature at the valve outlet.

An example of a mixing valve was used to facilitate the interpretation of the two proportional valves operation, as schematically represented in Figure 4.7, where $\dot{m}_x$ is the mass flow rate at each branch and T_x the corresponding temperature.

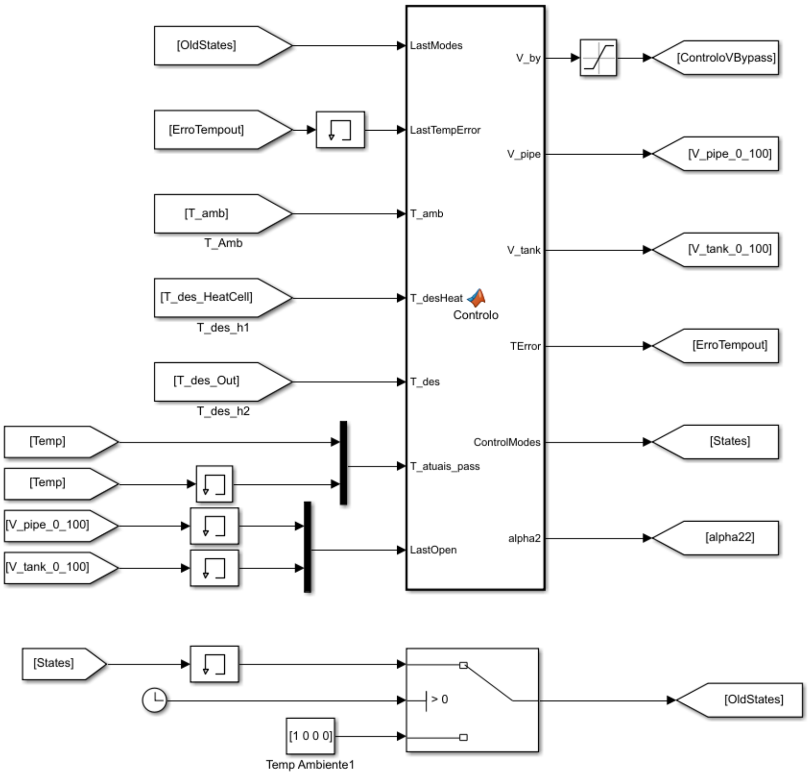

Figure 4.6: Block diagram of the implemented control strategy

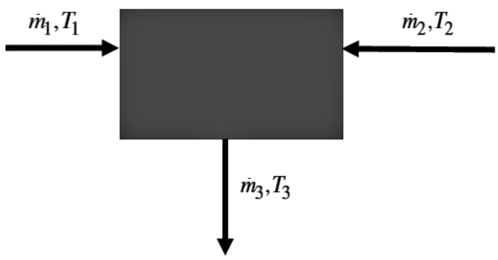

Figure 4.7: Schematics of intersection points

Assuming the junction point as thermally isolated, from the mass conservation equation, Equation 3.1, comes:

$$0 = \dot{m}_1 + \dot{m}_2 - \dot{m}_3 <=> \dot{m}_3 = \dot{m}_1 + \dot{m}_2 \tag{4.4}$$

and the energy conservation equation, Equation 3.2 comes:

$$\begin{aligned} 0 &= \dot{m}_1 c T_1 + \dot{m}_2 c T_2 - \dot{m}_3 c T_3 \\ T_3 &= \frac{\dot{m}_1}{\dot{m}_3} T_1 + \frac{\dot{m}_2}{\dot{m}_3} T_2 \\ T_3 &= \alpha T_1 + (1-\alpha) T_2 \end{aligned} \tag{4.5}$$

because the energy inside the system is constant, there are no heat exchanges ($\dot{Q}$) from the junction or mechanic work ($\dot{W}_{cv}$). Kinetic energy and potencial energy changes are irrelevant in this case, and the specific enthalpy can be expressed as $dh = cdT$, where c, the specific heat capacity, is considered to be constant.

Finally, it is obtained that

$$\alpha = \frac{\dot{m}_1}{\dot{m}_3} = \frac{T_3 - T_2}{T_1 - T_2}. \tag{4.6}$$

Applying to the tank and main pipe case, where T_d is the desired temperature, T_{pipe} is the temperature measured in the main pipe and T_{res} is the temperature inside the tank, α is the theoretical fraction of bypass flow rate the valve should have.

$$\alpha = \frac{T_d - T_{res}}{T_{pipe} - T_{res}} \tag{4.7}$$

As explained previously, when the control switches to mode S2 (tank reload) the valves connecting the segment from the main pipe outlet and the segment from the tank operate as a mixing valve. The valve opening of the main pipe is proportional to α, and the opening of the tank outlet is its corresponding to 1, that is $(1 - \alpha)$.

For instance, if for a desired temperature of 40 °C and the water temperature inside the tank is of 15 °C, if the temperature from the main pipe equals the desired temperature ($T_{pipe} = T_d$), then $\alpha = 1$. Therefore, the valve connected to the main pipe is fully open (100%) and the tank valve is closed (0%). As the temperature of the water flowing through the main pipe increases ($T_{pipe} > T_d$) the value of α is less than 1 meaning both valves are open but the opening of the main pipe valve is wider than the of the valve attached to the tank. The α value will keep decreasing as the temperature in the tank rises, and, consequently, the opening of the tank valve enlarges. Once the tank temperature reaches the desired value ($T_{res} = T_d$) the operating mode switches to S3, normal operation mode.

The third valve, attached to the cold water input, is commanded by a proportional controller. This valve opening is calculated by multiplying the current temperature deviation value, $e(t)$, to a proportional gain constant, represented by k_p. The deviation is, in this case, the difference between the real-time output and the desired temperature.

$$V_{bypass}(t) = K_p e(t) \tag{4.8}$$

This control is featured in every control mode, but is emphasized on the normal operating mode S3.

Chapter 5

Dynamic analysis

In this chapter the different configuration solutions are modeled in a simulated environment and analysed in order to choose the final solution design. For this, the basic parameters of the simulation are established, the results obtained from the different configurations are compared, and, finally, the final solution is modeled and analysed.

5.1 Thermal model parameters

In order to achieve an accurate simulation, a list of parameters was established. The information in Table 5.1 includes data about the water circuit, the valves, and the heat cell.

Table 5.1: Established parameters

Parameter	Value
Water desired temperature	40 °C
Inlet water temperature	15 °C
Water setpoint temperature	45 °C
Water mainline pressure	3×10^5 Pa
Discharge coefficient	0.7
Orifice diameter	0.013 m
Heat cell maximum output power	58000 W
Water bulk modulus	1×10^8 Pa
Water specific heat	4186 J/kg °C

Figure 5.1 represents the output flow rate profile taken to replicate the user interaction, through sudden changes on the required hot water flow rate, to evaluate the performance of each layout. This profile include sudden output flow rate increases form 2 L/min to 10 L/min and from 2 L/min to 14 L/min, and decreases from 10 L/min to 2 L/min and 14 L/min to 2 L/min. A time delay is foreseen for the evolution of the temperature associated to the heat cell operation. As such, the initial increase of flow rate from 2 L/min to 10 L/min is not the most appropriate case to assess the performance of each of the solution options in the event of a possible temperature undershoot. However, the performance can be assessed afterwards as a

temperature undershoot is prone to occur when a sudden flow rate increase occurs with a step from 2 L/min to 14 L/min. In order to evaluate the different models reaction to the possible occurrence of a temperature overshoot, at t=190 s the flow rate decreases from 14 L/min to 2 L/min, as it is one of the most accentuated variations in flow rate.

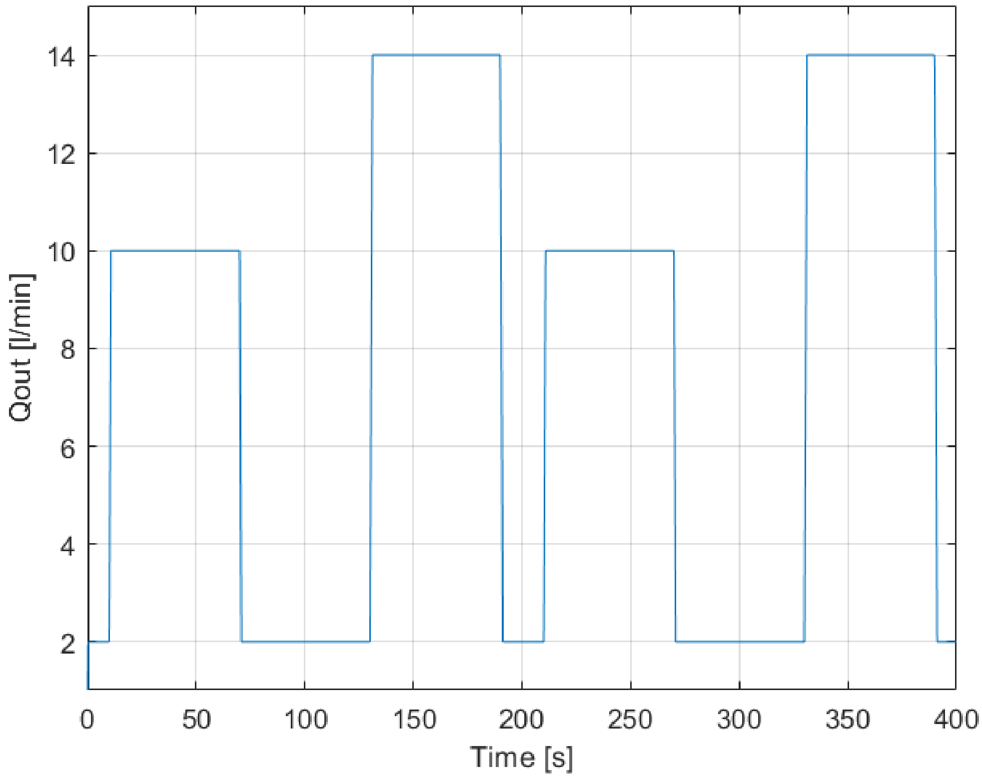

Figure 5.1: Hot water output flow rate

5.2 Different layouts comparison

This section includes the comparison of the different configurations regarding the waiting time and the temperature overshoot and undershoots. The complexity of the analysis increases as more components are added. Starting with the most basic configuration and gradually increasing the complexity, the most suitable layout will be identified.

The most basic design consists only of the main pipe connected to the heat cell. This simple configuration serves as a reference to the other layout results. In Figure 5.2 is the output temperature for the reference configuration as a result of the changes in the output flow rate profile presented in Figure 5.1.

The output temperature reaches the desired value of 40 °C in 21.12 s. This value represents the waiting time for hot water. Regardless of the configuration selected, this values cannot be improved due to the fact that it is directly associated to the slow dynamics of the heat cell. As such, it is intended that the waiting time obtained in the final solution is similar to this value.

When the output flow rate steps from 2 L/min to 14 L/min (at t=130 s, and also at t=330 s), a temperature undershoot with a maximum of 9.69 °C is registered for a period of 13.5 s. When the output flow rate steps from 14 L/min to 2 L/min, (at t=190 s and again at t=290 s) occurs a temperature overshoot with a maximum of 10.25 °C for a period of 26.2 s.

This layout highlights the problems related to the user's thermal comfort associated with domestic heating water devices. Therefore, it is necessary to design a solution that minimizes the occurrence of temperature undershoots and overshoots in order to promote the thermal comfort and water savings.

