Faculdade de Engenharia da Universidade do Porto

Smart Hydraulics Controller

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FINAL VERSION

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Major Automation

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Resumo

Smart Hydraulics Controller é um tema inserido na dissertação da Faculdade de Engenharia da Universidade do Porto, sugerido pela Bosch Termotecnologia, SA. Visa controlar o aquecimento de águas domésticas para um maior conforto e poupança ao nível do consumidor. Não só poupanças de energia mas também baixas emissões de poluentes.

Um dos problemas mais relevantes do aquecimento de água a gás é o controlo da temperatura de saída, para não haver variações bruscas que põe em causa o conforto do utilizador.

Neste projecto, foram estudados os objectos presentes num aquecedor de água a gás, para uma melhor interpretação dos conceitos usados num aquecedor como também os fenómenos presentes no aquecedor, como a transferência de calor, as várias formas de se transferir energia e também o permutador de calor, que é o objecto do aquecedor de água a gás onde ocorre a transferência do calor. Foram recolhidos vários métodos de controlo e feito o estudo de todos os métodos, para assim ser escolhido o que melhor se adequa ao objetivo proposto.

Depois deste estudo mais intenso sobre a teoria de um aquecedor, foi feito uma modelação na plataforma Matlab/Simulink de todo o sistema de aquecimento de água a gás, com atuadores, sensores, tubagens com o objetivo de modelar o sistema real com a implementação de várias formas de controlo para o sistema. Todos os procedimentos realizados no desenvolvimento deste modelo e da própria simulação são relatados neste documento.

Foi feito com sucesso o simulador de todo o sistema, tendo em conta todas as variáveis existentes.

Vários testes com diferentes temperaturas e diferentes caudais foram feitos para validar o sistema, e o resultado foi bastante satisfatório em todos os testes.

Abstract

Smart Hydraulics Controller is a subject inserted in the dissertation of the Faculty of Engineering of Oporto´s University, suggested by Bosch Thermotechnology, SA. It aims to control the heating of domestic water for increased comfort and savings at the consumer level. Not only energy savings for the consumer but also low emissions of pollutants.

One of the most important problems of gas water heating is the control of the output temperature so that there are no abrupt changes that undermine user´s comfort.

In this project, we studied objects that are present in a gas water heater, so as to have a better interpretation of the concepts used in a heater but also studied the phenomena present in the heater, such as heat transfer, the several ways of transferring energy and also heat exchanger, which is the object of the gas water heater where heat transfer occurs. Various control methods have been collected and made the study of all methods for choose the best for proposed goal.

After this study more intense on the theory of a heater water was made a model in Matlab/Simulink of entire gas water heater system in order to model the real system with the implementation of various forms of control for the system. All procedures performed in the development of this model and the simulation itself are reported here.

It was successfully done all simulator of the system, taking into account all existing variables.

Several tests with different temperatures and different flow rates were made to validate the system, and the result was quite satisfactory in all tests .

Acknowledgments

Firstly, I want to thank my teacher and advisor António Pina Martins for his constant help and experience which helped me complete this thesis.

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Abbreviations and Symbols

List of abbreviations (sorted alphabetically)

ADC	Analog to digital converter
AFR	Air-Fuel Ratio
DAC	Digital to analog converter
DEEC	Department of Electrical and Computer Engineering
ECU	Eletronic Control unit
FEUP	Faculty of Engineering – University of Porto
MF	Membership function
ODE	Ordinary differential equation
RPM	Revolutions per minute
SA	Sociedade Anónima
WF	Water Flow

List of symbols

Q	Transferred heat flow
k	Thermal conductivity of the material
L	distance
T	Temperature
Ra	Rayleigh number
Re	Reynolds number
ΔP	Pressure gradient
G	gravitational acceleration
μ	Viscosity
j*	energy flux density
s	surface emissivity
σ	Stefan-Boltzmann constant
m	mass
C_{flow}	Fan law flow coefficient
$C_{pres.}$	Fan law pressure coefficient
C_{power}	Fan law power coefficient
$\dot{m}$	Mass flow
M	Molar mass
P	Pressure
Q	Heat
Kv	Flow coefficient of valve

Chapter 1

Introduction

This thesis has as main objective the control of a gas water heater in order to improve comfort and reduce energy consumption, which will be controlled through several actuators that are already present in the water heater. This chapter presents the context, objectives and motivation to carry out this thesis.

1.1 Context

This issue arose in the context of Master Thesis of Electrical and Computer Engineering, proposed by Bosch Thermotechnology, SA.

The difficulty in obtaining a stable temperature at the outlet of a water heating system is one of the main problems of a water heater. The existence of undershoots and overshoots is considered an obstacle for the stability of the water temperature. This is, during use, water temperature does not vary due to the various obstacles that may occur, which causes inconvenience to the user.

1.2 Objectives

Therefore, the objective is to study several concepts, in order to select the best type of control of the temperature of the water that remains in the user-requested values, thus improving comfort and efficiency of the appliance. Furthermore, it is requested to develop a suitable controller in MATLAB / SIMULINK and validate the solution by comparing with a measured values.

1.3 Motivation

Gas water heater is the domestic equipment that is used more for this purpose. Almost all households have this equipment. One of the main factors of choice is energy efficiency. We are in an era where “saving” is a word that is present in the daily lives of all people, thus the extreme importance of this issue. In addition by having a better control of the water heater, greater comfort for the user is achieved, which is another essential factor when choosing equipment. Based on these three main factors, the work will be focused in improving comfort, decreasing consumption and low Nox emissions.

Another motivation is the ability to carry out this work in a manufacturing environment, a company based on innovation and research, very well-known Bosch Thermotechnology, SA.

1.4 Document Structure

The document is divided in five chapters and it is present here.

The first chapter is to introduce the context of this dissertation, the objetives presents here and also the motivation of this work.

Chapter 2 is a bibliography revision of all parts referred to the system in study.

Chapter 3 details the modulation made for all system and control architecture.

Chapter 4 is a demonstration of control architecture and its results.

Chapter 5 is a reflection and discussion of results. Presents too the whole project work and possible future work.

Chapter 2

State of Art

This section studied the theoretical basis of the system as well as the technologies used to perform the control of the gas water heater. First will be described the operation of a gas water heater. Next, the methods used for heat transfer and lastly, the study of several existing control methods.

2.1 Gas water heater

Nowadays, a water heater is essential in a home. The comfort it gives is much appreciated by users, mainly in winter; people are pleased to have hot water throughout their home for household doings and for personal hygiene.

A domestic gas water heater is generally constituted by a water circuit; the gas inlet; a burner; fan; a heat exchanger surrounded by a coil; a pressure sensor; a smoke exhaust and a pressure valve. Here we have the constitution of the water heater in greater detail.

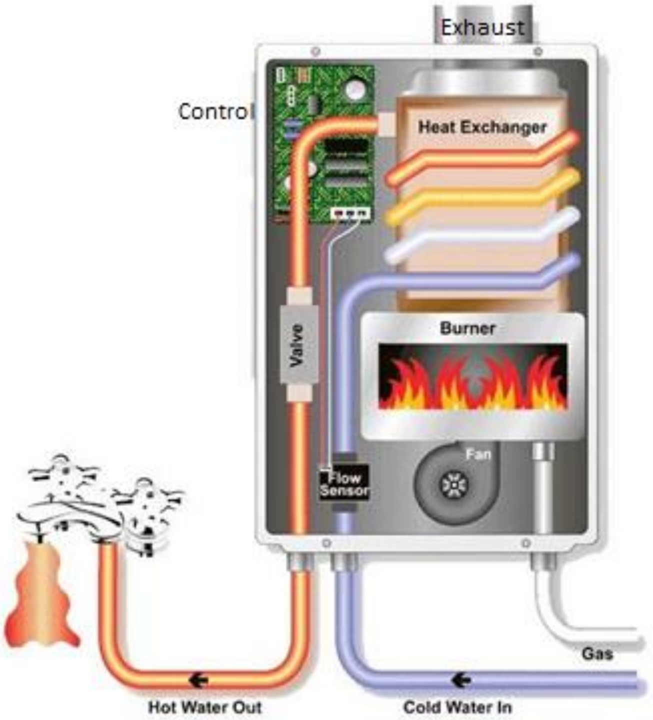

Figure 1: Description of water and gas heater (Bosch, 2016)

Gas Admission- where the gas supply to the water heater is made, more precisely to the combustion chamber so that combustion can later be realized. Normally, natural, propane or butane gas is used.
Cold Water In- is the main feature of the system, and takes the water to the heating circuit.
Flow Sensor- It provides the controller with the water flow requested by the user and indicates when it is necessary to turn on the heater. It also serves as the water flow limiter.
Fan- It is responsible for the air inlet to the combustion chamber. With the RPM control it is possible to control the air flow.
Burner- The flame is ejected controllably to the exchanger, so as to obtain a stable flame.
Heat Exchanger- This is where the heat transferred by the flame / gas accumulates, so that it can later transmit heat to the surrounding water pipes of the heat exchanger. The efficiency of the heater depends on the heat transfer capacity of the material.
Exhaust- It is responsible for outgassing effects of combustion.
ECU- Control unit and also human interface. This is where the user can choose what he/she wants, in this case the outlet temperature and water flow.
Valve- Water outlet pressure valve.
Hot water out- It is the final "product". The hot water output is going to interact with the user for comfort.

The working process can be described by the following stages:

1- Hot water tap is turned on.
2. The water enters the heater.
3. The water flow sensor detects water.
4. The computer turns on the burner automatically.
5. The water circulates in the surrounding exchanger circuit.
6. The water reaches the previously designated temperature.
7. When the tap is closed, the system shuts down.

2.2 Energy transfer

Energy transfer in the form of heat can occur by three different processes, namely:
-Conduction;
-Convection;
-Radiation;

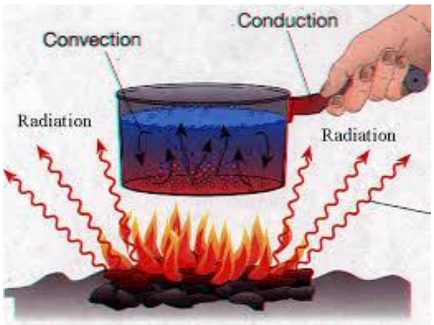

Figure 2: Energy transfer in heat

These processes will be described in more detail below.

2.2.1 Conduction

When two bodies at different temperatures are placed in contact, there is heat transfer from the high temperature body to the low temperature body.

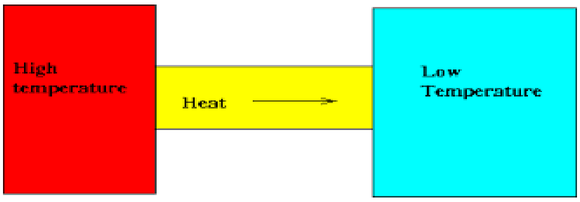

Figure 3: Energy transfer by conduction

It is known that the higher the temperature variation incurred, the greater the amount of energy transferred in the form of heat. Conduction occurs in solids, and will not depend only on temperature differences but also on the distance of the two bodies in contact

The formula for determining the flow of heat transferred depends on these two factors which results in equation (2.1):

$$Q = -k \,.\frac{(T2-T1)}{L} \qquad (2.1)$$

Where k is the thermal conductivity of the material; L the distance between the bodies and the temperature T1 and T2 of the corresponding bodies.

2.2.2 Convection

Convection is another process of energy transfer in the form of heat, but in this case for liquid or gas.

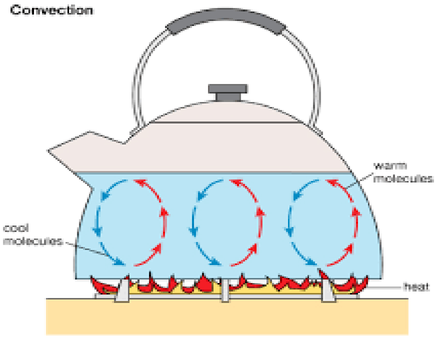

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Figure 4: Convection

Convection works as follows: the water at the bottom is heated and its temperature increases. As the temperature increases, it becomes less dense than cold water and therefore tends to rise, forcing cold water to descend. When coming down, it is heated and thus its temperature rises. It becomes less dense and rises to the surface, forcing the water that is on the surface to descend to be heated. Therefore currents of warm water rising and cold water descending are formed. These currents are named convection currents. Thus, all the water temperature is increased. This method not only works with fluids but also with air.

The formula for thermal convection is determined by the Rayleigh number (2.2):

$$Ra = \frac{\Delta\rho. g. L^3}{D. \mu} \qquad (2.2)$$

Where ΔP is the difference of densities; g is the gravitational acceleration; L is the length of convection; D is the diffusivity; and μ is the viscosity.

2.2.3 Radiation

Thermal radiation is when heat is transferred by electromagnetic waves. Human beings receive heat of the sun in the same way. The Stefan-Boltzmann law (2.3) determines the total energy radiated by the surface area unit.

$$\mathrm{j = s.\sigma.T^4} \tag{2.3}$$

Where s is the surface emissivity, σ is the Stefan-Boltzmann constant and T is the temperature of the body.

2.3 Heat exchanger

In the case of a gas water heater, heat is transferred by the exchanger. The exchanger is used to transfer heat from a medium to another. An exchanger is typically used to heat or cool a fluid, and the most important factor in this method is the constituent material of the exchanger, it must be a material with a high coefficient of thermal conductivity.