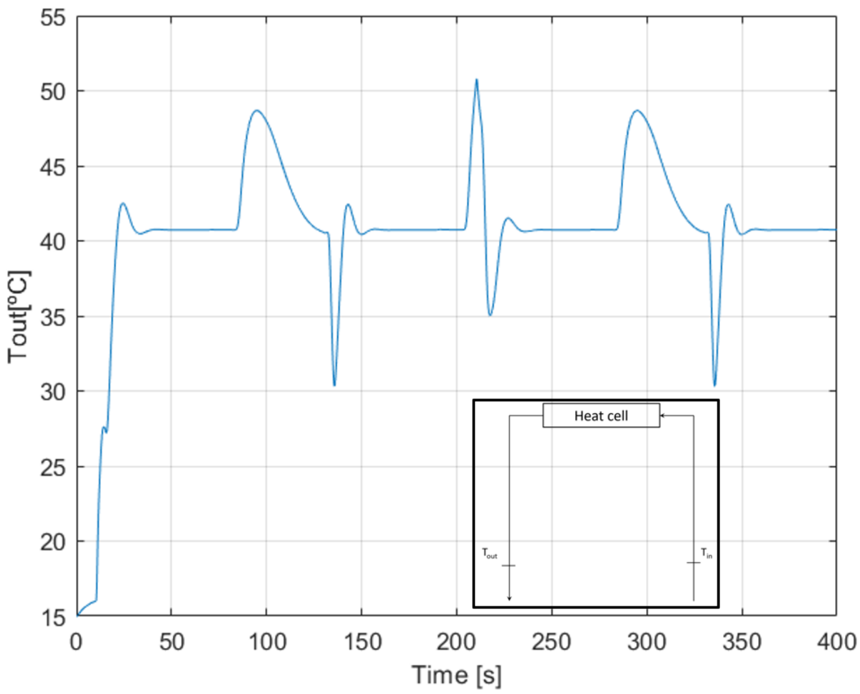

Figure 5.2: Output temperature for the reference (basic) configuration

On the second case, the inclusion of the tank in the layout was tested, referred in Section 3.3 as configuration proposal 3. The tank allows to have a thermal capacity when temperature undershoots tend to occur. However, it is well known that it may result in an increase of the waiting time.

In this example, a 2 L tank is mounted directly after the heat cell, without a bypass valve. The output temperature of this configuration is presented in Figure 5.3.

Approximately, at t=130 s as well as t=330 s a sudden rise of water demanded occurs, thus creating the conditions for a temperature undershoot. However, the hot water stored inside the tank acts as a thermal buffer. Reason why this configuration presents an improvement in comparison with the reference, as the temperature variation extended for 12.5 s, with a maximum of 2.12 °C. A 2 L volume tank was considered in the example. As this value is one of the factors that influences the ability of the system to overcome a potential temperature undershoot it is analyse in detail in the next section.

Regarding the temperature overshoot, this configuration indicates a small

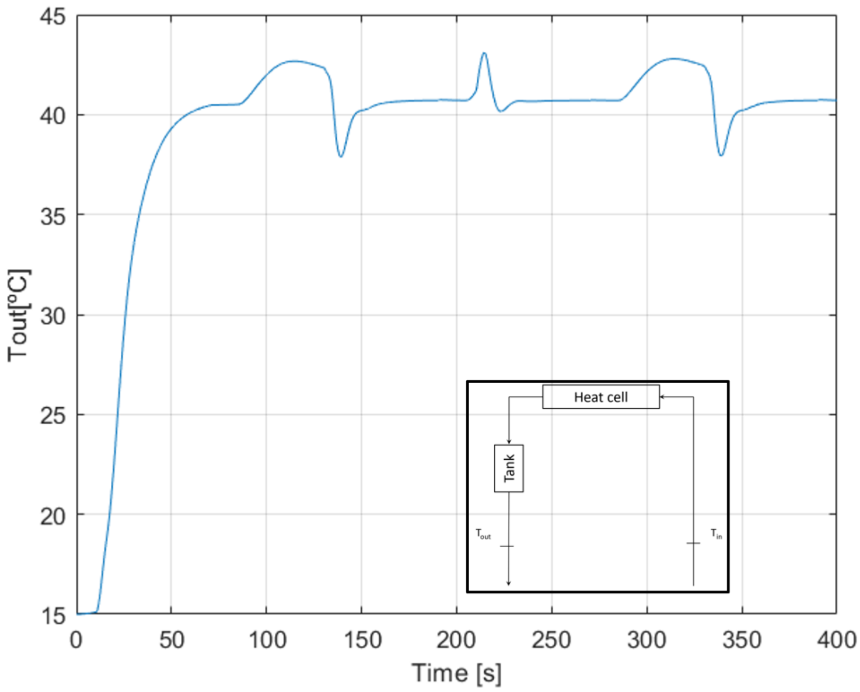

Figure 5.3: Output temperature for the configuration with the tank

improvement as the temperatures overshoot lasted for 10.3 s (half the time) and with a fluctuation of 3.1 °C, when compared with the reference. This value is considerably lower because, initially, the tank was filed with water at the desired temperature which delays the potential temperature overshoot. However, the decrease of flow rate triggers the heat cell to increase the output temperature, filling the tank with a temperature higher than the desired temperature.

As anticipated, a higher waiting time of 58.1 s was registered. This value is almost three times higher than that of the reference. To prevent the waiting time to increase and simultaneously take advantage of the benefits of the inclusion of the tank, this component must be mounted in parallel with the main pipe from the heat cell output. This way, temperature undershoots can be prevented without compromising the waiting time.

In the third proposal, hot water from the heat cell mixes with cold water from a bypass valve. This valve is connected to the main cold water. This simple configuration allows to control the water output temperature in order to avoid a temperature overshoot situation, introduced in Section 3.3 as configuration proposal 1.

The possibility of temperature overshoot occurring when the flow rate decreases (at t=190 s, as well as 100 s later) has notably decreased due to this configuration. The inclusion of a bypass valve resulted in an insignificant temperature variation, with a maximum of 0.55 °C. This variation is barely noticed in the output temperature for this configuration, Figure 5.4, when compared with the temperature overshoots registered in the reference configuration.

As expected, this layout was unable to minimize the temperature undershoots that occurred throughout the analysis. The highest of the several temperature undershoot that occur with this configuration registered a maximum of 9.84 °C for 6.5 s. The waiting time was the same as that of the reference configuration.

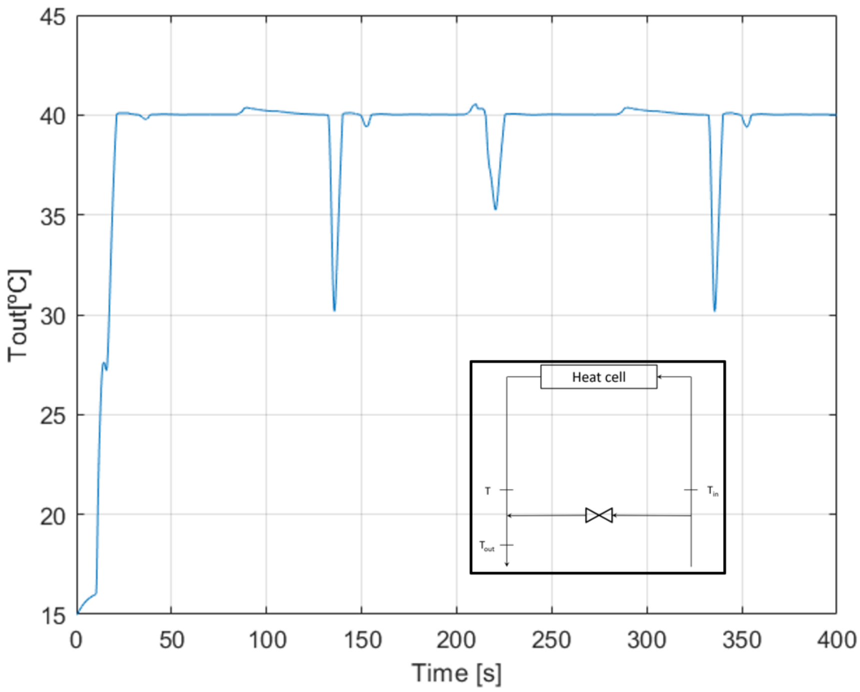

Figure 5.4: Output temperature for the configuration with the bypass

Shown in Figure 5.5 is the overlapping of the different configurations, including the reference configuration. The reference configuration output temperature (blue line) presents the highest reached values of temperature overshoots and undershoots for longer period of time, meaning that the thermal system takes longer to readjust back from the perturbations in the output flow rate.

From this comparison it is evident that the configuration with the tank (orange line) is able to minimize the effects of the sudden increase of output flow rate. The waiting time is considerable higher than the reference. As explained previously, the advantages of including this component in the final solution are enhanced when it is mounted in parallel with the main output pipe of heat cell and controlled with a valve, introduced in Section 3.3 as proposals 4.

Regarding the sudden decreases of output flow rate the difference between the output temperature of the configuration with the bypass valve (yellow line) and the reference is distinct. This layout solution was able to effectively minimize the temperature overshoot when there was a sudden decrease in the output flow rate, almost completely eliminating the occurrence of a temperature overshoot without compromising the waiting time.

The combination of these configurations allow achieving the goal of minimizing the temperature undershoots and overshoots, as well as establishing the lowest value possible for the waiting time. Including the bypass valve assembled as in the configuration proposal 1 from Section 3.3 and the tank in parallel with the heat cell main pipe output, introduced in Section 3.3 as configuration proposal 4, the final

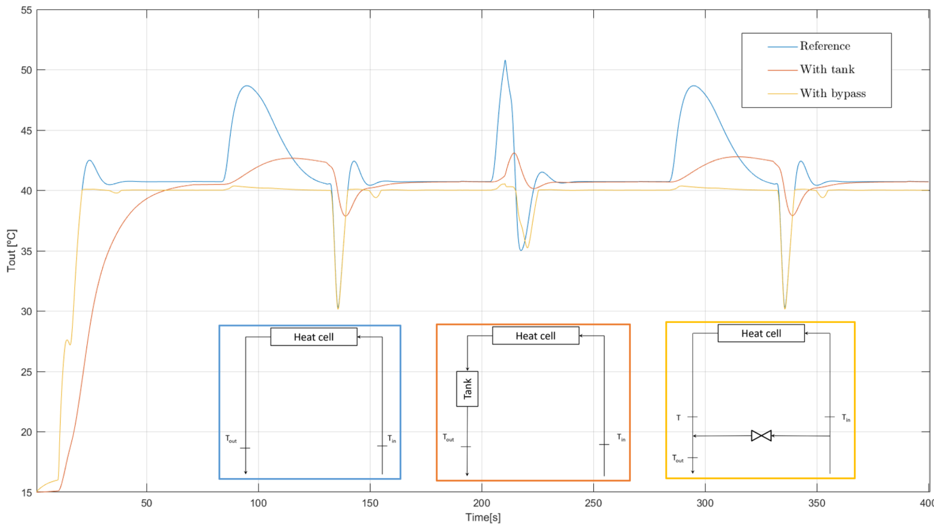

Figure 5.5: Output temperature comparison between the three configurations

solution resembles configuration proposal 7.

5.3 Parametric analysis of the tank

The analysis from the previous section led to the conclusion that the inclusion of a tank in the layout influenced the occurrence of temperature undershoot. For this reason, this section focuses on the study of the relationship between the tank volume, the temperature setpoint of the heat cell and the temperature undershoot measured. The temperature undershoots depend on many factors, including:

- the inlet water temperature,
- the sudden rise of the water flow rate (a more abrupt flow rate step translates into a more intense temperature undershoot),
- the heat cell control (since the control robustness can properly minimize the undershoot),
- the tank volume (larger the volume of the tank, less intense the undershoot),
- the difference between the desired temperature and the setpoint temperature of the heat cell (higher this difference, lower the undershoot).

To solve this problem, the model was simulated for different volumes of the tank and temperature setpoits of the heat cell. The cold water enters the device at 15 °C, the desired temperature is 40 °C, and the same sudden changes on the output flow rate as in Figure 5.1 were considered. Tank volumes ranging up from 0.5 L to 2 L were simulated along with heat cell setpoint temperatures from 40 °C to 55 °C.