There are several types of exchangers, such as tubular, plates and also finned surfaces. The one used in this case is tubular, and will be detailed.

For the analysis of exchangers, we can make an energy coefficient exchanged between the fluid / hot air with the fluid / cold air. This coefficient is described by equation (2.4):

$$\mathrm{Q = (Abase + Afin).h.(Tfluido - Tsuperficie)} \tag{2.4}$$

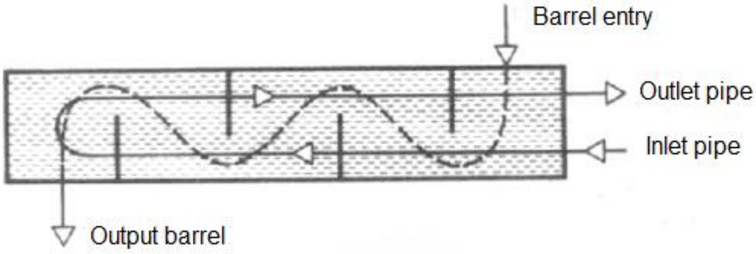


Figure 5: Functioning of heat exchanger

The system works as follows: warm air enters the barrel, which contains the pipes with the water to be heated. Hot air passes through the tubes, heating the water, leaving the barrel. Water undergoes the circuit until the requested temperature is reached, thus leaving the pipes hot.

2.4 Fluid Mechanics

Fluid mechanics studies the mechanics of liquids, gases and plasmas and the forces involved in them. A part of fluid mechanics is fluid dynamics that studies the effect of forces on fluid motion.

Fluid dynamics also treats the pressure drop in pipes. All pipes have pressure losses, but differ from material to material, and differ from lines to curves, valves, etc. It is caused by friction, height difference in the pipes, variation of kinetic energy and this leads us to a calculation of pressure drop. The resistance to flow in a liquid can be characterized in terms of the viscosity of the fluid if the flow is smooth.

2.4.1 Fluid pressure drop for pipes

To calculate the fluid pressure drop, it's necessary to use Reynolds equation (2.5), to determine the pipe friction coefficient and finally determine the pressure drop.

$$\mathrm{Re} = \frac{\omega . \mathrm{D}}{\mathrm{v}} \tag{2.5}$$

Where ω flow velocity, D is the diameter of the pipe and v is liquid kinematic viscosity.

There are two types of flows, the laminar flow and the turbulent flow which is chosen by Reynolds number. If Re < 2320, it's laminar flow. Laminar flow is more common in small pipes and low velocities. It is characterized by displacement of cylindrical layers in orderly shape. The velocity of the fluid is bigger in the center of the pipe, and decreases sharply to zero in wall pipe. The pressure drop of laminar flow doesn't depend on the roughness of the pipe.

If Re >2320, it is turbulent flow. There is an irregular movement of fluid particles in transverse directions of the main flow and the velocity of turbulent flow is more uniform through the pipe than in laminar flow. In this type of flow, the pressure drop depends on the roughness of pipe.

After deciding if it is turbulent or laminar flow, the next step is to determine the pipe friction coefficient, λ that have two different ways, one for laminar flow and another for turbulent flow.

Pipe friction coefficient to laminar flow (2.6):

$$\lambda = \frac{64}{\mathrm{Re}} \tag{2.6}$$

Pipe friction coefficient to turbulent flow is through the Colebrook equation (2.7):

$$\frac{1}{\sqrt{\lambda}} = -2.\log[\frac{2.51}{\mathrm{Re} . \sqrt{\lambda}} + \frac{\mathrm{k}}{\mathrm{D}} .0.269] \tag{2.7}$$

Where g is acceleration of gravity, Re Reynolds number, k is roughness and D is diameter of pipe. In the following chart, the roughness coefficient is represented

Surface	**Absolute Roughness Coefficient - *k* -**	
	(m) 10^{-3}	***(feet)***
Copper, Lead, Brass, Aluminum (new)	0.001 - 0.002	3.33 - 6.7 10^{-6}
PVC and Plastic Pipes	0.0015 - 0.007	0.5 - 2.33 10^{-5}
Stainless steel	0.015	5 10^{-5}
Steel commercial pipe	0.045 - 0.09	1.5 - 3 10^{-4}
Stretched steel	0.015	5 10^{-5}
Weld steel	0.045	1.5 10^{-4}
Galvanized steel	0.15	5 10^{-4}
Rusted steel (corrosion)	0.15 - 4	5 - 133 10^{-4}
New cast iron	0.25 - 0.8	8 - 27 10^{-4}
Worn cast iron	0.8 - 1.5	2.7 - 5 10^{-3}
Rusty cast iron	1.5 - 2.5	5 - 8.3 10^{-3}
Sheet or asphalted cast iron	0.01 - 0.015	3.33 - 5 10^{-5}
Smoothed cement	0.3	1 10^{-3}
Ordinary concrete	0.3 - 1	1 - 3.33 10^{-3}
Coarse concrete	0.3 - 5	1 - 16.7 10^{-3}
Well planed wood	0.18 - 0,9	6 - 30 10^{-4}
Ordinary wood	5	16.7 10^{-3}

Table 1: Roughness coefficient

Another way of calculation, through the Reynolds number, the pipe friction coefficient can be calculated based on Moody Diagram.

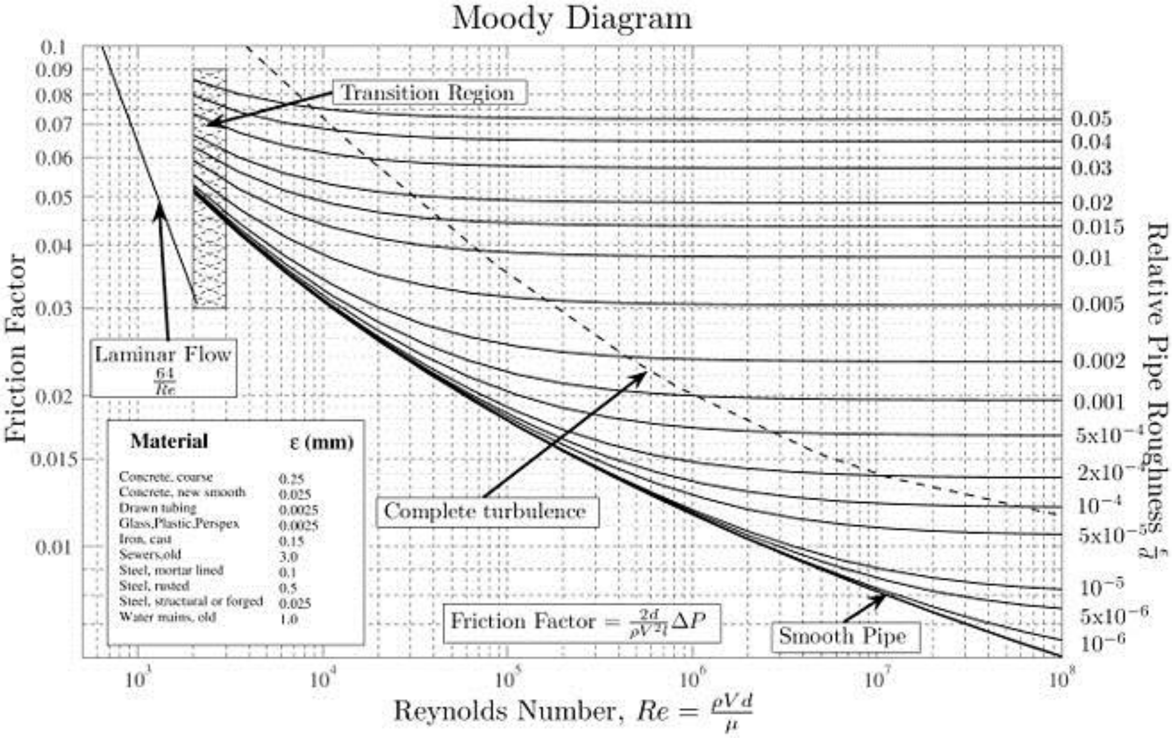


Figure 6: Moody Diagram (Wikipedia, 2016)

With this, the final step to determine pressure drop through equation (2.8).

$$\Delta P = \frac{8 \, . \, \lambda \, . \, L \, . \, Q^2}{\pi^2 \, . \, g \, . \, D^5} \tag{2.8}$$

Where λ is Pipe friction coefficient, L is length of pipe, D is pipe diameter, g is gravity and Q is flow.

2.4.2 Fluid located pressure drop

Located pressure drop is pressure drop in curves, valves or connectors. The formula to calculate is equation (2.9)

$$\Delta P = k \, . \, \lambda \, . \, L \, . \, (\frac{v^2}{2g}) \tag{2.9}$$

When k is curve or valve coefficient, λ is friction coefficient, L the length of pipe, v is velocity and g is gravity.

Curve or valve coefficient is tabulated and λ is calculated by the same formula. The next chart represents curves and valves coefficient.

Type	K
Open valve	0.2
Half-open Valve	5.6
90º curve	1
45º curve	0.4
Extension	$(1-(D_1/D_2)^2)^2$

Table 2: k coefficient

2.5 Control Methods

For this work we propose a control method for a linear or non-linear system with several inputs and outputs. The monitoring will be focused on the combustion so that at the outlet there are no offsets of the required temperature, improving comfort of the user.

Its objective is to optimize the response and stability, but also improve the monitoring of reference and the rejection of system disturbance.

The entire system cannot be controlled by the controller; there are several obstacles that do not allow the system to be fully controlled. Thus from the beginning you need to consider these adversities so that the final result can be correct, we must also make a made good interpretation of the sensors and actuator. A weak system can be achieved through several incorrect actions, for example: incorrect assembly botched, low resolution, lack of precision, among others. Several control methods for the project will be presented below.

2.5.1 PID

This is the control method with best known feedback, due to its simplicity of implementation, its robustness and quality of the results, as its name suggests, there are three different parts, the proportional part, the integral part and derivative part . There are several ways to configure a PID controller, these being for example P, I, D, PI, PID, among others; the most used in the control are P, PI and PID.

2.5.2 Proportional

It is the simplest method of construction and control. The output signal is adjusted proportionally to the error by entering a steady-state error. The equations (2.10) shows the proportional action:

$$u(t) = Kp.e(t) \tag{2.10}$$

$$C(s) = Kp$$

Where Kp is the proportional gain. A proportional controller is basically an amplifier with adjustable gain.

2.5.3 Proportional-Integral

Improves steady regime against the Proportional and corrects the offset that may occur. PI controllers are commonly used in process industries with slow variables such as pressure, flow, etc.

The equation below shows the proportional-integral action:

$$u(t) = Kp.\left[e(t) + \frac{1}{T_f}\int_0^T e(\tau)d\tau\right] \tag{2.11}$$

$$C(s) = Kp.\left[1 + \frac{1}{sT_f}\right] = Kp.\frac{(s + \frac{1}{T_I})}{s} \tag{2.12}$$

2.5.4 Proportional-Integral-Derivative

It is the best known and most used controller. It can be used in several systems from systems with a single input and a single output to multiple inputs and multiple outputs. In this type of controller, the integral mode is used to eliminate the steady error caused by large variations; the derivative mode, stabilized, allowing increased gain and reduction of the oscillations, allowing higher speed of response.

$$u(t) = Kp.\left[e(t) + \frac{1}{T_I}.\int_0^t e(\tau)d\tau + T_D.\frac{de(t)}{dt}\right] \tag{2.13}$$

$$C(s) = Kp.\left[1 + \frac{1}{s.T_I} + sT_D\right] = Kp.\frac{(s^2.T_I.T_D + sT_I + 1)}{sT_I} \tag{2.14}$$

The PID controllers must be sized correctly otherwise the system will become unstable. The methods used to adjust the PID gains are Ziegler-Nichols and Cohen-Coon.

2.5.4.1 Ziegler-Nichols in Open loop

This method determines the Kp, Ti and Td values from the transient response characteristics of the system. Its objective is to obtain a maximum overshoot of 25%.

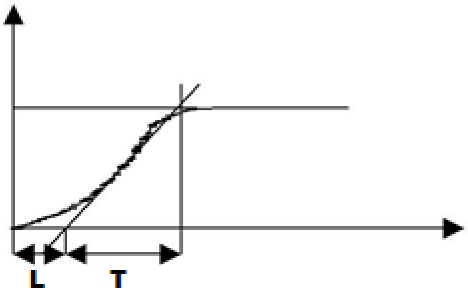


Figure 7: Ziegler-Nichols method in open loop

A chart is shown with the determination of Kp, Ti and Td values.

Controller type	Kp	Ti	Td
P	$\frac{T}{L}$	∞	0
PI	$0.9\ \frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\ \frac{T}{L}$	2L	0.5L

Table 3: PID tunning

2.5.4.2 Ziegler-Nichols in closed loop

In closed loop, we calculate the critical K (Kcr) considering only the proportional gain, ie, Td is equal to 0 and Ti equal to infinity. Furthermore it is necessary to determine the frequency of oscillation and the critical period (Pcr).

Controller type	Kp	Ti	Td
P	$0.5K_{CR}$	∞	0
PI	$0.45K_{CR}$	$\frac{1}{1.2}P_{CR}$	0
PID	$0.6K_{CR}$	$0.5P_{CR}$	$0.125P_{CR}$

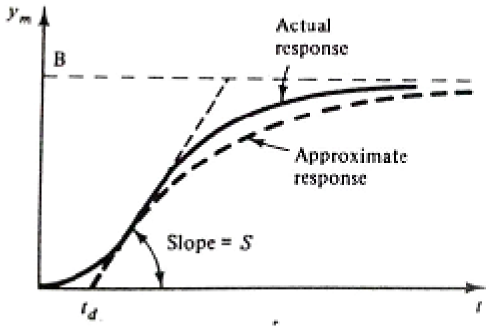
Table 4: PID tuning in closed loop

2.5.4.3 Cohen-Coon

This method is performed in open loop and needs only a condition for determining the control parameters. Compared to the Ziegler-Nichols method it is easier and safer. To accomplish it, it is necessary to follow the following steps:

1. Leave the system at steady state in normal charge;
2. Place the controller in manual mode;
3. Apply a variation in size degree A at the controller output, or in signal to the valve;
4. Store the record output (controlled variable) in time;
5. Return the system to automatic.

This model has three parameters, they are the gain K, the dead time Td, and time constant τ.



$K = \frac{\text{steady state output}}{\text{input at steady state}} = \frac{B}{A}$

$\tau = \frac{B}{S}$ Where S is the slope at the inflection point.

t_d= time until the system responds

Figure 8: Response Model

	K_c	τ_i	τ_d
Proportional(P)	$\frac{\tau}{K * t_d}\left(1 + \frac{t_d}{3\tau}\right)$		
Proportional-integral (PI)	$\frac{\tau}{K * t_d}\left(0.9 + \frac{t_d}{12\tau}\right)$	$t_d \frac{30 + 3^{t_d/\tau}}{9 + 20^{t_d/\tau}}$	
Proportional-integral-derivative(PID)	$\frac{\tau}{K * t_d}\left(\frac{4}{3} + \frac{t_d}{4\tau}\right)$	$t_d \frac{32 + 6^{t_d/\tau}}{13 + 8^{t_d/\tau}}$	$t_d \frac{4}{11 + 2^{t_d/\tau}}$

Table 5: Gains of K_c, τ_i and τ_d

In general, it is noted that the gain of the PI is less than the gain of the P because the integral makes the system more sensitive and even more unstable. On the other hand the derivative action allows higher gains for its stabilizing effect.

2.5.5 Fuzzy Method

One of the most viable alternatives to PID controllers is the logic Fuzzy. So it is studied in this thesis. The Fuzzy logic supports the modes of reasoning which are approximate to the required result and provides the basis for the development of modeling and control systems. In more complex systems, this logic has difficulty in covering all the possibilities that may arise.

An example of fuzzy logic is:

- IF the temperature is low THEN increase heat output. Operators follow natural rules of reasoning for better analyses and determination of the final result.

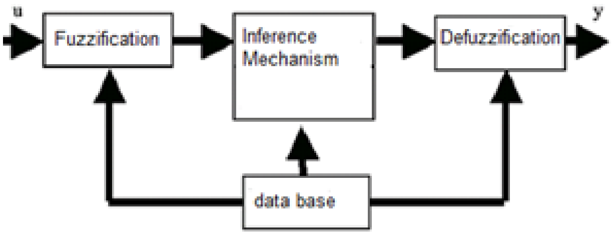


Figure 9: Diagram of Fuzzy Blocks

A Fuzzy controller consists of 5 steps. The first step is the transformation of problematic variables into fuzzy values. The second step is the use of fuzzy operators. Posteriorly an implication that serves to define "weights" in the result or remodel the function is applied. The fourth step is the combination of all possible outcomes. The last step is the *defuzzification*, which returns the desired numerical values in the fuzzy logic.

2.5.5.1 Fuzzification

Fuzzification is the transformation of the problem variables in fuzzy values. This is, each input value is associated with a relevance function, Membership, which enables us to obtain the degree of truth of the proposition. Then the degree of relevance of the proposition is determined. And limit the input value between 0 and 1.

There are several types of Membership, such as the ones demonstrated in the image below:

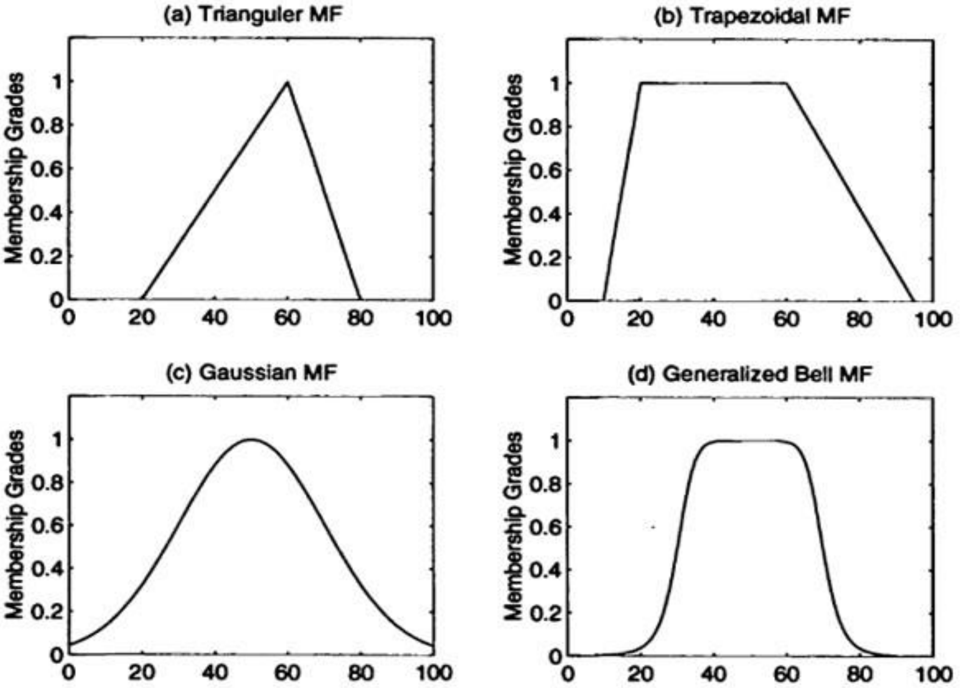


Figure 10: Examples of membership functions

2.5.5.2 Inference

This is where the fuzzy operators are applied, as well as the clear logic operators: AND and OR. It also applies the implication operator to set the weight in the result. An example is "Service is excellent OR quick service THEN payment is high." Finally in this stage, all the combinations of fuzzy outputs is made. For this implication mechanism, there are several different methods, but the most suitable are the "*Mamdani*" and "*Takagi-Sugeno*". *Mandani* is a linguistic controller and *Takagi-Sugeno* expresses the results in numerical values and non-Fuzzy sets as *Mandani* method.

2.5.5.3 Defuzzification

In this stage the interpretation of fuzzy sets and the return on numerical values is made. The most common methods are -maximums; - Average maximum; -centroid; -height. The objective is to obtain a single numerical value that best represents the fuzzy values.

Chapter 3

Project Modelling

To understand and forecast all the variables, it is necessary to know how it works and only after develop the modelling. The gas water heater system was developed in Matlab/Simulink environment.

The main feature of this model, taking all the variables into this system, is to be capable to simulate a real utilization. With this model, it is possible to simulate several operative situations, and through them plan the best way to control the system, without having the necessity to use an equipment to realize this assay.

In this chapter, the most important modules for the system modelling are explained, and where I have given more focus. This system contains all delays in sensor reading, delays and pressure drop in pipes, for a better and more efficient control.

Then the whole system is demonstrated for a better understanding. The most important modules in this project are Gas valve, blower, water and bypass valve.

The logic behind the system is through a reference temperature, ECU controls gas valve, blower and water valve to lead output temperature to reference temperature. And if output temperature “transmits” to ECU that temperature is bigger than reference temperature, it commands bypass valve to bring output temperature to reference temperature.

Figure 11 describes that behavior by ECU.

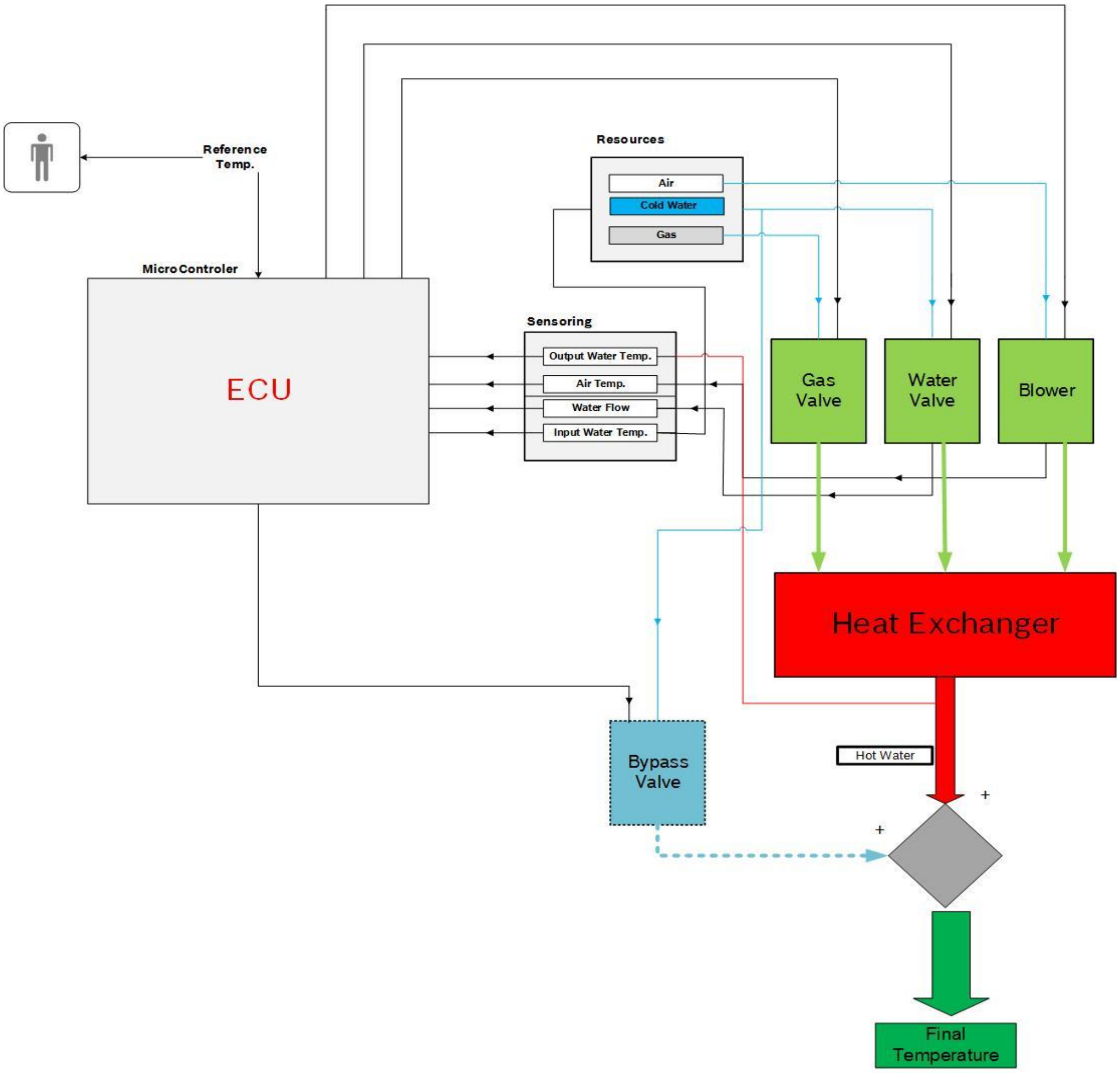


Figure 11: System diagram

3.1 Gas Valve

Gas valve is an important actuator for the burner in order to deliver energy for combustion. It is important to control the valve so that it can provide the exact gas flow to the burner in order to make the best combustion, and also together with the blower become the combustion in a stoichiometric mixture.

Gas valve can be driven through a step-motor or electromagnetically. It allows modelling the gas flow. In order to control this valve we must note the different pressures, inside and outside the valve. The next image demonstrates a valve.