To evaluate in detail the occurrence of temperature undershoot, the more intense flow rate increased was selected, when the output flow rate steps from 2 L/min to 14 L/min.

This happens two times throughout the simulation at t=130 s and at t=340 s. Although the flow variation is the same in both situations, it is expected that in the first situation the tank is still not filled with water at the desired temperature and, therefore, unable to eliminate the possible occurrence of temperature undershoot. This problem intensifies with higher volumes of the tank. For that reason, the ability to overcome the occurrence of a temperature undershoot was evaluated at t=330 s. The temperature undershoot registered as a function of the tank volume and of the heat cell set point temperature is shown in Figure 5.6.

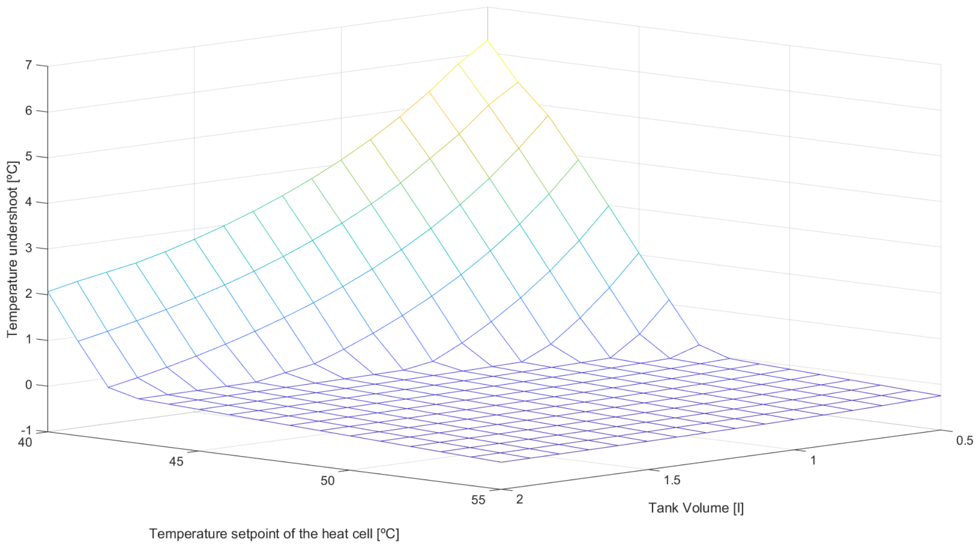

Figure 5.6: Temperature undershoot as a function of the tank volume and of the heat cell set point temperature

It is possible to observe as the tank's volume increases, the maximum recorded temperature undershoot decreases. Likewise, with the increase of the heat cell temperature, the temperature undershoot decreases. For the majority of tank volumes and heat cell setpoint temperatures combinations there is no undershoot. This is observed for tank volumes bigger than 0.9 L when the heat cell setpoit temperature varies from 43 °C to 55 °C.

Lower setpoint temperatures, thus smaller differences between this temperature and the desired temperature, lead to higher and inadmissible values of temperature undershoots.

A bigger tank translates in a higher cost not only due to the required material to manufacture this component, but also due to the overall dimensions of the final solution. On one hand, a tank with a capacity of 0.5 L has proven to be able to overcome the temperature undershoots except when there is small difference between the heat cell setpoit temperature and the desired temperature. Besides, from a manufacturing perspective this volume is not cost-efficient. On the other hand, a tank of 2 L capacity solves the temperature undershoots even for lower values of the heat cell setpoit temperature. Considering mass manufacturing, this dimension is not the most reasonable. For that reason, the volume of 1 L was selected as the most appropriate dimension for the tank, allowing the whole device to fit in a smaller volume.

5.4 Final layout analysis

Output temperature fluctuations naturally occur even with an ideal layout and a robust control system. Reason why it is necessary to establish a range of admissible output temperatures. It is assumed that are admissible temperature undershoots and overshoots within an interval of 1 °C.

The final layout incorporates the components analyzed in the previous section, which promoted the minimization of temperature undershoots and overshoots, improving the user's thermal comfort. The flow rate from each of the three segments of this configuration are controlled by a proportional valve. Shown in Figure 5.7 is the final solution configuration.

The cold water enters the device at T_{amb}, is heated in the heat cell to the setpoint temperature. Afterwards, the heated water can either flow through the main pipe or to the tank depending on several factors: the operation mode, the output temperature, T_{out}, the temperature of the water in the pipe, T_{pipe} and in the tank, T_{tank}. The output flow rate from these components, Q_{pipe} and Q_{tank}, as well as from the bypass valve, Q_{bypass}, are controlled with proportional valves in order to output the desired temperature.

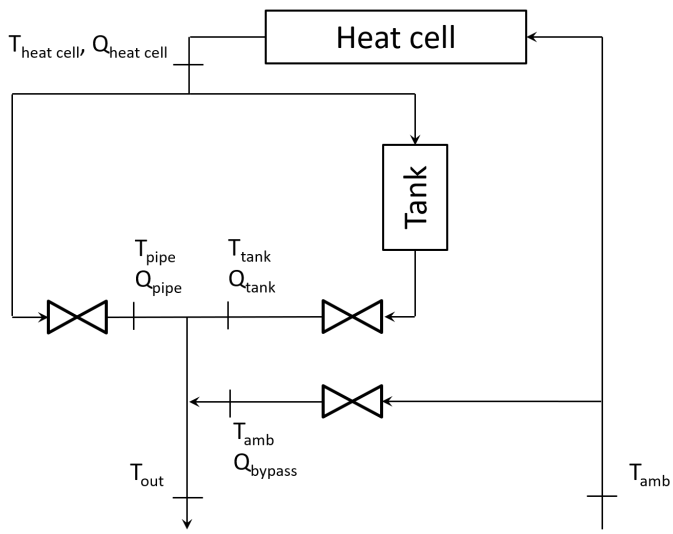

Figure 5.7: Configuration of the final layout

For a desired output temperature of 40 °C, the temperature undershoots and overshoots values, as well as the waiting times from the simulation of the selected tank volume of 1 L for different heat cell setpoint temperatures are summarized in Table 5.2 (negative values indicate no occurrence of temperature undershoots).

Results show that for setpoint temperatures from 44 °C to 55 °C, the temperature overshoots and undershoots are within the admissible interval of 1 °C. Therefore, for the 1 L selected volume of the tank, temperature overshoots and undershoots were eliminated for the majority of heat cell setpoint temperature. However, for lower temperature values the risk of scalding injuries is reduced.

Table 5.2: Simulation results for different heat cell setpoint temperatures

Setpoint temperature [°C]	undershoot [°C]	overshoot [°C]	waiting time [s]
40	4.0859	0.1655	22.79
41	3.2071	0.1975	22.53
42	2.2922	0.2287	22.30
43	1.3570	0.2603	22.07
44	0.4158	0.2944	21.87
45	-0.0159	0.3284	21.68
46	-0.0485	0.3621	21.50
47	-0.0811	0.3955	21.33
48	-0.1136	0.4287	21.16
49	-0.1459	0.4617	21.01
50	-0.1782	0.4945	20.85
51	-0.2103	0.5271	20.70
52	-0.2424	0.5594	20.55
53	-0.2743	0.5916	20.40
54	-0.3061	0.6235	20.27
55	-0.3378	0.6552	20.12

From an energy consumption viewpoint, a higher heat cell setpoint temperature requires a higher thermal power. Also, greater the difference between the heat cell setpoint temperature and the desired temperature lower the efficiency of the heating system. Thus, a difference of 5 °C between these temperatures, the heat cell setpoint temperature and the desired outlet temperature, was chosen as a compromise solution. Finally, the setpoint temperature of 45 °C for the heat cell was selected for further analysis.

Figure 5.8 shows the time evolution of the flowrates through the various components of the final solution. The time evolution of the output temperature, the temperature measured in the heat cell, on the main pipe and on the tank are shown in Figure 5.9.

From the analysis of the flow rate and temperature figures, it is possible to observe the control strategy effect. Initially, the heat cell heats the water to a higher temperature than desired and the water flows through the main pipe (operating mode S1). As the temperature from the main pipe surpasses the desired temperature, the valve connected to the tank acts as a bypass valve to achieve the desired temperature since the its temperature is colder than the desired temperature (operating mode S2). Meantime the water temperature in the tank continues to increase, causing the tank valve to gradually open when the pipe valve closes in the inverse proportion. Once the tank temperature exceeds the desired temperature, the bypass valve opens progressively to achieve the desired output temperature (operating mode S3). When a sudden and unpredictable increase of demanded hot water occurs, the different components act accordingly to prevent a temperature undershoot occurrence. To output the desired temperature, overheated water stored in the tank combines with the cold water from the bypass. The same happens when a sudden and unpredictable decrease of flow rate occurs. In order to avoiding a temperature overshoots, the bypass valve opens accordingly. Lastly, this configuration and control system allow to maintain the waiting time close to the reference value, at 21.68 s.

The conclusions that arise from this analysis are that the final layout solution is able to minimize the temperature undershoots and overshoots, without raising the waiting time, therefore promoting the user comfort and water saving.

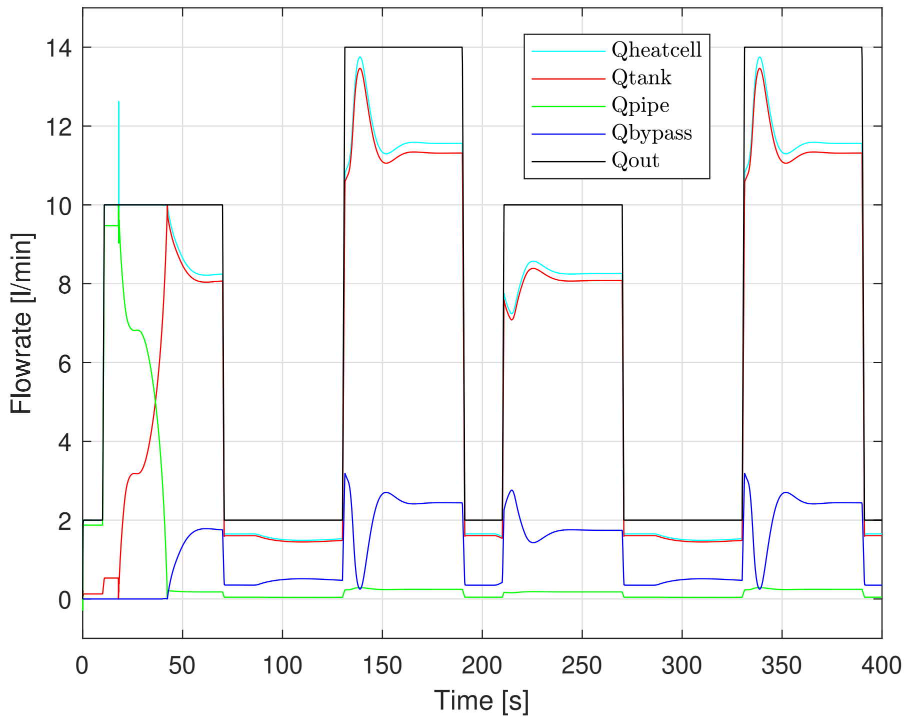

Figure 5.8: Water flowrate through each component

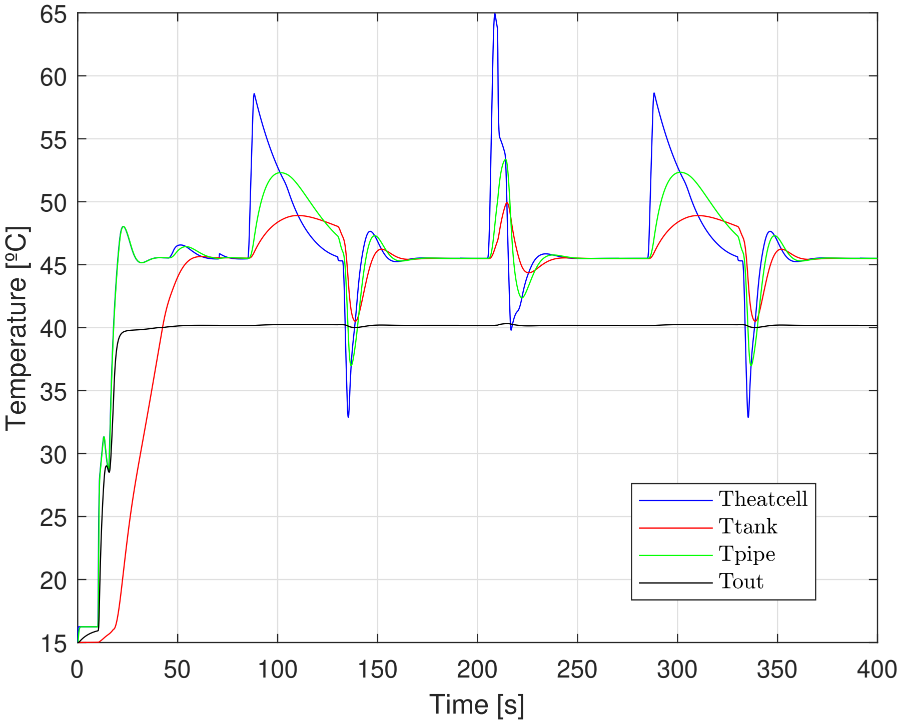

Figure 5.9: Water temperatures at each component

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Chapter 6

Device design

This chapter presents some solution proposals in order to be adopted to implement the developed and simulated device. These proposals are analyzed from a cost-benefit perspective as well as their advantages and disadvantages, and ultimately selected the most appropriate architecture. However, developing a low-cost prototype was not a requirement as it is a proof-of-concept prototype. Thus, preferably selecting components existing on the market with the least possible integration effort, for example, not requiring the develop complex electrical circuits.

6.1 Developed solution

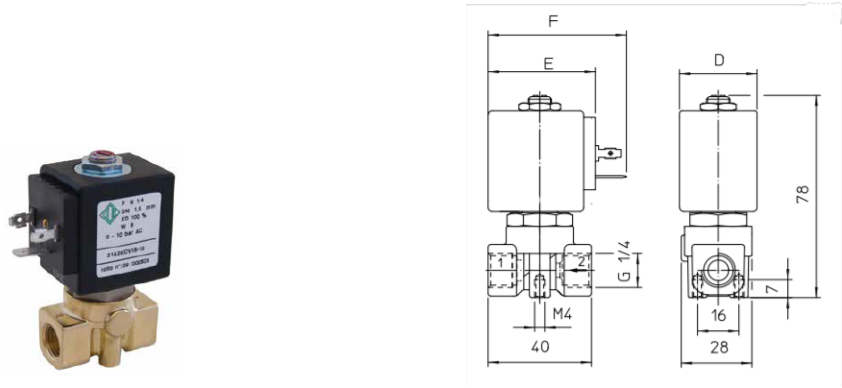
This section includes the mechanical, hydraulic, thermal, and electrical designs. As first step, it is necessary to select the components with the required characteristics for this device. At that point, the design of the prototype can be established.

Valve

In order to achieve the most compact solution, the components that limit the overall design and assembly of the other parts need to be selected first. In this case, it is the 2-way proportional solenoid valve. The desired solenoid valve needs to have the following characteristics:

- suitable for water;
- able to regulate water flow rate up to 15 L/min;
- withstand pressure up to 10 bar;
- voltage control signal (ideally form 0 to 10 V).

After a thorough search for possibilities in the market, beyond the characteristics listed above, the selection of this component was based on the connection size and type, and cost. Finally, the 2/2 way proportional acting *21A PRP N.C.* valve from *ODE* [12] was selected, which is shown in Figure 6.1 (a). It features a flow control solenoid valve, good repeatability and low hysteresis, and a flow curve according to the selected coil. Furthermore, it presents a 1/4" threaded connection, 8 W coil, and can be installed in any position. Its overall dimensions are $40mm \times 78mm \times 26mm$ (see Figure 6.1 (b)), with datasheet being available in the Appendix A. In addition, this valve can operate at temperatures from -10 °C up to $+140$ °C, which is a broader range than required.



(a) (b)

Figure 6.1: 21 A PROP solenoid proportional valve from ODE [12]

The valve is powered by an electrical plug. Disregarding the cable, the dimensions of the plug are roughly $42mm \times 27mm \times 27$ mm, which is mounted on one of the valve sides. The schematics of the electrical plug are shown in Figure 6.2.

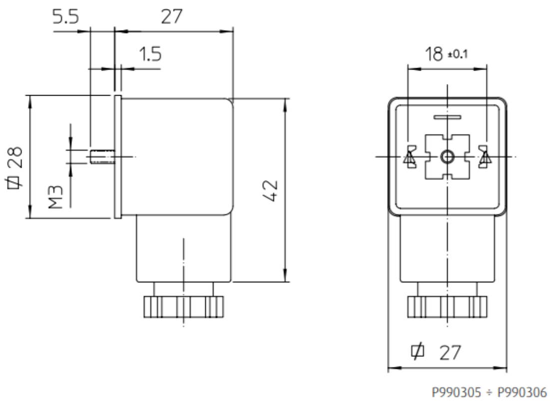
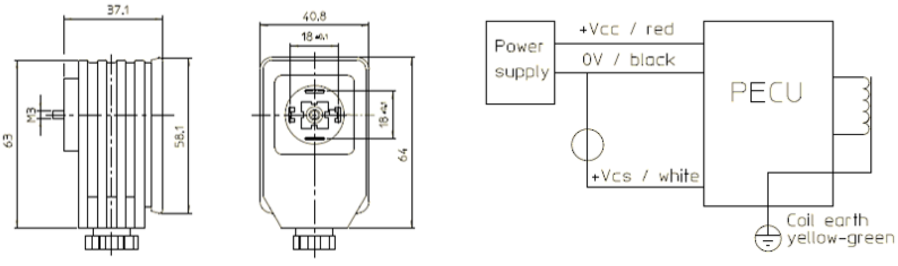


Figure 6.2: Schematics of the proportional solenoid plug [12]

The valve is controlled by a proportional electronic control unit (PECU), suitable for a ODE [12] proportional flow valve with an 8 W coil. This control unit uses a pulse width modulation (PWM) signal, allowing a real-time reaction to the valve state and faster valve regulation. In Figure 6.3 (a) a schematic of this component is presented, including its dimensions. The supply voltage is 24 V DC and the input can either be a voltage or a current control signal. In this case, a voltage control signal is expected for the proportional valve, with an input in the range from 0 to 10 V. The wiring diagram with the designated connections is shown in Figure 6.3 (b). For further analysis, the datasheet is available in Appendix B.



(a) (b)

Figure 6.3: Characteristics of PECU [12]

Tank

A tank is required to act as a thermal capacitor. The capacity of the tank must be low enough to avoid being considered a tank water heater. As established on the previous chapter, the tank has a volume of 1 L. Considering that there are few tanks available in the market with this capacity, this component is to be manufactured for this purpose. For a more simpler and easy manufacture, the tank has a cylindrical shape. Its dimensions were obtained through a basic iterative process based on the overall dimension of the prototype and the fact that it should be integrated in the selected configuration. The internal dimensions were established as 100 mm for diameter and 127 mm for height to achieve the desired capacity. In the tank, the water with the highest temperature rises and the coldest sinks at the bottom. The aim is to eliminate the coldest water as soon as possible and replace it with hot water. For this reason, the water from the heat cell enters the tank on its top and exits from its bottom. The upstream inlet and the downstream outlet are ensured by a threaded connection to the adjoining pipes. In figure 6.4 a 3D view of a CAD representation of the tank is presented.

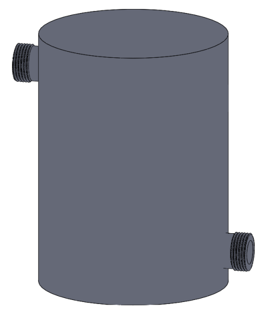


Figure 6.4: CAD of the tank

Temperature sensors

As mentioned, temperature sensors play a crucial role in monitoring the behaviour of the device. The selected configuration requires four temperature sensors. The first one measures the cold water inlet temperature of the device. The second sensor measures the water output temperature from the heat cell. The third sensor in located after the tank outlet. And the last temperature sensor monitors the output hot water temperature from the device. The location of each temperature sensor is shown in Figure 6.5.

These temperature sensors must be waterproof, as well as their assembly in the prototype must be leak-proof. Thus, the temperature sensor must have a threaded connection and an o-ring or a similar leak-proof solution.

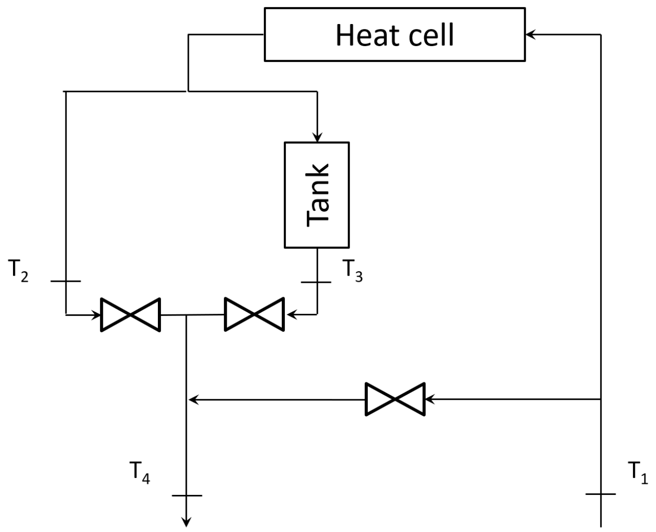


Figure 6.5: Location of the temperature sensors

Temperature sensors can be divided in two categories: analog or digital. The first type is simpler and thus less expensive but is more affected by electric noise. The digital sensor resolution represents the smallest division of the device scale. An advantage of the analog temperature sensors is the wider temperature range when compared with the digital sensors. However, for this purpose, this is not relevant because only measurements between 0 and 70 °C are required. The cost of digital sensors have declined over the last years, and when purchased in bulk quantities become even affordable.

There is a wide range of temperature sensors, varying in accuracy, temperature range, and costs. Resistance temperature detector, more commonly referred as RTD, is an analog temperature sensor. As the temperature of the metal rises, so does the electric resistance, measured in Ohms. This value is then converted to temperature. This translates to a typical response time between 0.5 and 5 s, thus making RTD not suitable for this project, where a shorter time response is essential.

Following the same working methodology, thermistors measure the temperature based on the variation of the electric resistance. There are two types of thermistors: negative temperature coefficient, NTC, and positive temperature coefficient, PTC. As the name implies, with NTC thermistors as the temperature rises the resistance decreases. With PTC thermistors the resistance increases as the temperature rises. For this device, NTC thermistors present some advantages as accurate measurements within the 0 °C to 70 °C range and lower cost. However, the response time can increase drastically depending on the size and material of the sensor.

Another option is the LM35 precision centigrade temperature sensors by *Texas Instruments*. This device output voltage is linearly-proportional to the Centigrade temperature. This sensor does not require any external calibration and features accurate measurements over a −55 °C to 150 °C range. Thermal conductance, heat, mass and fluid velocity affect the time response.