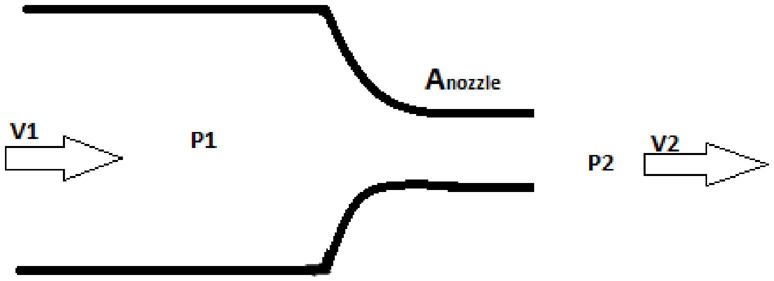


Figure 12: Functioning of gas valve

In the gas valve, the variation of flow is described by Bernoulli equation. In equation (3.1), P1 e V1 is pressure and velocity inside. P2 e V2 is pressure and velocity outside of the valve. The variable z is the height of the valve.

$$P_1 + \frac{1}{2}\rho_1 . v_1^2 + \rho_1 g z_1 = P_2 + \frac{1}{2}\rho_2 . v_2^2 + \rho_2 g z_2 \quad (3.1)$$

In this case,$z_1 = z_2$, $\rho_1 = \rho_2$ and v_1 is lower than v_2, v_1 is considered equal at zero. Now, to simplify the equation (3.2).

$$P_1 = P_2 + \frac{1}{2}\rho v_2^2 \quad (3.2)$$

It is now possible to estimate the gas flow (3.4) as a function of ΔP, pressure gradient (3.3).

$$\Delta P = \frac{1}{2} \times \rho_{fuel} \times \left(\frac{\dot{V}_2}{A_{nozzle}}\right)^2 \quad (3.3)$$

$$\dot{V}_2 = \sqrt{\frac{2 \times \Delta P \times {A_{nozzle}}^2}{\rho_{fuel}}} \quad (3.4)$$

3.1.1 Implementation

This model of gas valve needs a valve position given in mA and also a segmentation position. Segmentation position is because the burner is divided in segments. It is divided in three segments where each one has several nozzles, and each nozzle gives a different capacity. The more the nozzles, the more the gas flow and the more power for the burner.

The burner has 3 segmentations, A, B and C, how can understanding in the next figure.

A is the “pilot” segment, only for ignition. The segment with fewer nozzles, therefore the segmentation is less powerful. This means that all others segments are already burning to propagate the flame. B is second segment; it is bigger than A. Lastly segment C which is the combination of A and B and consequently the most powerful.

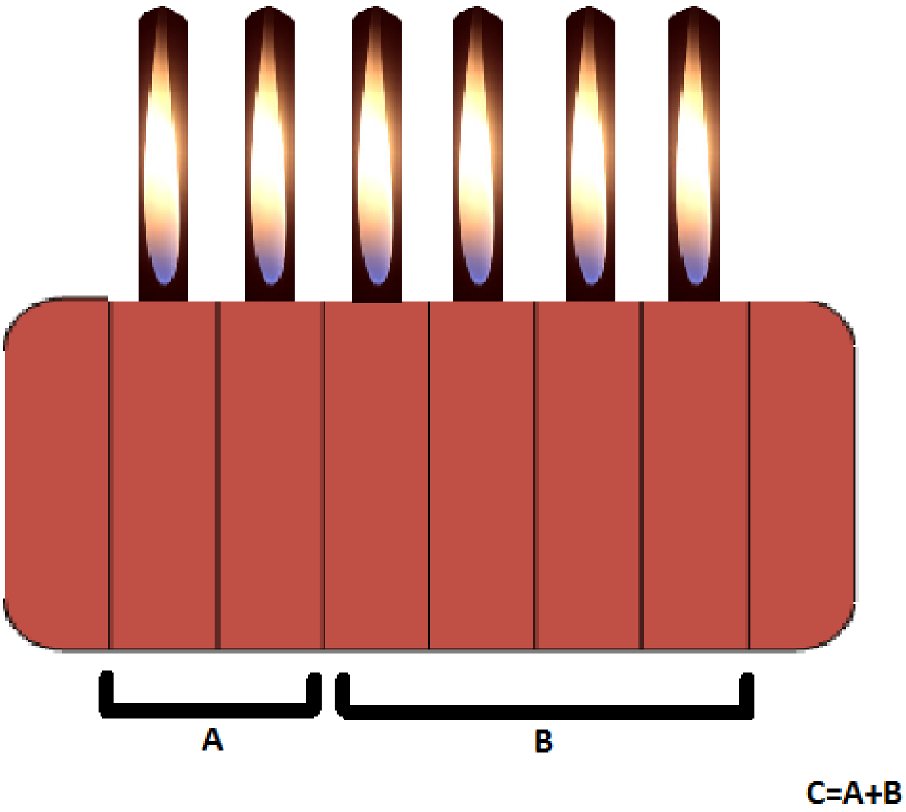


Figure 13:Segmentation of burner

The block of gas valve in Simulink is demonstrated in the next image. The valve position shows how much the valve needs to be open. The valve has one minimum of current and a maximum for open and close totally. Section selection tells how many segments are needed. With the flow per nozzle and number of nozzles, the total gas flow can be calculated.

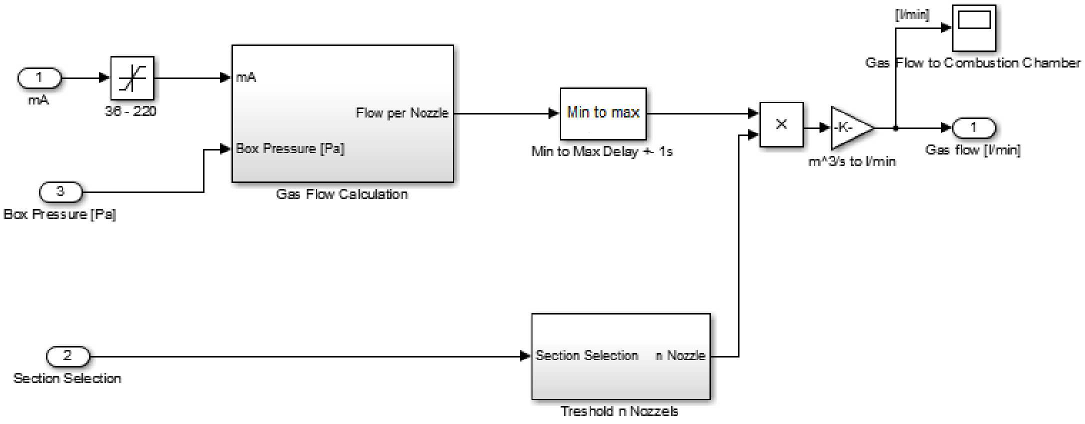


Figure 14: Gas valve simulation

Inside the “Gas Flow Calculation” block it is the equation of gas flow estimation through pressure variation and current.

3.2 Blower

The air flow is directly associated to gas flow in order to have the right amount of air in combustion. Each fan has a fan performance curve that relates the pressure rise with air flow for different fan speeds. A fan has a system resistance curve too. Usually fan suppliers provide the fan curves for a limited fan speed. It is then necessary to know the right pressure rise and air flow for a specific fan speed. This can be achieved using the fan laws.

The fan laws are described next as flow rate law (3.5), pressure rise law (3.6) and power law (3.7) respectively.

$$C_{flow} = \frac{\dot{V}}{D^3 N} \tag{3.5}$$

$$C_{pres.} = \frac{\Delta P}{\rho D^2 N^2} \tag{3.6}$$

$$C_{power} = \frac{W}{\rho D^5 N^3} \tag{3.7}$$

Where D is Fan diameter, N is Fan speed, ΔP is pressure rise and $\dot{V}$ is air flow. As flow through the system is increased, the pressure required increases by the square of that increase. Once one point of flow and pressure is measured for the system, the system curve can be estimated. And the points where system resistance curve intercept fan curve is the perfect operating point for a specific pressure. The next image describes fan performance curve and system resistance curve.

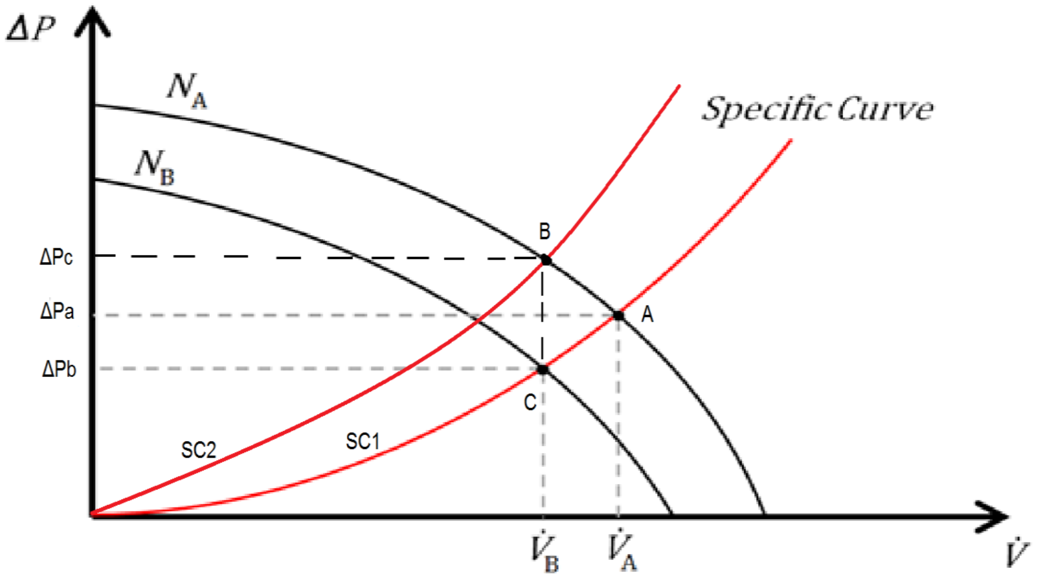


Figure 15: System curves

Two methods can be used to reduce air flow from $\dot{V}_a$ to $\dot{V}_b$. The first method is to restrict the air flow by partially closing a damper in the system. This action causes a new system performance curve (SC2) where the required pressure is greater for any given air flow. The fan will now operate at “B” to provide the reduced air flow $\dot{V}_b$ against higher pressure ΔPc.

The second method to reduce air flow is reducing the speed form N1 to N2, keeping the damper fully open. The fan would operate at “C” to provide the same $\dot{V}_b$ but at a lower pressure ΔPb.

Another important factor for air flow calculation is the inlet air density. Combining some equation like ideal gases equation (3.8) (3.9) (3.10) (3.11) with density and molar equation, it is possible to determinate that the most important factors are temperature and pressure.

$$PV = nRT \tag{3.8}$$

$$\rho = \frac{m}{V} \tag{3.9}$$

$$n = \frac{m}{M} \tag{3.10}$$

$$\rho = \frac{MP}{RT} \tag{3.11}$$

Applying Bernoulli’s equation for fluids it is possible to calculate the air flow variation with inlet air density (3.12).

$$P_{ref} + \frac{1}{2}\rho_{ref}v_{ref}^2 = P_{new} + \frac{1}{2}\rho_{new}v_{new}^2 \tag{3.12}$$

3.2.1 Dynamic Response

A blower has a time response because of friction and inertia. With the characteristic transfer function it’s possible to model the time variance of the system. Experimental tests say that response of the blower is similar to a first order lag element.

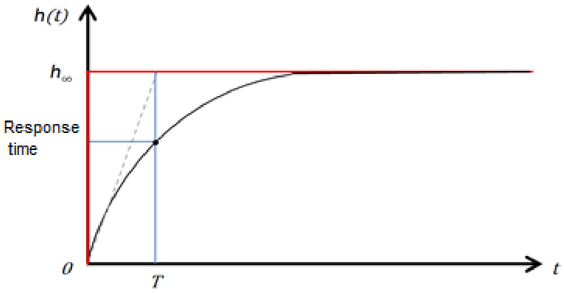


Figure 16: System response time

$$h(t) = h_\infty\left(1 - e^{-t/T}\right)u(t) \tag{3.13}$$

The corresponding transfer function (3.14):

$$G(s) = \frac{k}{1 + Ts} \tag{3.14}$$

To estimate the time constant T, it was measured a step signal how input from zero to a fixed value speed, and it read a value that reach approximately 63% of its final value.

3.2.2 Implementation

The Simulink model of the blower is represented above.

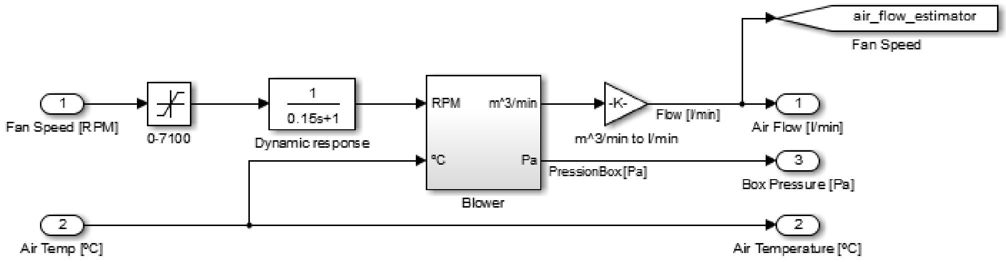


Figure 17: Blower simulation

In this image the blower system with the response delay is represented. In the above figure the block “Blower” which has the specific curve of the blower is represented.

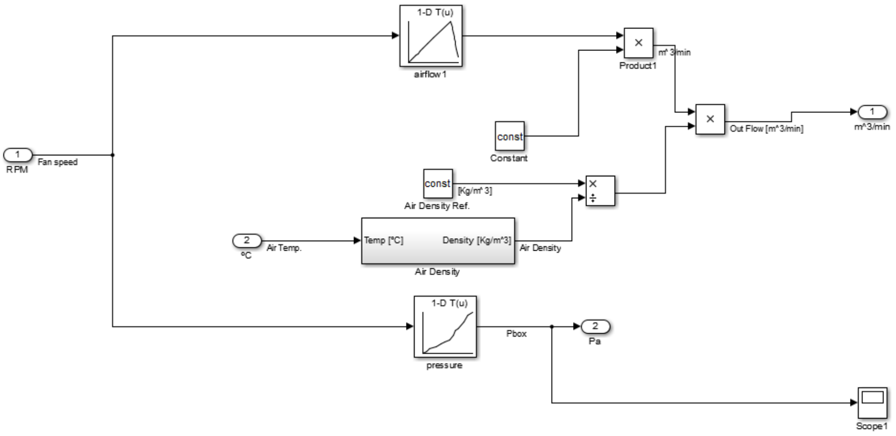


Figure 18: Blower block

The block “Air density” implements the equation that air temperature changes the air flow.