A quick response from the temperature sensor is crucial for the valves regulation. Since the measurement time depends on the fluid and on its flow, it is expected to lower the response time between the data conversion and the data transmission to the micro-controller. In this way, a digital temperature sensor presents a big advantage when compared with the analog ones. To achieve an almost immediate response time the digital thermometer DS18B20 by *Maxim Integrated* measures, processes and sends the temperature value within a second (the datasheet is available in Appendix C). According to the manufacturer, it converts the measured temperature to a 12-bit digital word in a maximum time interval of 750 ms. In addition, this device is able to connect several sensors to the micro-controller with the same 1-Wire bus because each sensor has a unique 64-bit serial code. This sensor has a wide operating temperature and presents an accuracy of ± 0.5 °C over the range of −10 °C to 85 °C, this containing the range of temperature of interest. Furthermore, this device has two operation options. The first one is the conventional external power supply connected to the V_{DD} pin. The V_{DD} supply voltage is between 3.0 to 5.5 V and supply current during active temperature conversion of 1 mA. The other operation options are to be powered directly from the data line, also noted as "parasite mode". This is very useful in cases of space constrain applications as this one. However, to assure that the DS18B20 has sufficient supply current a MOSFET is required to pull the bus directly. The selected temperature sensor includes a 1/4" threaded connection to simplify the assembly on the prototype, incorporates an o-ring to ensure a leak-proof connection as well as a shorter probe (roughly 10 mm long and 6 mm diameter).

Pipes and fittings

In plumbing applications, as well as in either tankless or tank water heaters, the connections, fittings and pipes have standard sizes and materials. There are several types of connections and fittings used in different applications, with different characteristics.

Regarding the threaded connection, the standard thread can be divided in bst (British standard thread), nst, or iso, among others. Some connections present the "G" letter which stands for gas, meaning this connection thread has a smaller pitch. Others present a "N" or no additional letters, which stands for regular threaded connection.

On one hand, the temperature sensors have an 1/4" male threaded connection. On the other hand, the proportional valve has a G 1/4" inch female threaded connection. Thus, to maintain the consistency throughout the device, 1/4" threaded connections were required. The intersections between two or more pipes are ensured by Tee connectors or by a cross connector. Since the device is limited to a small volume, an elbow connector is used whenever a 90° turn is required. As expected, the assembly between the connections must be male-female or vice-versa. So, in some cases male-male fittings are required to ensure the proper connections. These connections were carefully chosen in order to ensure a leak-prof assembly of the temperature sensors as well as the proportional valves.

The pipe's material, in plumbing applications, are usually copper or polyethylene, also known as PEX, as well as CPVC. Copper pipes on average last longer than PEX pipes. However, copper pipes must be cut to size and have elbows (to fit in place) because it is a rigid material, while PEX pipes can bend and adapt more easily around corners. Beyond the installation labor cost of the adaptors, copper is more expensive than polyethylene. PEX is progressively more used in this kind of applications as it is the most effective material in terms of heat dissipation and easy assembling. For that reason, 1/4" PEX pipes were selected for this device.

In this particular application, each pipe requires different lengths according to its placement on the device. The dimensions of the pipes inside the device are: 10 mm, 22 mm and 30 mm.

Mixing block

For a better understanding of the purpose of the next component, the device was separated into three segments. The first segment represents the heated water that flows from the heat cell through the pipe. The second segment characterizes the water stored in the small tank. The third, and last segment includes the cold water that enters the device at the ambient temperature.

During the normal operation, the water flows from the three segments at different temperatures. In order to achieve thermal equilibrium, these must be mixed before hot water leaves the prototype. In order to achieve this purpose, a mixing block was added to the device.

This simple component, shown in Figure 6.6, features three inlets and one outlet. Each inlet is aligned with the respective segment. And the outlet is facing the bottom of the device, concentric with the output pipe from the device. Located near the output is the fourth and last temperature sensor, thus probing the hot water output temperature. The design incorporates 1/4" channels that allow the water to be mixed. The connection with the segments' pipes are ensured by threaded connections.

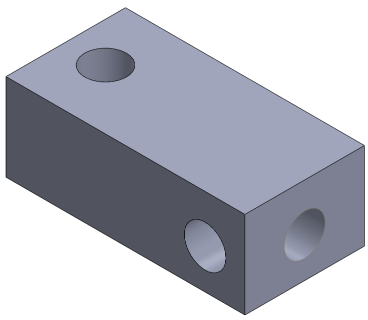


Figure 6.6: CAD of the mixing block

Controlling hardware

The device requires a controlling hardware to manage the operations that take place in it. The controlling hardware is crucial to manage the device's operations. The selected hardware should be compact, able to store and run the program and connect the several components throughout the device.

The most suitable hardware is a micro-controller due to its compact design and the ability to control a specific operation in a system. This type of hardware usually includes a CPU (central processing unit), an internal memory and programmable input/output peripherals. An advantage is that the program can be coded on a computer and later compiled and transferred to the micro-controller internal memory. That program can be executed autonomously in the micro-controller.

There are a few different micro-controllers in the market, each one with distinct characteristics. The ARDUINO MEGA rev3 was selected because it is compact and easy to program, shown in Figure 6.7.

The Ardunino Mega presents many advantages for this project, such as the open-source Arduino Software (IDE) for programming and a C/++ based program language. This micro-controller can be powered by a 5 V USB connection, for example the USB port of a computer, or by a 6 to 20 V external power supply from a AC to DC converter to the power jack. The recommended voltage is from 7 to 12 V. The ARDUINO Mega 2560 is a micro-controller based on the ATmega2560, which has 256 Kb flash memory, where 4 Kb are for EEPROM (Electrically-Erasable Programmable Read-Only Memory), allowing data to be stored in case the power supply is cut off, and can be read and written with the EEPROM library.

Regarding the input/output peripherals, this ARDUINO shield model presents 54 digital pins that can be used as inputs or outputs, of which 15 provide PWM (Pulse Width Modulation) and 16 additional analog pins. The pin-out diagram is available in Appendix D.

A straightforward approach of the ARDUINO Mega role in the device is to read the voltages from the temperature sensors and output the required voltages to command each proportional valve in order to achieve the desired water temperature. This setpoint temperature is established by the user on the display interface.

Although the models were simulated using the Matlab/Simulink platform the portion of the code concerning control of the proportional valves was programmed in a similar language of the micro-controller for an easier transition.

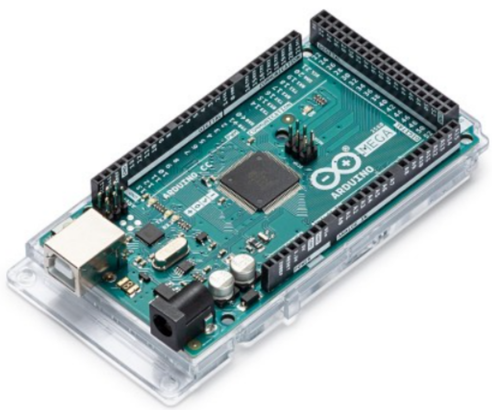


Figure 6.7: ARDUINO Mega 2560 Rev3

Display

The primary function of the screen is to serve as an interface between the control of the device and the user. To control the device, it is necessary to establish the water heating temperature in the heat cell, which corresponds approximately to the temperature at which the water is at the inlet of the device. Knowing this value and the information from the temperature sensors allows the controller to establish the opening position of each of the proportional valves. There are different ways to establish the setpoint temperature. One of them is through push buttons, to properly adjust the temperature and a regular display to oversee the selection operation. Another one is using a component that combines these two functions, such as a touch screen display. This solution presents significant improvements over the previous one, since it reduces the number of parts required, and simplifies the electrical connections as well as the assembly of the device.

In this particular application there is no need for a large screen. Therefore, a small touch display becomes more cost-efficient when compared to the option to purchase a normal display and at least three buttons. For these reasons, the 2.4 inch LCD TFT touchscreen display was selected, which is presented in Figure 6.8.

This is a shield display, not requiring connections with jumpers or a breadboard, allowing to be directly inserted into the ARDUINO. This shield features a 320×240 resolution panel with 65 k color LCD (as in liquid crystal layout). In addition, it features 8-bit data and 4 command lines, and works with an operating tension from 3.3 V up to 5 V. The display graphic interface presents a basic schematics to facilitate the user's interaction. This exhibits the setpoint temperature of the water in the heat cell and the buttons that allow the user to adjust that value.

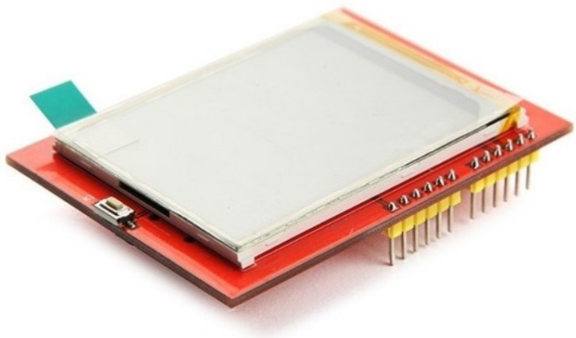


Figure 6.8: Touchscreeb 2.4" LCD dysplay

Prototype layout

The purpose of this device is to be attached to an existing or new domestic TGWH. The inlet and outlet (water and gas) connections are located underneath the water heater. Therefore, the device is to be assembled below the household appliance, as shown in Figure 6.9. The device is to be mounted to the wall the same way as the TGWH, using a metal support fixed to the wall securing the device. Adaptor may be required for the connection between the TGWH and the device. The distance between them is limited by the clearance of the TGWH gas inlet connection. The connection of the hot water for domestic use as well as cold water supply line are located underneath the device.

Within the device, the cold water enters from the bottom and connects to the heater from the top. Whereas the hot water enters the device from the top and the water at the desired temperature leaves from the bottom. A schematics of this is shown in Figure 6.10,

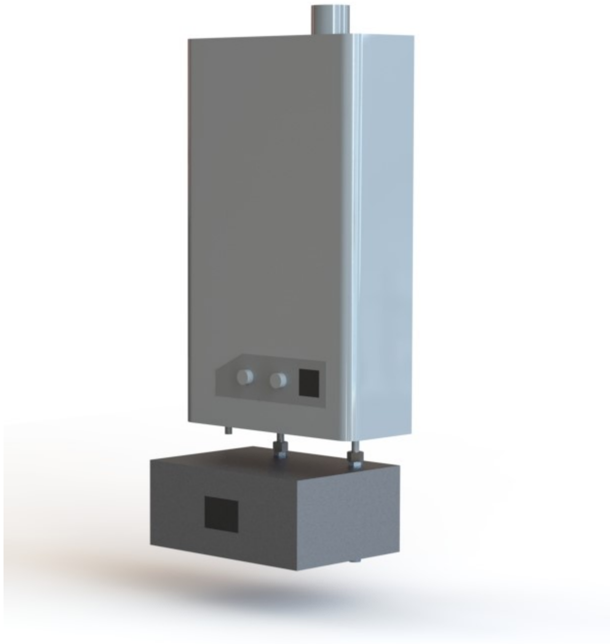


Figure 6.9: Render of the assembly

where the blue arrow represent inlet and outlet of the cold water and the red arrow of the hot water.

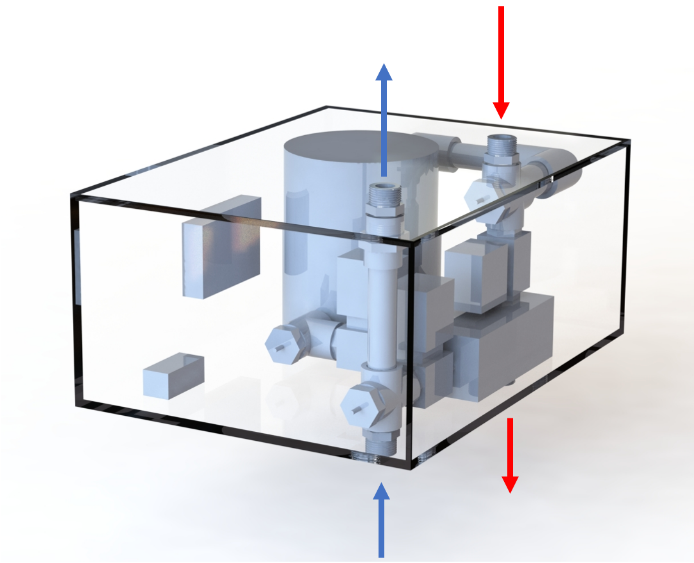


Figure 6.10: Inlet and outlet graphical representation

Establishing the location of the external connections to the device allows to design the interior of the device. A key characteristic of the selected proportional valve is its ability to be assembled in any position. This facilitates the assembly in small places like in this case. The display is assembled on the front facing side of the device.

Shown in Figure 6.11 is a render of the inside of the device with the indication of the main components, where it is possible to observe the connections between them as well as the arrangement of the components in order to obtain a more compact design. In addition, the mechanical design along with the bill of materials are presented in the annex E.

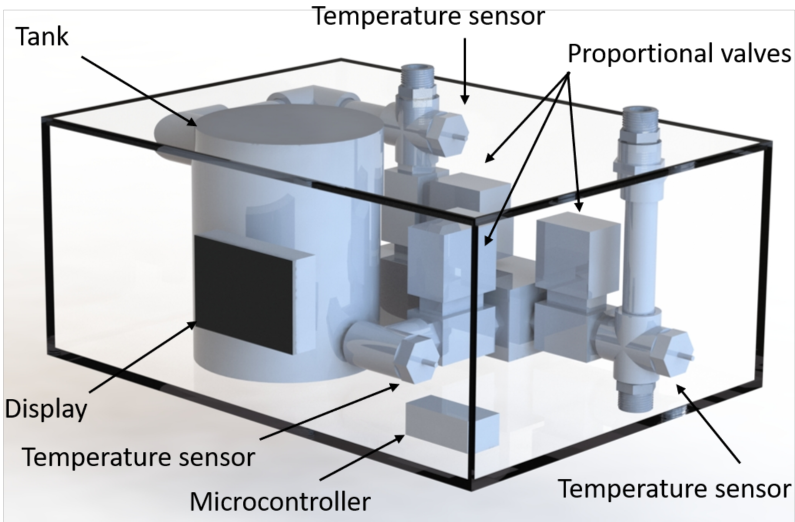


Figure 6.11: Render of the device interior components

Chapter 7

Final conclusions

7.1 Conclusions

The main goal of this work is to propose a solution that promote thermal comfort domestic water heating systems and to reduce the waiting time during the cold start of the water heater. Temperature overshoots and undershoots may result from sudden changes on the water flow rate induced by the users. These situations cannot be anticipated, as they are usually the consequence of unpredictable users' actions.

The proposed device can be added both to previously existing TGWH or to new TGWH, to prevent temperature overshoots and undershoots (increase thermal comfort) and reduce the waiting time and its associated water waste.

A dynamic model was developed to describe the thermal, fluidic and mechanical behavior of the different components of the proposed solution. The model was implemented on the Matlab/Simulink platform. The study of the fundamental components has been highlighted, including the volume of the tank that gives the required thermal inertia to the system.

The solution developed in the present work to minimize the temperature overshoots and undershoots and reduce the waiting time includes the adequate control strategy that takes advantage of the thermal capacity of a tank to minimize the temperature undershoots. Also, for the same purpose, it sets the lowest heat cell setpoint temperature to obtain the desired effect. To address the temperature overshoots problem, a bypass valve is used. In this case, the output desired temperature is achieved by mixing the cold input water with the overheated water from the heat cell. Lastly, this strategy combined with the control of the proportional valves, allows reduction of the water wasted.

Finally, the mechanical, thermal, fluidic and electrical design of the final solution was developed. The selection of each component was based on the data from the simulations and the datasheets' components available in the market. Also, the layout of the device was thought in order to be as compact as possible.

In conclusion, the results obtained from the simulations correspond to the main objective of this work. The system proposed and analysed seems to be a valid solution, capable of keeping the temperature overshoots and undershoots of the water heaters within the established narrow limits. Therefore, not producing a negative affect on the users' comfort when sudden changes occur in the water flow rate. In addition, the reduction of the waiting time in cold starts of the TGWH was achieved, thus promoting also water savings.

7.2 Suggestions for future works

This work was developed during the COVID-19 pandemic. As such, one of the initially proposed objectives was not possible to accomplish, given the imposed restrictions. The initial pre-pandemic goal was to assemble the designed solution and to test it, obtaining experimental results of its operation.

It is proposed for future works to complete the task that could not be developed under these circumstances, such as the assemble of all the components and finalizing the experimental tests necessary to prove the performance of the developed and proposed device.

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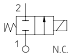
Appendices

Appendix A

2/2 way proportional acting 21A PRP N.C. Valve from *ODE*

CE



FEATURES

- Flow control solenoid valve
- Good repeability and low isteresys
- Different flow curves depending on the coil (contact our Customer Service)

TECHNICAL SPECIFICATION

- **Body material:** Brass UNI EN 12165 CW617N
- **Armature tube:** Stainless Steel AISI 300 series
- **Plungers:** Stainless Steel AISI 400 series
- **Spring:** Stainless Steel AISI 300 series
- **Media:** water, inert gases, mineral oils, gasoline
- **Ambient temperature:** See coils catalogue page for its compatibility
- **Fluid temperature:** -10°C +140°C with FKM seals
- **Design pressure PS:** 40 bar
- **Protection class:** IP65 (complete with electric plug)
- **Electrical conformity:** IEC 335

AVAILABLE ON REQUEST

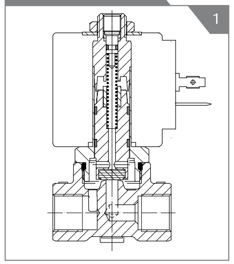
Proportional Electric Control System suitable on request, please consult the technical department for additional information

21A	2	KC	V	15	
Model valve	2= G 1/4	K= N.C.	V= FKM	15 20 25 30 45 55	Orefice 10^{-1}mm

B	D	A	08	024	A	S
B= 30mm Ø 13	D EN 175301-803	A= Class F	**08**= 8W	**024**= 24V	C= DC	S= Without Approval
U= 36mm Ø 13		V= Class H	**12**= 12W	**112**= 110V-120V	A= AC	S= Without Approval

PIPE	Ø (mm)	Kv (l/min)	MAX VISCOSITY cSt (°E)	PRESSURE min	PRESSURE MAX MOPD (bar) COIL TYPE AC			DC			GAS CODE	NPT CODE	DRAWING REFERENCE
					B	U	G	B	U	G			
G 1/4	1,5	1,4	21(3)	0	-	-	-	10	10	-	21A2KCV15-10		1
	2	2	21(3)		-	-	-	10	10	-	21A2KCV20-10		2
	2,5	3,2	21(3)		-	-	-	8	8	-	21A2KCV25-08		3
	3	4	21(3)		-	-	-	5	5	-	21A2KCV30-05		4
	4,5	6,4	21(3)		-	-	-	1,5	1,5	-	21A2KCV45-1X		5
	5,5	9	21(3)		-	-	-	-	1	-	21A2KCV55-01		6

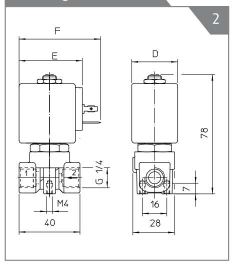
Section



REPAIR KIT
KT130KCV55-I

RELATED ITEMS
- P990305: Electrical plug EN 175301-803 Pg9
- P990306: Electrical plug EN 175301-803 Pg11

Drawing Reference

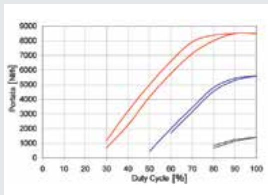


INSTALLATION
- Can be installed in any position
- Maintenance and instruction sheet available in each solenoid valve box

Flow Curve

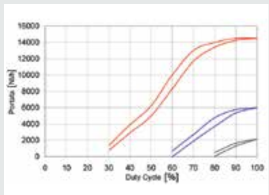
Produced with coil (8W); for 12W curve please consult technical departement

Coil 8W 1



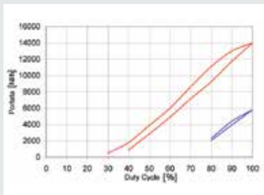
21A2KCV15-10

Coil 8W 2



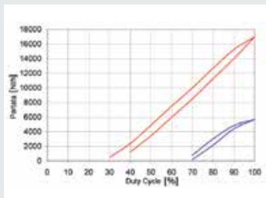
21A2KCV20-10

Coil 8W 3



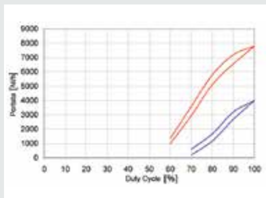
21A2KCV25-08

Coil 8W 4



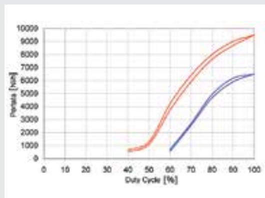
21A2KCV30-05

Coil 8W 5



21A2KCV45-1X

Coil 12W 6



21A2KCV55-01

Dimensionale Table

Figure	Coil Type	D mm	E mm	F mm
2	B	30	42	54
	U	36	48	60

Appendix B

Proportional electronic unit to control the proportional valve

Electronic Driver for Proportional Solenoid Valves

PECU5000/

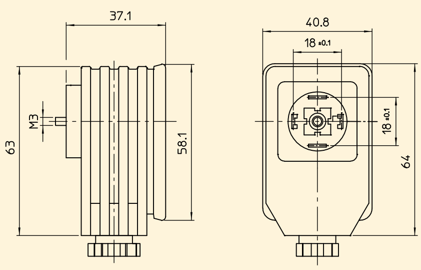
DESCRIPTION:

PECU (Proportional Electronic Control Unit) can be used on all ODE proportional flow valves with Din connector (both on 8W and 12W coils). To maintain a specific flow rate, current through the coil must be kept constant and indipendent from variations of coil resistance caused by temperature alterations. The control unit (PECU) uses a PWM (Pulse Width Modulation) signal that thanks to the dither technology is able to increase precision and histeresys. PECU is able to do different checks in real time and perform a quick valve regulation.

APPLICATION:

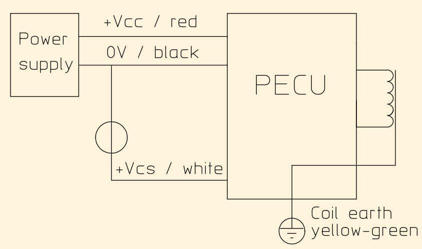
- Industrial flow control
- Industrial welding machinery
- Medical
- Dosing system

DIMENSIONS:



TECHNICAL DETAILS:

Supply voltage	24V DC - 5% + 10%
Input	0-10V or 4-20mA
Protection degree	IP 65
Operating temperature range	- 40°C + 80°C
Adjust by trimmer	- dither threshold frequency and amplitude - offset - rise/fall time
Electrical connection	EN 175301-803 paragraph 5.3.1
Connection cable	Ø 7 mm, -20°C + 80°C, flexible, oil and chemical proof (other lenght or temperature on request)

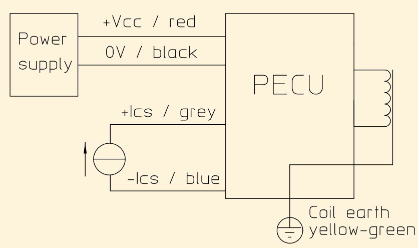


Connection diagram for 0-10V control signal

Code	Cable Lenght
PECU5000/1000	1000 mm
PECU5000/3000	3000 mm
PECU5000/5000	5000 mm

MATERIALS:

Body	PA6 + 30% glass fiber
Cover	Radel A-300
Gasket O-Ring	NBR



Connection diagram for 4-20mA control signal

The "ODE " reserves the right to carry out technical and aesthetic modifications without prior notification.