3.3 Stepper Valve

The function of stepper valve is to regulate the water flow in the system. It is in the stepper valve where pressure lost most occurs.

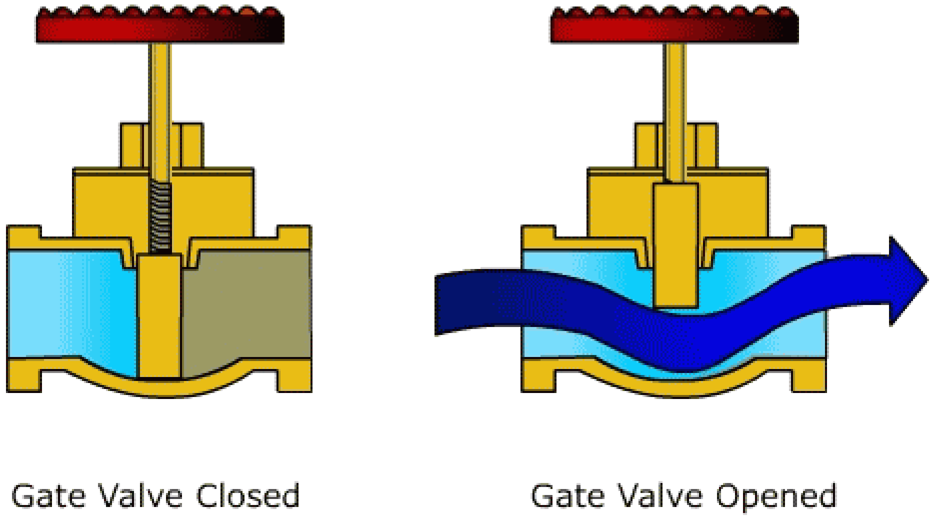


Figure 19: Functioning of stepper valve

A stepper valve opens or closes the membrane that interferes with water flow. The stepper contains a stepper motor that makes the membrane move. The main characteristic of the valve is water flow vs valve opening.

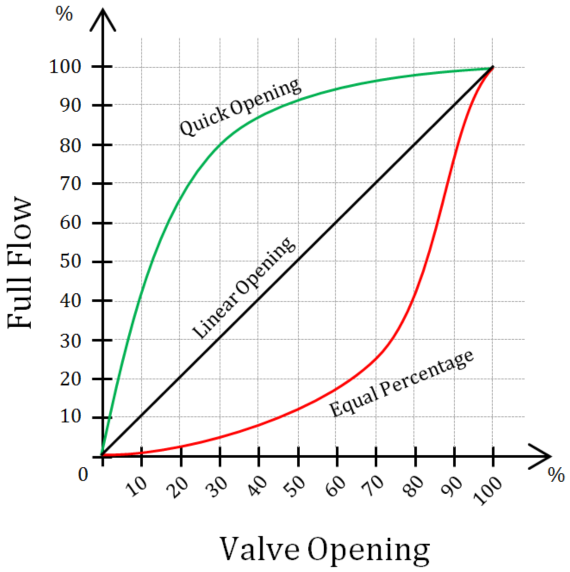


Figure 20: Curves of valve opening

The valve opening responds in three ways. An equal percentage, a linear opening and a quick opening as the graph shows.

3.3.1 Implementation

The valve has a characteristic curve that connects the water flow with the number of steps of the motor. This block has inside a look up table for this characteristic curve. The maximum steps of the valve are 2050, when the valve is fully closed, and 0 when fully open. When valve has 2050 steps, is closed and with 0 is totally open.

In the block, a pressure loss in the valve is calculated through the equation (3.15):

$$P2 = P1 - \sqrt{\Delta P} \tag{3.15}$$

Where P2 is the pressure at Valve output and P1 is the pressure at valve input.

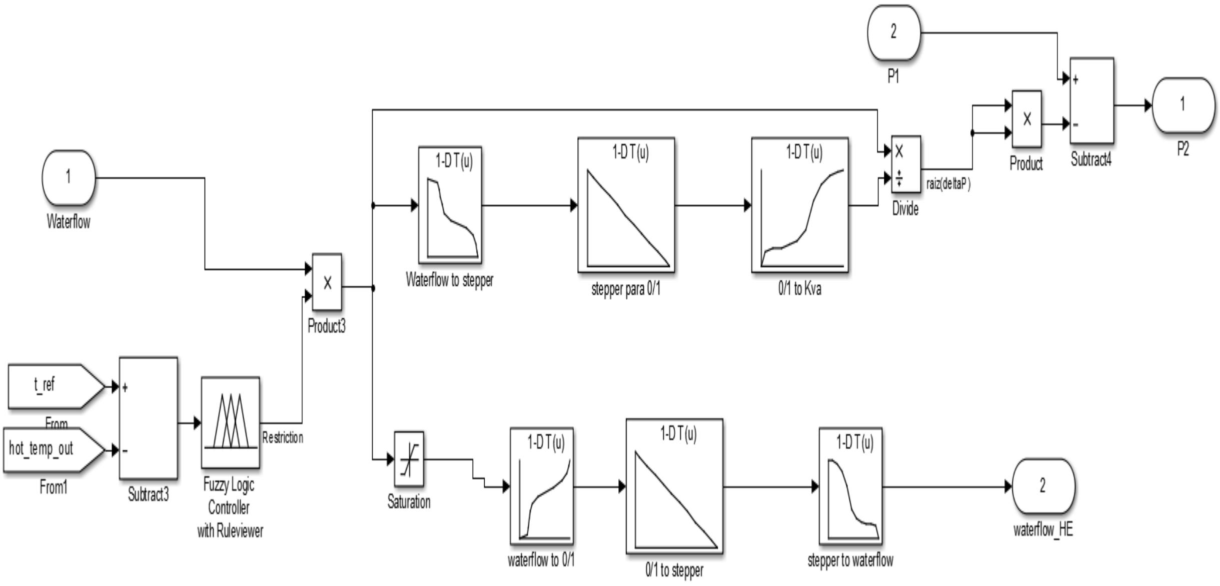


Figure 21: Stepper valve simulation

Also in this block, a restriction in the water flow is made. There is a fuzzy logic controller and look-up tables to describe the valve as output, the water flow that goes to heat exchanger and P2.

3.4 Bypass Valve

This valve is an electrical valve that is controlled by a current through a solenoid, and this current moves the plunger which in turn moves the membrane.

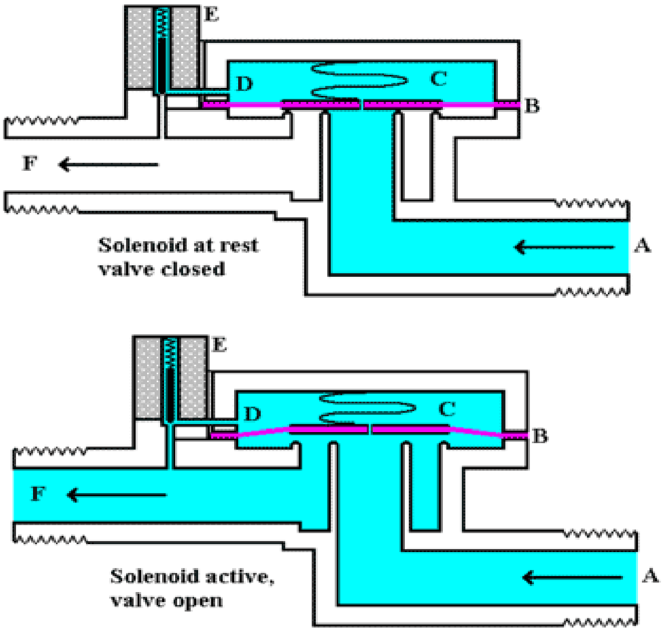


Figure 22: Funcioning of bypass valve (Bosch, 2016)

A is an input, where water goes into valve. B is the diaphragm, C and D is pressure chamber. E is the solenoid that makes plunger move and F is output. The equation (3.16) calculates the flow of the valve.

$$Q = k_v . \sqrt{\Delta P} \tag{3.16}$$

ΔP is pressure gradient between upstream and downstream and k_v is flow coefficient.

3.4.1 Implementation

This is modulated with a C code block that through a pressure gradient, sections of many pieces containing in valve and current required, calculates the water flow passing through the valve. In this block look-up table to link a flow to a plunger position through a current is represented. Another thing present in block is a flow restriction with a fuzzy logic controller.

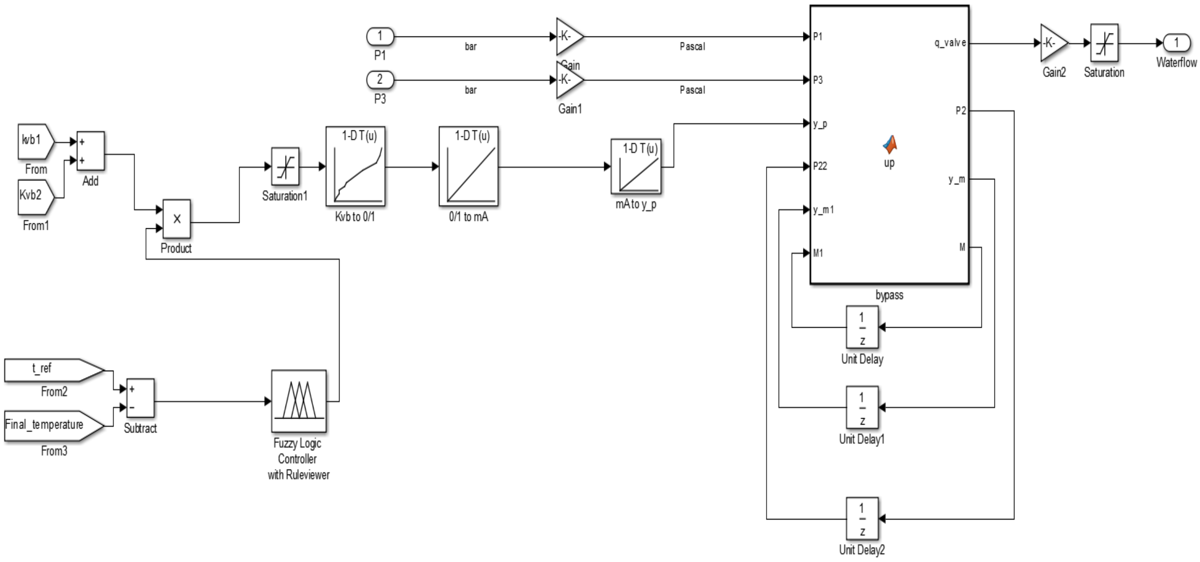


Figure 23: Bypass valve simulation

0

The sub-block “bypass” contains the C code of valve. The sections of several pieces have been measured and with some equations (3.17) and (3.18).

$$\mathrm{valve_{flow}} = \mathrm{Cd_{valve}} \,.\, \mathrm{Svalve} \,.\, \sqrt{2 \,.\, \mathrm{Wd}.\, |P1 - P3|} \tag{3.17}$$

$$\mathrm{Svalve} = \pi \,.\, \sqrt{1 + m^2} \,.\, \frac{m \,.\, y\_m}{m^2 + 1} \,.\, \left(D_{\mathrm{down}} - y_m . \frac{m}{m^2 + 1}\right) \tag{3.18}$$

Where Cd_{valve} is the resistance coefficient of the orifice. Svalve is the area of water passage when the valve is open. Wd is water density, P1 is pressure in input of valve and P3 is in output. Y_m is the position of the membrane which is influenced by the pressure.

3.5 Pipe Simulation

The model has blocks for all the pipes that make up the water heater, differentiating the lines from curves and valves. Each block contains pressure loss and time delay corresponding to that pipe. For each pipe it is known the length, the internal diameter and section in that part.

The way this block is done, it can be implemented in any gas water heater system, because it only shows the pipe, and for another model, it is only necessary changes the length, internal diameter and section pipe.

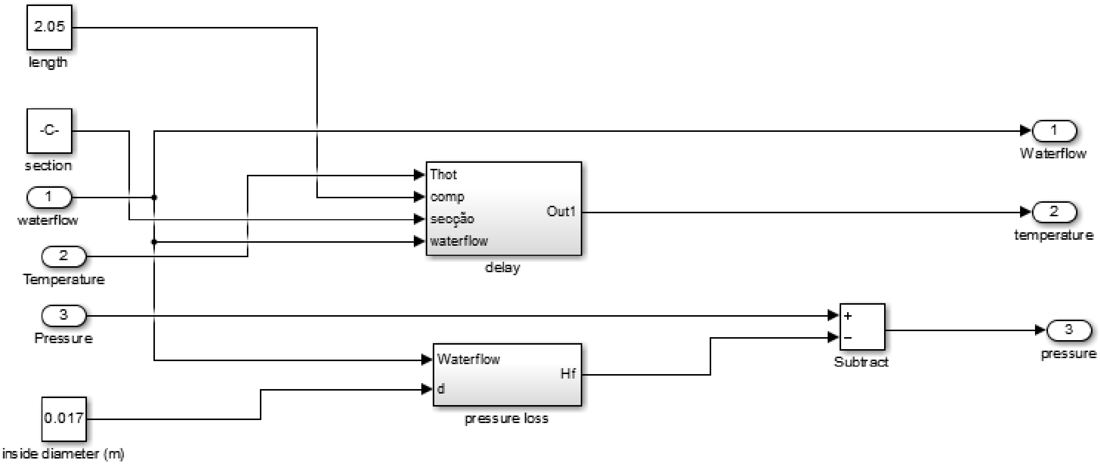


Figure 24: Pipe block

For the delay block, the transport delay in pipe is calculated through the equation (3.19)

$$d = \frac{\text{Length . Section}}{\text{Water flow}} \cdot \frac{6000}{1000} \tag{3.19}$$

D is in seconds and this delay interferes in temperature particles.