Appendix C

Digital therometer DS18B20 by *Maxim integrated*

DS18B20

Programmable Resolution 1-Wire Digital Thermometer

General Description

The DS18B20 digital thermometer provides 9-bit to 12-bit Celsius temperature measurements and has an alarm function with nonvolatile user-programmable upper and lower trigger points. The DS18B20 communicates over a 1-Wire bus that by definition requires only one data line (and ground) for communication with a central microprocessor. In addition, the DS18B20 can derive power directly from the data line ("parasite power"), eliminating the need for an external power supply.

Each DS18B20 has a unique 64-bit serial code, which allows multiple DS18B20s to function on the same 1-Wire bus. Thus, it is simple to use one microprocessor to control many DS18B20s distributed over a large area. Applications that can benefit from this feature include HVAC environmental controls, temperature monitoring systems inside buildings, equipment, or machinery, and process monitoring and control systems.

Applications

- Thermostatic Controls
- Industrial Systems
- Consumer Products
- Thermometers
- Thermally Sensitive Systems

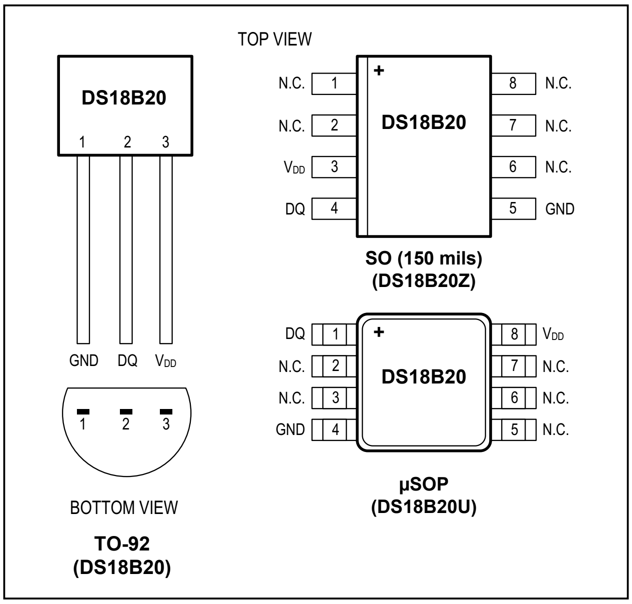
***Ordering Information* appears at end of data sheet.**

1-Wire is a registered trademark of Maxim Integrated Products, Inc.

Benefits and Features

- Unique 1-Wire® Interface Requires Only One Port Pin for Communication
- Reduce Component Count with Integrated Temperature Sensor and EEPROM
  - Measures Temperatures from -55°C to +125°C (-67°F to +257°F)
  - ±0.5°C Accuracy from -10°C to +85°C
  - Programmable Resolution from 9 Bits to 12 Bits
  - No External Components Required
- Parasitic Power Mode Requires Only 2 Pins for Operation (DQ and GND)
- Simplifies Distributed Temperature-Sensing Applications with Multidrop Capability
  - Each Device Has a Unique 64-Bit Serial Code Stored in On-Board ROM
- Flexible User-Definable Nonvolatile (NV) Alarm Settings with Alarm Search Command Identifies Devices with Temperatures Outside Programmed Limits
- Available in 8-Pin SO (150 mils), 8-Pin µSOP, and 3-Pin TO-92 Packages

Pin Configurations



19-7487; Rev 6; 7/19

Absolute Maximum Ratings

Voltage Range on Any Pin Relative to Ground ....-0.5V to +6.0V
Operating Temperature Range .... -55°C to +125°C
Storage Temperature Range .... -55°C to +125°C
Solder Temperature ....Refer to the IPC/JEDEC J-STD-020 Specification.

These are stress ratings only and functional operation of the device at these or any other conditions above those indicated in the operation sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods of time may affect reliability.

DC Electrical Characteristics

(-55°C to +125°C; V_{DD} = 3.0V to 5.5V)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Supply Voltage	V_{DD}	Local power (Note 1)		+3.0		+5.5	V
Pullup Supply Voltage	V_{PU}	Parasite power	(Notes 1, 2)	+3.0		+5.5	V
		Local power		+3.0		V_{DD}	
Thermometer Error	t_{ERR}	-10°C to +85°C	(Note 3)			±0.5	°C
		-30°C to +100°C				±1	
		-55°C to +125°C				±2	
Input Logic-Low	V_{IL}	(Notes 1, 4, 5)		-0.3		+0.8	V
Input Logic-High	V_{IH}	Local power	(Notes 1,6)	+2.2		The lower of 5.5 or V_{DD} + 0.3	V
		Parasite power		+3.0			
Sink Current	I_L	$V_{I/O}$ = 0.4V		4.0			mA
Standby Current	I_{DDS}	(Notes 7, 8)			750	1000	nA
Active Current	I_{DD}	V_{DD} = 5V (Note 9)			1	1.5	mA
DQ Input Current	I_{DQ}	(Note 10)			5		µA
Drift		(Note 11)			±0.2		°C

Note 1: All voltages are referenced to ground.
Note 2: The Pullup Supply Voltage specification assumes that the pullup device is ideal, and therefore the high level of the pullup is equal to V_{PU}. In order to meet the V_{IH} spec of the DS18B20, the actual supply rail for the strong pullup transistor must include margin for the voltage drop across the transistor when it is turned on; thus: $V_{PU\_ACTUAL} = V_{PU\_IDEAL} + V_{TRANSISTOR}$.
Note 3: See typical performance curve in Figure 1. Thermometer Error limits are 3-sigma values.
Note 4: Logic-low voltages are specified at a sink current of 4mA.
Note 5: To guarantee a presence pulse under low voltage parasite power conditions, V_{ILMAX} may have to be reduced to as low as 0.5V.
Note 6: Logic-high voltages are specified at a source current of 1mA.
Note 7: Standby current specified up to +70°C. Standby current typically is 3µA at +125°C.
Note 8: To minimize I_{DDS}, DQ should be within the following ranges: GND ≤ DQ ≤ GND + 0.3V or V_{DD} – 0.3V ≤ DQ ≤ V_{DD}.
Note 9: Active current refers to supply current during active temperature conversions or EEPROM writes.
Note 10: DQ line is high ("high-Z" state).
Note 11: Drift data is based on a 1000-hour stress test at +125°C with V_{DD} = 5.5V.

AC Electrical Characteristics–NV Memory

(-55°C to +125°C; V_{DD} = 3.0V to 5.5V)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
NV Write Cycle Time	t_{WR}			2	10	ms
EEPROM Writes	N_{EEWR}	-55°C to +55°C	50k			writes
EEPROM Data Retention	t_{EEDR}	-55°C to +55°C	10			years

AC Electrical Characteristics

(-55°C to +125°C; V_{DD} = 3.0V to 5.5V)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Temperature Conversion Time	t_{CONV}	9-bit resolution	(Note 12)			93.75	ms
		10-bit resolution				187.5	
		11-bit resolution				375	
		12-bit resolution				750	
Time to Strong Pullup On	t_{SPON}	Start convert T command issued				10	µs
Time Slot	t_{SLOT}	(Note 12)		60		120	µs
Recovery Time	t_{REC}	(Note 12)		1			µs
Write 0 Low Time	t_{LOW0}	(Note 12)		60		120	µs
Write 1 Low Time	t_{LOW1}	(Note 12)		1		15	µs
Read Data Valid	t_{RDV}	(Note 12)				15	µs
Reset Time High	t_{RSTH}	(Note 12)		480			µs
Reset Time Low	t_{RSTL}	(Notes 12, 13)		480			µs
Presence-Detect High	t_{PDHIGH}	(Note 12)		15		60	µs
Presence-Detect Low	t_{PDLOW}	(Note 12)		60		240	µs
Capacitance	$C_{IN/OUT}$					25	pF

Note 12: See the timing diagrams in Figure 2.
Note 13: Under parasite power, if t_{RSTL} > 960µs, a power-on reset can occur.