In pressure loss block, a lot of equations are represented that characterized the pressure loss in that pipe. It has two different blocks for pressure loss, one for straight pipes and another for curved pipes

The equation for straight pipes is (3.20)

$$\Delta P = \frac{8 . F . L . WF^2}{d^5 . \pi^2 . g} \tag{3.20}$$

Where F is friction factor, L is length, WF is water flow, d is internal diameter and g is gravity.

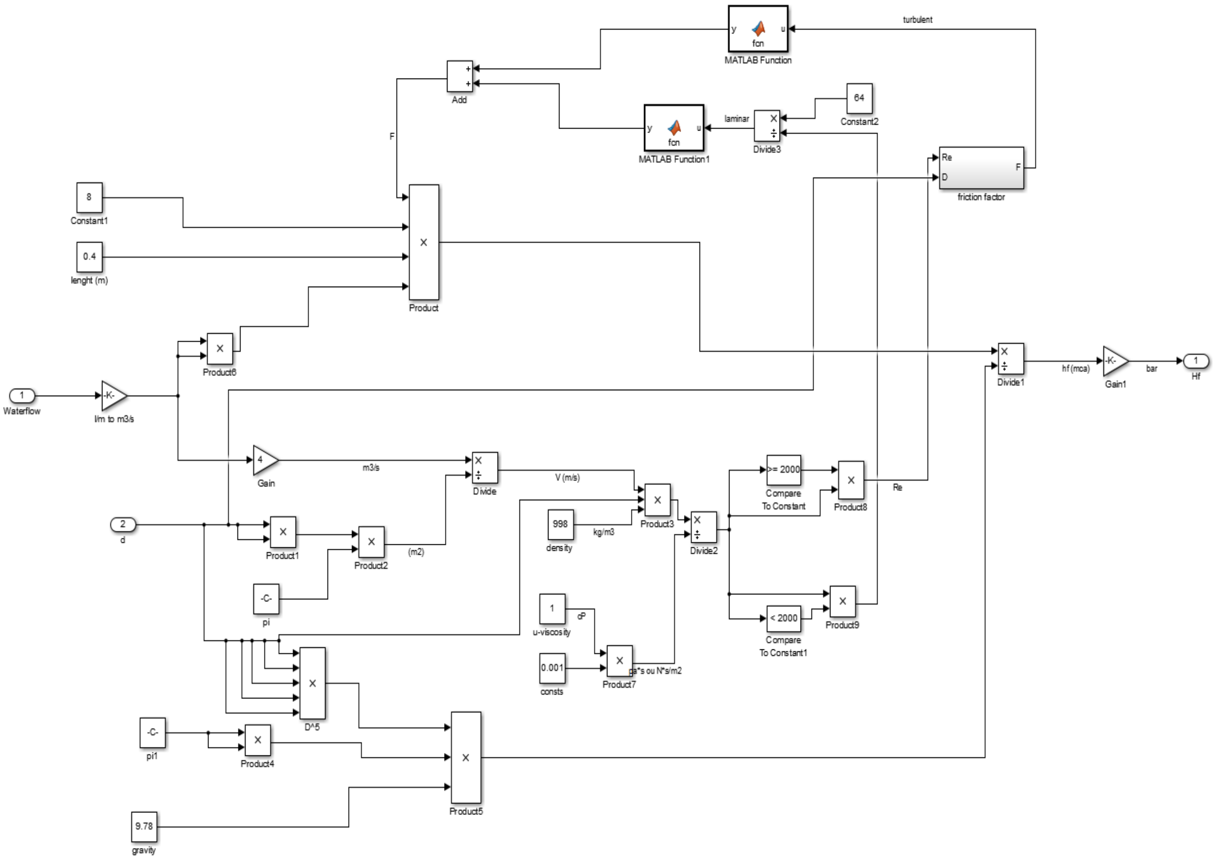


Figure 25: Pressure Loss calculation

There is a different equation for the pressure losses in curved pipes (3.21).

$$\Delta P = \frac{WF^2}{g^2}.k.L.F \qquad (3.21)$$

In this equation, k is a curve coefficient and it is a tabulated value, L is length and f is friction factor for the pipe. This equation is demonstrated in figure 26.

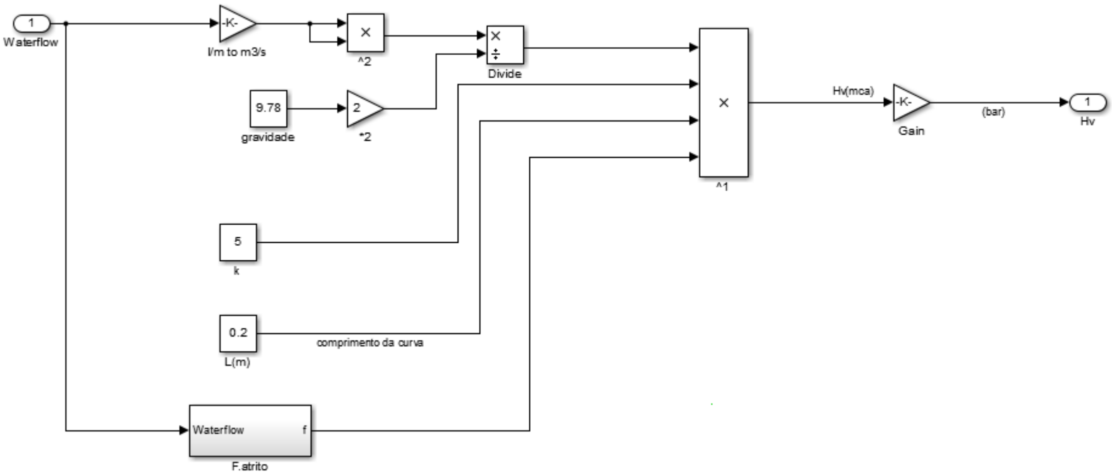


Figure 26: Pressure loss in curves or obstacles

3.6 Control Architecture

The model has two different controls. Control architecture is divided in two parts, the fuzzy control and bypass control. These methods are mainly to control the stepper valve and bypass valve in order to control the outlet temperature and stabilize it when flow changes occur for better comfort for the user.

3.6.1 Bypass control

Before introducing the bypass control, it is important to understand the physics behind the control. As studied in state of art, for pipe system it is considered the mass conservation principle. How it is demonstrated in figure 28, WF initial is equal to WF final.

The bypass control is based in a mixing rate, β equation (3.22).

$$\beta = \frac{T_A - T_{out}}{T_A - T_B} \tag{3.22}$$

This mixing rate comes from the next figure, where T_A is the heat exchanger outlet temperature, T_{out} is T_{set} or mixing temperature. And T_B is inlet temperature. Another consideration that must be taken into account is that the range in β must be saturated between zero and one.

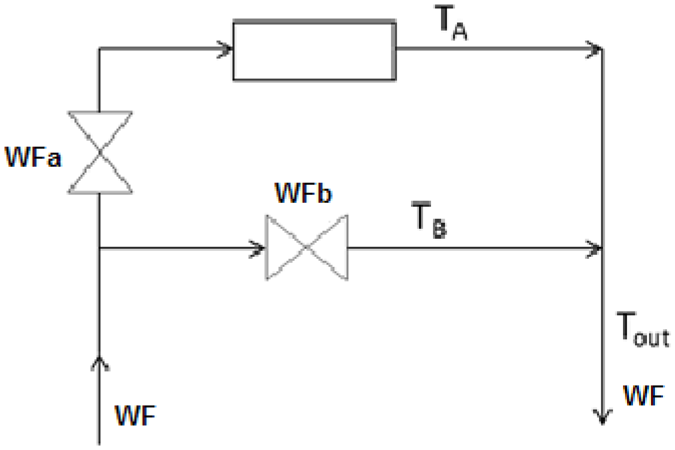


Figure 27: Bypass method

The mixing rate (3.23) is simply defined as the ratio of the bypass flow WF_B and the stepper flow WF_A:

$$\beta = \frac{WF_B}{WF_A + WF_B} \tag{3.23}$$

The flow coefficient of both valves is given by Kv_A and Kv_B which expresses the flow rate passing through the valve. Curves of Kv_A and Kv_B are determined experimentally for different operating conditions. The position of the valve is fixed by applying a constant and known current (bypass) or motor speed (stepper).

Once the flow coefficient of each valve is known, the mixing rate can also be expressed as a follow equation (3.24)

$$\beta = \frac{Kv_B}{Kv_A + Kv_B} \tag{3.24}$$

$$Kv_A = Kv_B(\frac{1}{\beta} - 1\,) \tag{3.25}$$

Now, starting from the equation (3.25), it was solved for different values of mixing rate.

The control is around β. If β is higher than a measured value, opens the bypass valve at maximum capacity, and stepper valve is controlled by equation (3.26)

$$Kv_A = Kv_B(\frac{1}{\beta} - 1) \tag{3.26}$$

And now if β is lower than a measured value, the stepper valve is set at maximum capacity and the bypass valve is controlled through equation (3.27),

$$Kv_B = \frac{Kv_A}{\frac{1}{\beta} - 1} \tag{3.27}$$

3.6.2 Implementation

The model has a block to calculate Kv_A and Kv_B through the mixing rate and the equations shown before.

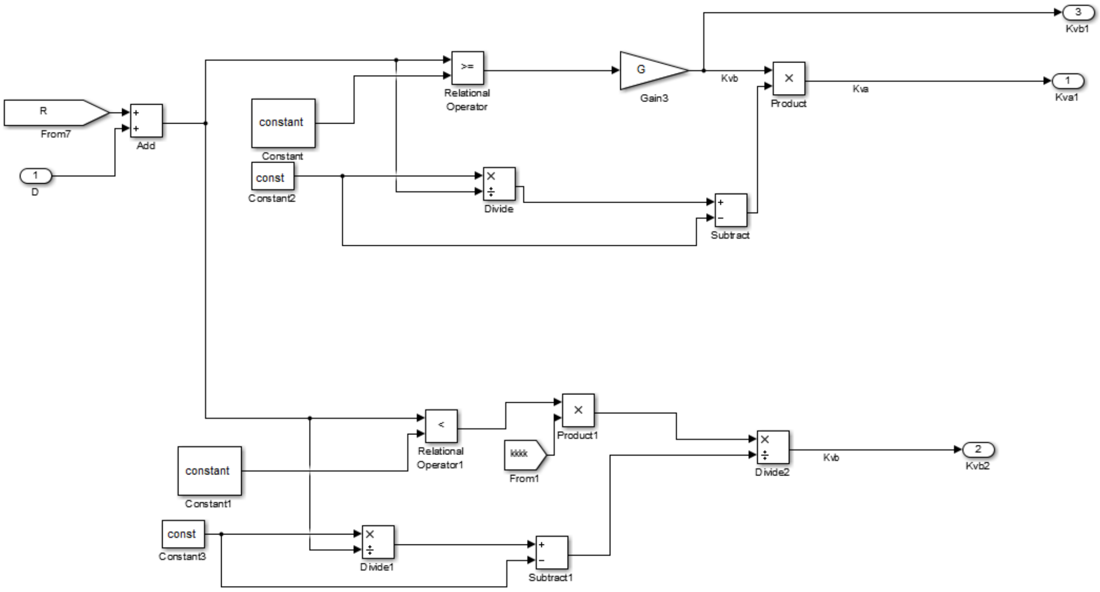


Figure 28: Coefficients flow calculation

After these calculations, Kv_A and Kv_B will control their valves directly, namely, the water flow passing in bypass valve is Kv_B and water flow in stepper valve is Kv_A.

3.6.3 Fuzzy control

Another control method present in the model is a fuzzy controller for the valves. A fuzzy controller has an output that can control water flow either in the stepper valve or bypass valve to stabilize outlet temperature.

The main objective of fuzzy control in bypass valve is when $T_{out} > T_{setpoint}$ or $T_{out} < T_{setpoint}$, the valve operates differently from normal. The controller has five rules to restrict or increase water flow by T_{out} to bigger or smaller than$T_{setpoint}$. These values are selected in order for small variations; the valve opens or closes, depending on the controller. The higher the variation, the bigger the controller action in the valve is. These values are also tested and showed.

The rules present in the controller are the following.

$$\text{Rule 1: IF} - 0.5 < \left(T_{setpoint} - T_{out}\right) < 0.5 \quad \text{then} \;\; C \text{ is } 1$$

$$\text{Rule 2: IF } 0.5 < \left(T_{setpoint} - T_{out}\right) < 2.5 \quad \text{then} \;\; C \text{ is } 0.8$$
$$\text{Rule 3: IF}\left(T_{setpoint} - T_{out}\right) > 2.5 \quad \text{then} \;\; C \text{ is } 0.5$$
$$\text{Rule 4: IF} - 2.5 < \left(T_{setpoint} - T_{out}\right) < -0.5 \quad \text{then} \;\; C \text{ is } 1.2$$
$$\text{Rule 5: IF}\left(T_{setpoint} - T_{out}\right) < -2.5 \quad \text{then} \;\; C \text{ is } 1.5$$

This output C will restrict or increase the water flow in bypass valve at maximum flow already calculated.

In order to control water valve a fuzzy control is also made in order to restrict water flow when T_A doesn't reach$T_{setpoint}$. The controller reads two signals, T_A and$T_{setpoint}$. It makes the difference between $T_{setpoint}$ and T_A and if it is negative, the controller restricts the water flow, because there is less water getting to the heat exchanger, the T_A rises faster and when T_A reaches $T_{setpoint}$, water valve returns to normal run. The rules present in this controller are represented next.

$$\text{Rule 1: IF } \left(T_{setpoint} - T_A\right) < -1 \quad \text{then} \;\; D \text{ is } 1$$
$$\text{Rule 2: IF} - 1 < \left(T_{setpoint} - T_A\right) < 1 \;\; \text{then} \;\; D \text{ is } 0.8$$
$$\text{Rule 3: IF } 1 < \left(T_{setpoint} - T_A\right) < 4 \;\; \text{then} \;\; D \text{ is } 0.5$$
$$\text{Rule 4: IF } \left(T_{setpoint} - T_A\right) > 4 \quad \text{then} \;\; D \text{ is } 0.2$$

Output D restricts water flow that goes to heat exchanger with the main objective of heating up the water.

3.6.4 Implementation

This fuzzy controller is implemented in a block from fuzzy logic toolbox. Then it represents input memberships of bypass controller.

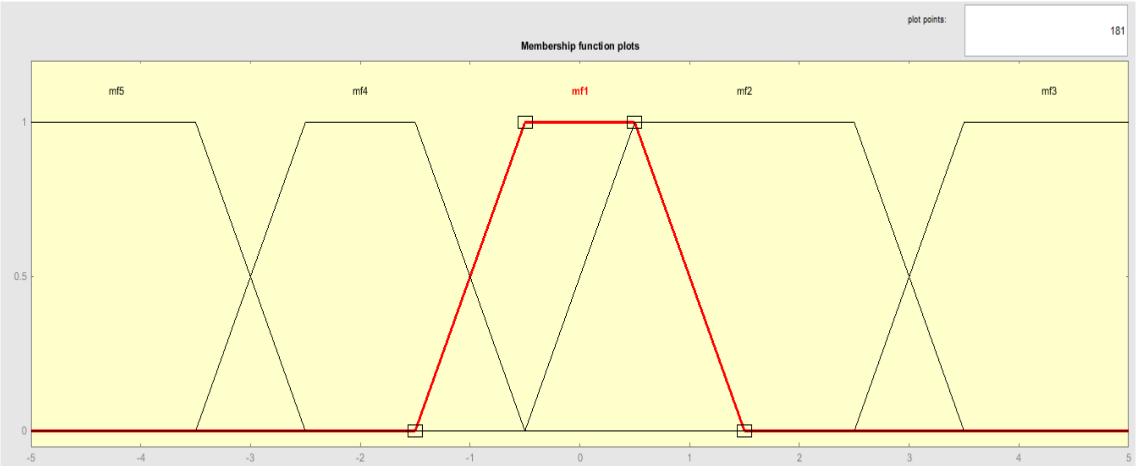


Figure 29: Input memberships of bypass

Mf1 describes rule 1:$-0.5 < (T_{setpoint} - T_{out}) < 0.5$, Mf2 rule2: $0.5 < (T_{setpoint} - T_{out}) < 2.5$; Mf3 rule 3: $(T_{setpoint} - T_{out}) > 2.5$;
Mf4 rule 4: $-2.5 < (T_{setpoint} - T_{out}) < -0.5$; And MF5 rule 5: $(T_{setpoint} - T_{out}) < -2.5$.

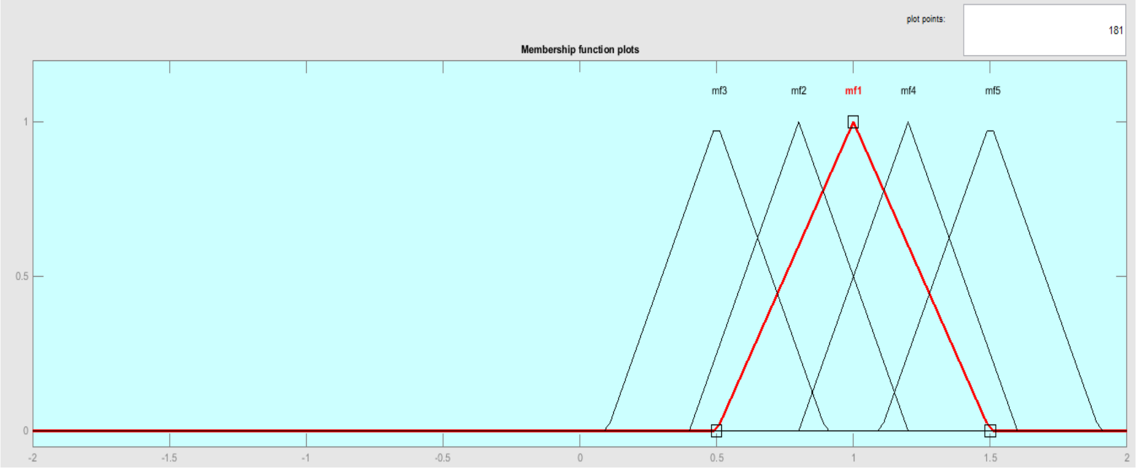


Figure 30: Output memberships of bypass

In this image, output memberships of bypass controller is demonstrated where MF1 is for rule 1, MF2 is for rule 2 and so on until MF5 for rule 5.

The following Memberships are related with water valve fuzzy controller like input and Output.

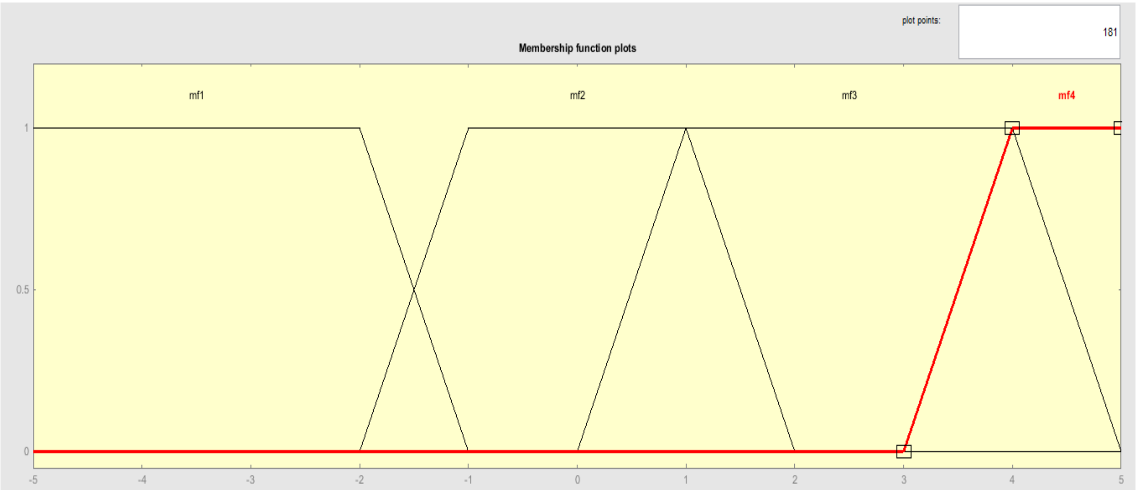


Figure 31: input membership of stepper valve

In this membership, MF1 is related at Rule 1, MF2 at rule 2, and until MF5 at rule 5.

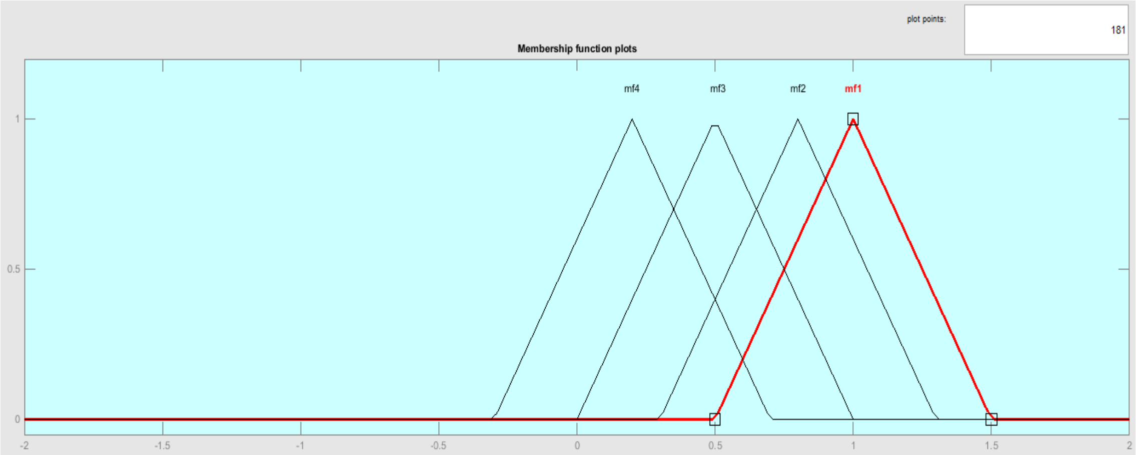


Figure 32: Output memberships of stepper valve

It is not enough make controller architecture, it is also necessary to implement the water heater microcontroller. As the microcontroller is limited, it must be taken into account the memory allocation, for to the end there is no lack of memory.

In next, it is demonstrated how microcontroller does the fuzzy control after the fuzzy code is downloaded to the microcontroller as a fuzzy table.

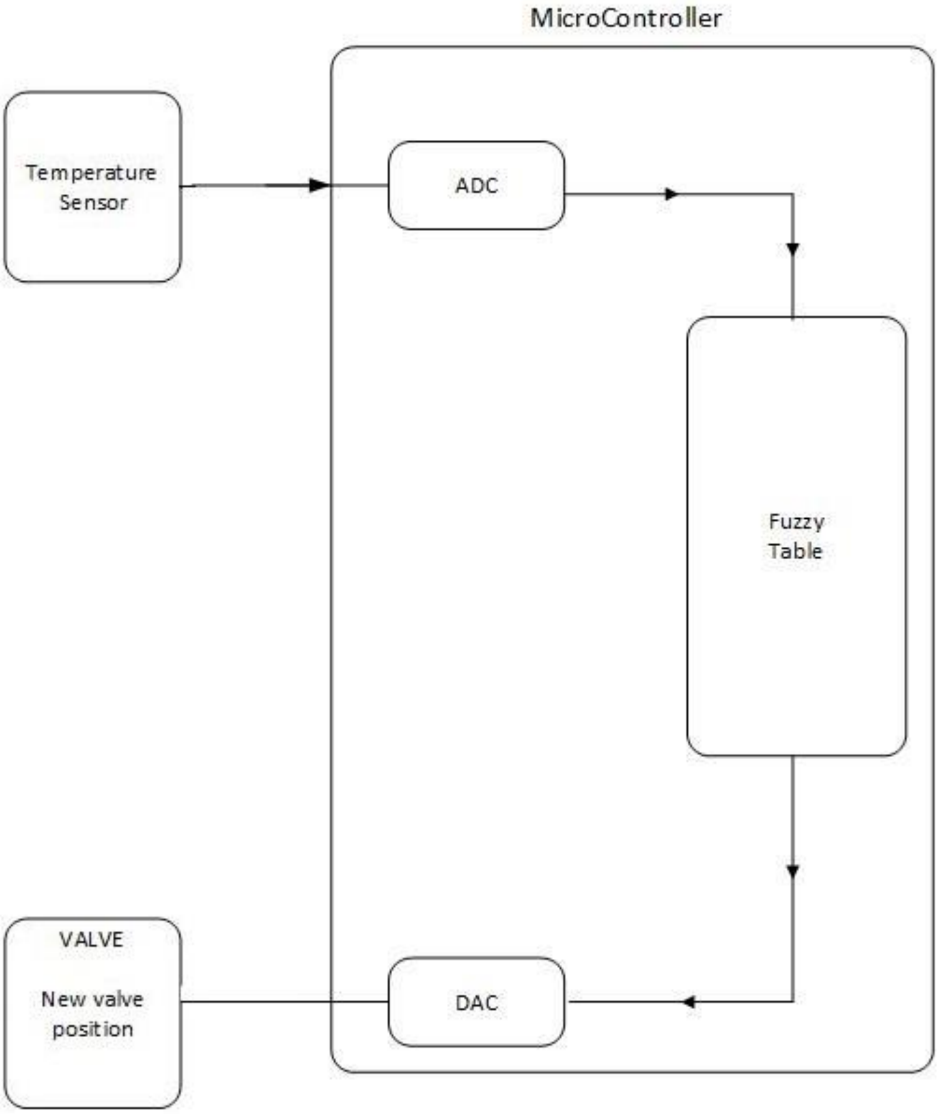


Figure 33: Funcioning of fuzzy control on microcontroller

A Temperature analog signal is sent to microcontroller. Microcontroller converts analog signal in digital signal on ADC converter. After, the digital value is interpreted in fuzzy table that it has a corresponding value as output. This same value is converted again in analog signal and sent to valve to set a new position.