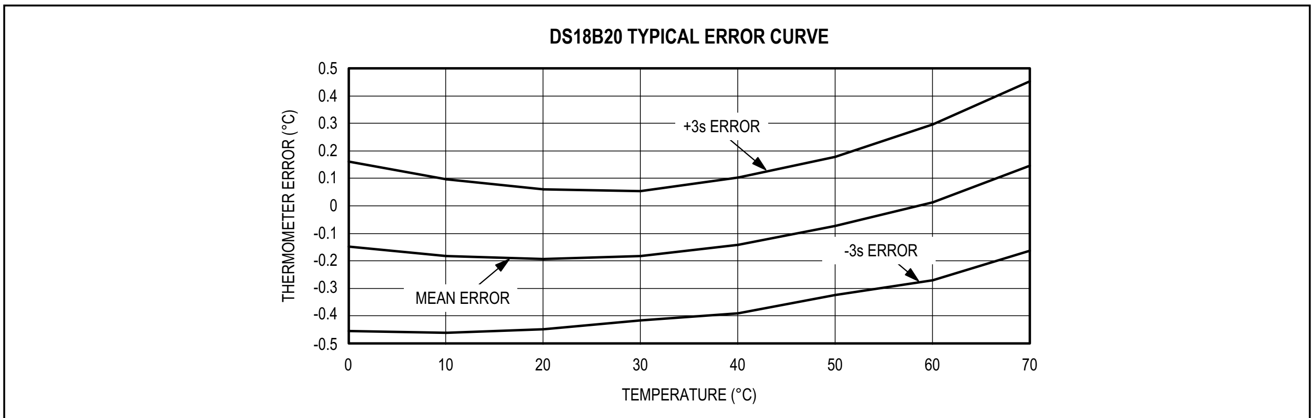


Figure 1. Typical Performance Curve

Appendix D

Arduino MEGA 2560 rev3

ARDUINO

ARDUINO MEGA 2560 REV3

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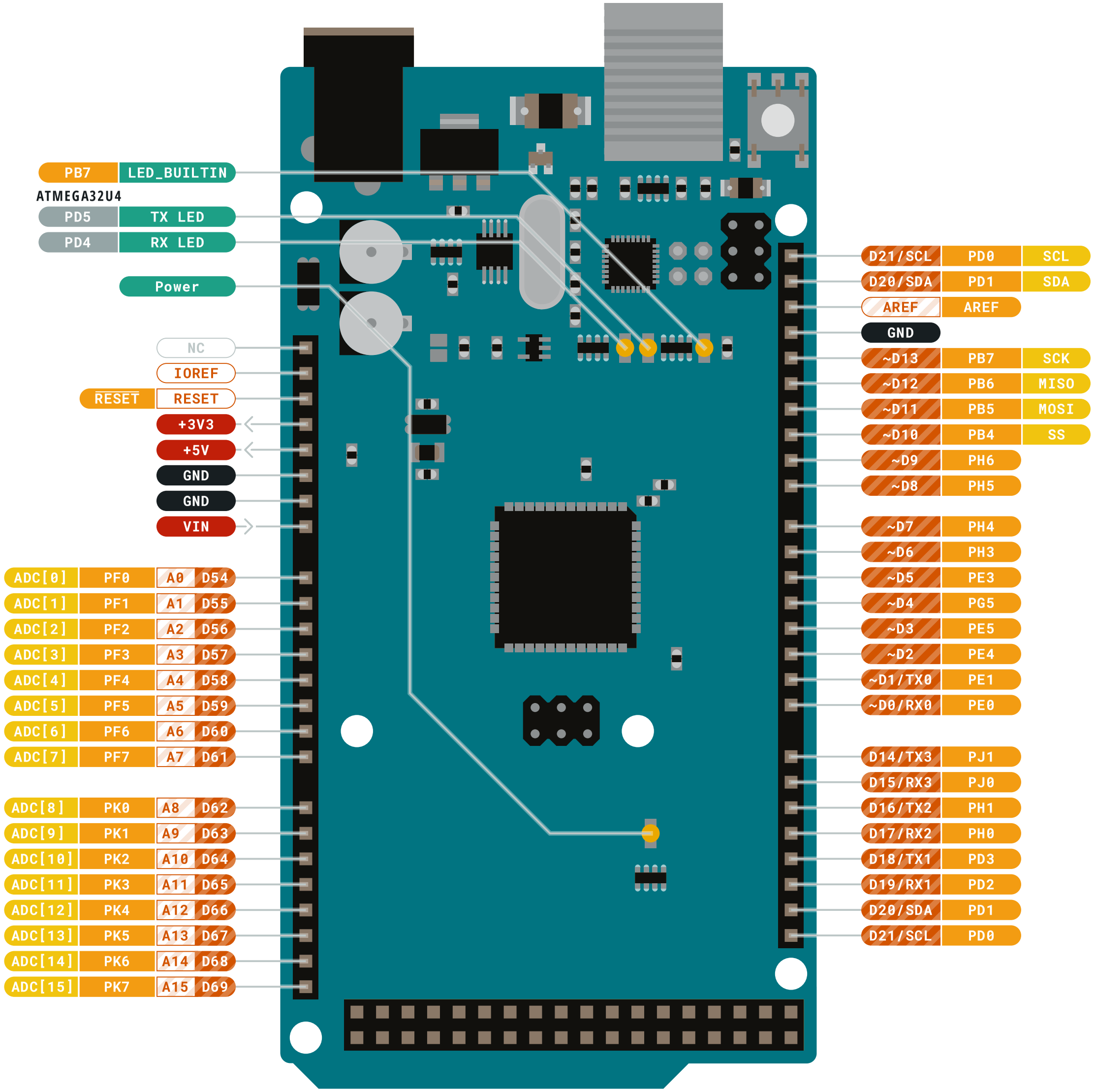


- Ground
- Power
- LED
- Internal Pin
- SWD Pin
- Digital Pin
- Analog Pin
- Other Pin
- Microcontroller's Port
- Default

MAXIMUM current per I/O pin is 20mA

MAXIMUM current per +3.3V pin is 50mA

VIN 6-20 V input to the board.

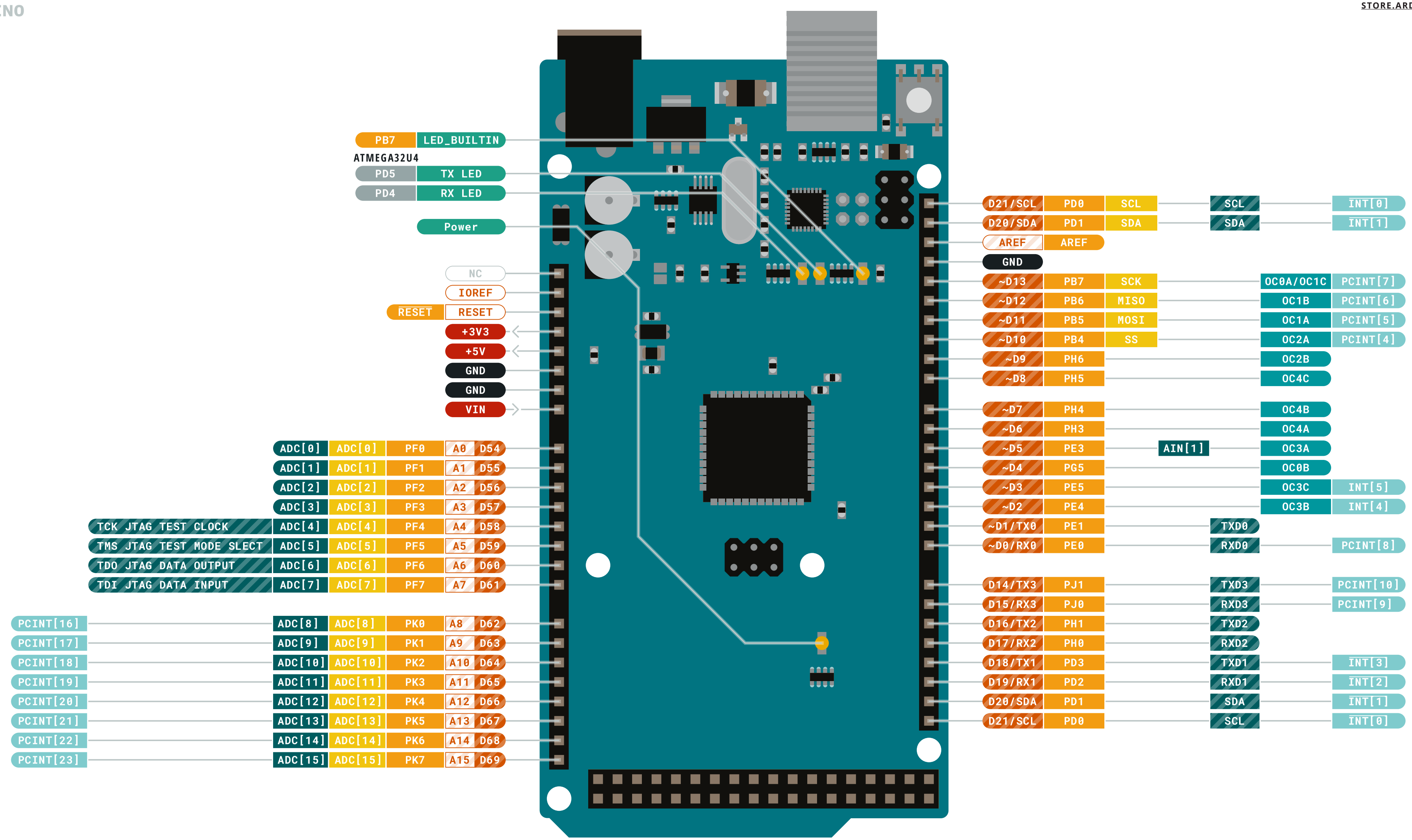
ARDUINO.CC

Last update: 17/06/2020

ARDUINO

ARDUINO MEGA 2560 REV3

STORE.ARDUINO.CC/MEGA-2560-REV3



- Ground
- Power
- LED
- Internal Pin
- SWD Pin
- Digital Pin
- Analog Pin
- Other Pin
- Microcontroller's Port
- Default
- Analog
- Communication
- Timer
- Interrupt
- Sercom

MAXIMUM current per I/O pin is 20mA

MAXIMUM current per +3.3V pin is 50mA

VIN 6-20 V input to the board.

ARDUINO.CC

Last update: 17/06/2020

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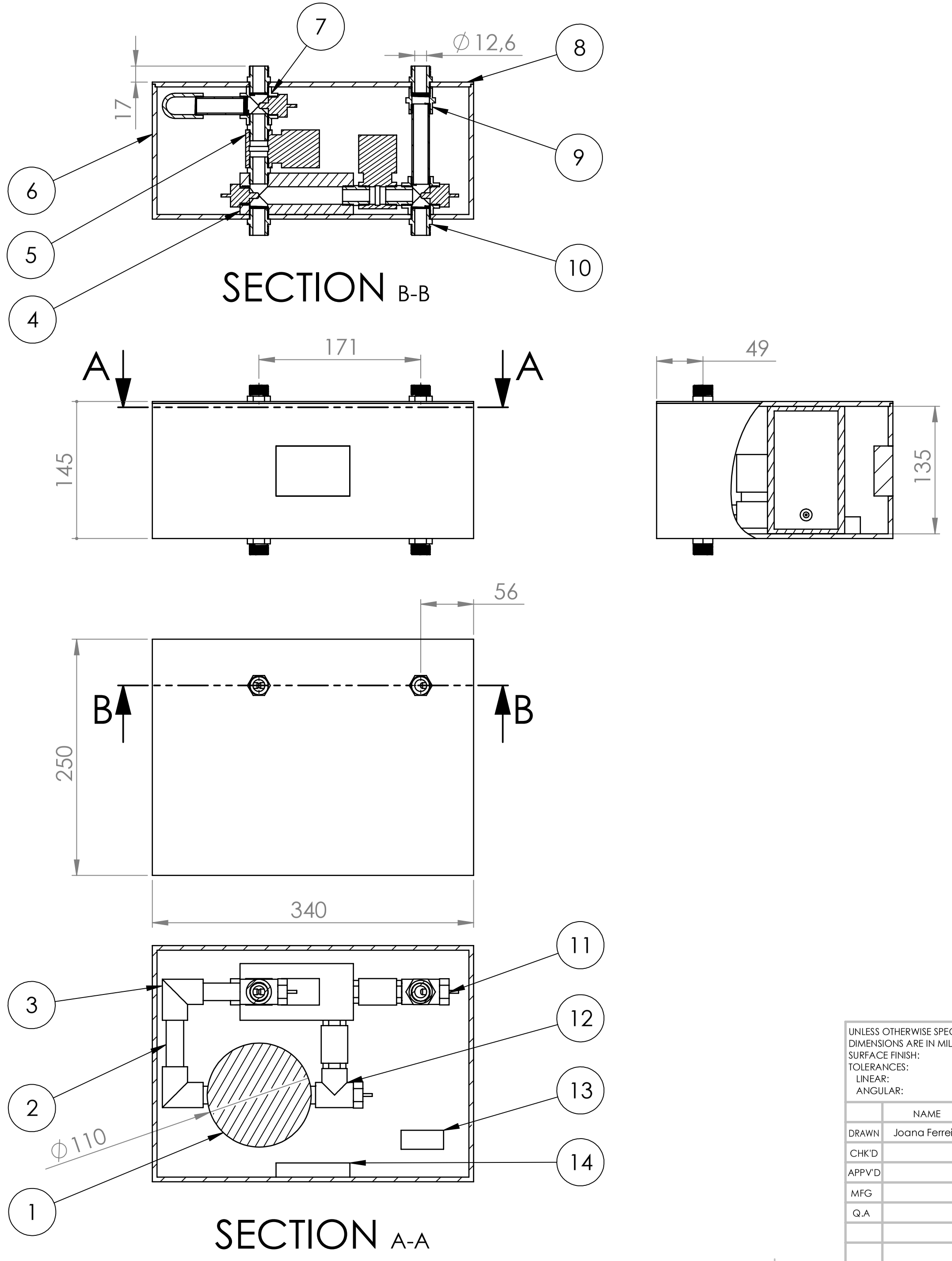
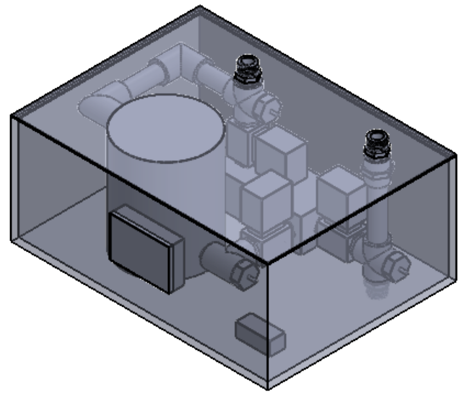
Appendix E

Mechanical design of the final project





ITEM NO.	DESCRIPTION	QTY.
1	Tank	1
2	1/4" Pipe	1
3	1/4" Elbow fitting	2
4	Mixing segment	1
5	Two-ways proportional valve	3
6	Outer box	1
7	1/4" Cross type fitting	2
8	Box cover	1
9	1/4" F-F adaptor	1
10	1/4" M-M adaptor	10
11	Temperature sensor	4
12	1/4" T type fitting	1
13	Microcontroller	1
14	Touch screen display	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Joana Ferreira		08/21
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Intelligent module

MATERIAL:

DWG NO.

A3

WEIGHT:

SCALE:1:5

SHEET 1 OF 1