3.7 Summary

With all these actuators and controls, it is possible to assemble all the parts and construct a complete system. Figure 34 demonstrates the whole model that doesn’t need a deep knowledge to use it.

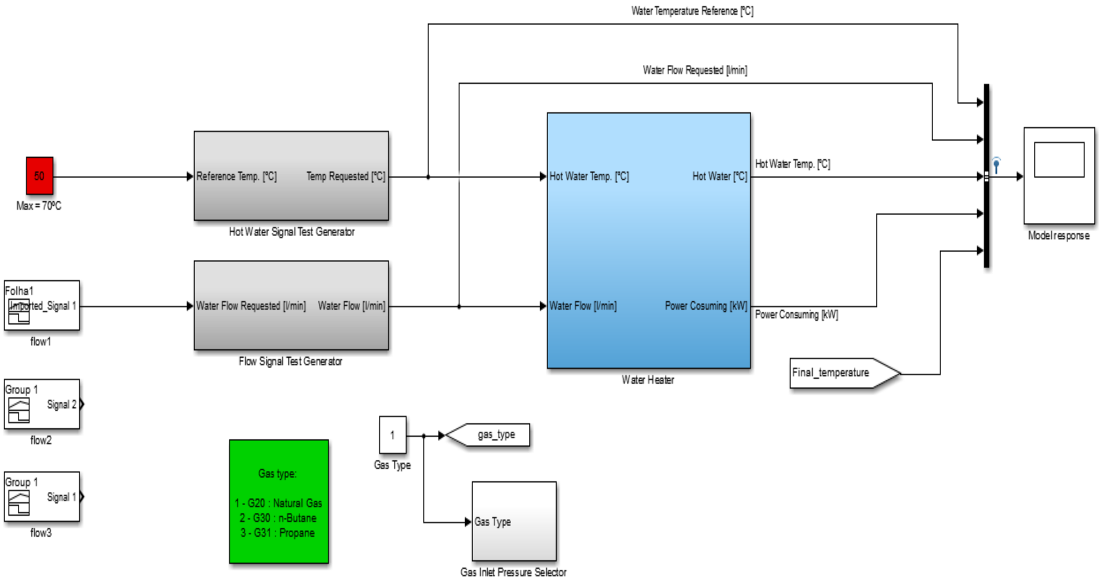


Figure 34: System overal diagram

This model is capable of being divided into several parts and can be used with other configurations like fire pressure gas water heater. It is easy to change the set point, initial flow and gas type for another, and make all the tests needed. It is also very intuitive to understand and know how to control the whole system. All subsystems have information of how to change and the range of the variables.

Chapter 4

Implementation and Results

In Project modelling the whole structure of a water heater for domestic use was considered. In this model it is important to understand two actuators, temperature sensor and water flow sensor.

The temperature sensor is an important resource because it controls the mixing rate and water inlet temperature that provides heat required for heating the water; it models its behavior and delays response in order to get a better approach with reality.

The water flow sensor is a key component because it is through it that flow changes are read, and if flow changes occur, all the possible behaviorism of the heater must be changed. For this sensor it is only possible to model the delay response.

4.1 Simulation

To simulate all this model it was necessary to choose a simulation time and a solver method.

The simulation time chosen was seven minutes and twelve seconds. It represents average use time for a bath or other utilization.

This is a dynamic system that computing its states at successive time steps. The step size is determinate by the solver. Solver is a variable step solver. This time reduces the step size to increase accuracy when the states change rapidly and increase step size when is not necessary taking steps, more properly when the states changes slowly. As model is continuous, Matlab/Simulink has three solvers of differential equations, ODE-45, ODE-23 and ODE-113.

The ODE-45 is the best choice because is more accurate and faster than the others. The method used to solving the differential equation was Dormand-Price. It uses six evaluations to calculate fourth or fifth order solutions.

It can be used a fixed step solver, but to determine one step size, the system would stay too slow or too fast. If it was used a step size big, it would be lost measurements, because system would change more quickly than the next measurement, and in the middle of these measurements, would stay important measurements.

Now if the step size was small, the accuracy would be better, but also couldn’t be necessary so many accuracy if the model has slow dynamic. Other point against small step size is a very slow simulation, and accuracy gains doesn’t pays off.

4.2 Bypass Control

The Bypass strategy is mixing different water temperatures with different flow ratios through a mixing rate β. The Objective of this control is to overcome temperature overshoots.

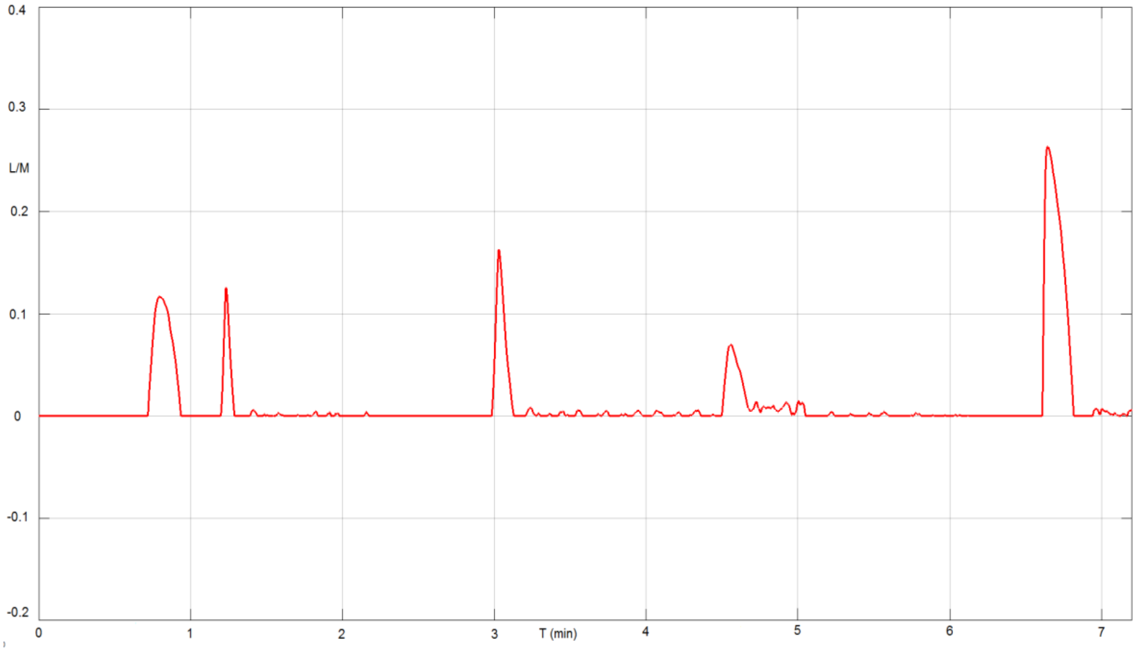


Figure 35: Results of mixing rate β.

β behavior (figure 35) is caused by the water temperature variations. Like β is calculated from the temperature and flow rate, it varies according to these variables.

In bypass strategy, we do not only calculate the mixing rate because of the characteristics of the hydraulic system. To control bypass valve we also need to calculate flow coefficient for bypass valve and stepper valve because of the connection between them. If by mixing rate β it doesn't reach the measured value, the Kv_A is always in maximum and Kv_B is calculated through that.

Kv_A is flow coefficient of stepper valve and Kv_B is flow coefficient of bypass valve.

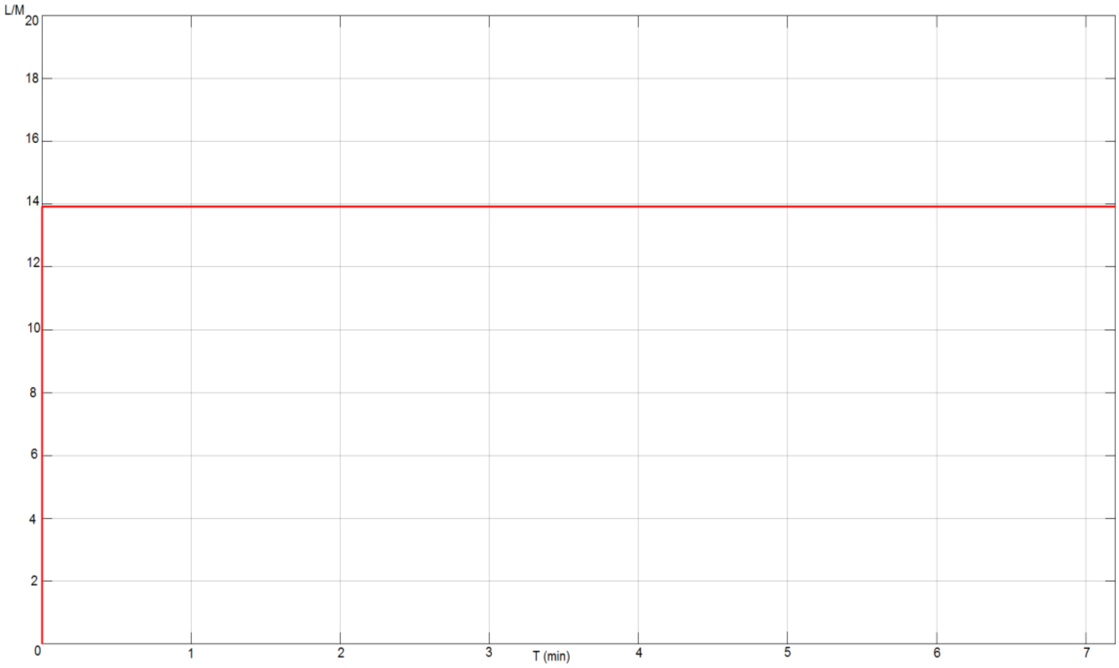


Figure 36: Calculating the flow coefficient from stepper, Kv_A.

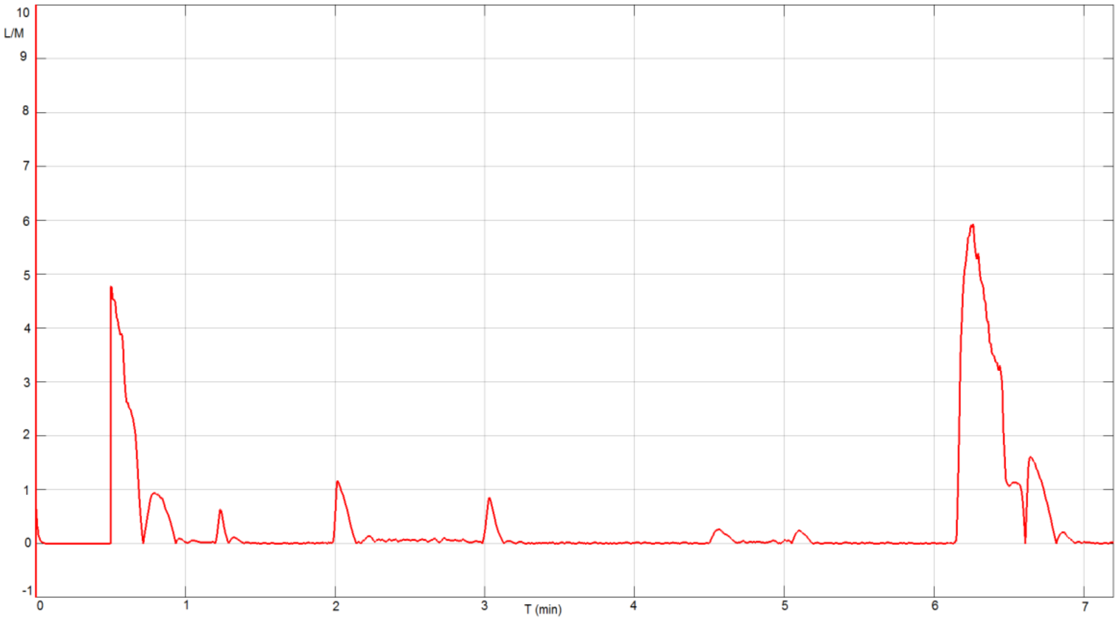


Figure 37: Results of flow coefficient calculation of bypass valve, Kv_B.

In figure 36, it is demonstrated Kv_A, and it is possible to see that Kv_A is always in maximum because β doesn't reach the measured value.

It is important to say that when a bigger flow change occurs in Kv_B (figure 37), mixing rate increases and for example, the peak present in time 6,6 is when a high flow change occurs. Then this control opens the bypass valve more, until Outlet temperature stabilizes.

4.3 Fuzzy Control

The fuzzy control has an important contribution for undershoots and overshoots. It controls water flow that goes to stepper valve and also bypass valve in order to open or close the valve.

Defuzzification use centroid method because centroid evaluates all values of membership instead the others methods. Centroid returns the center of area under the curve. In figure 38 it is represented input and output memberships of stepper valve. The area with color it is the membership area that represent actual value of input or output.

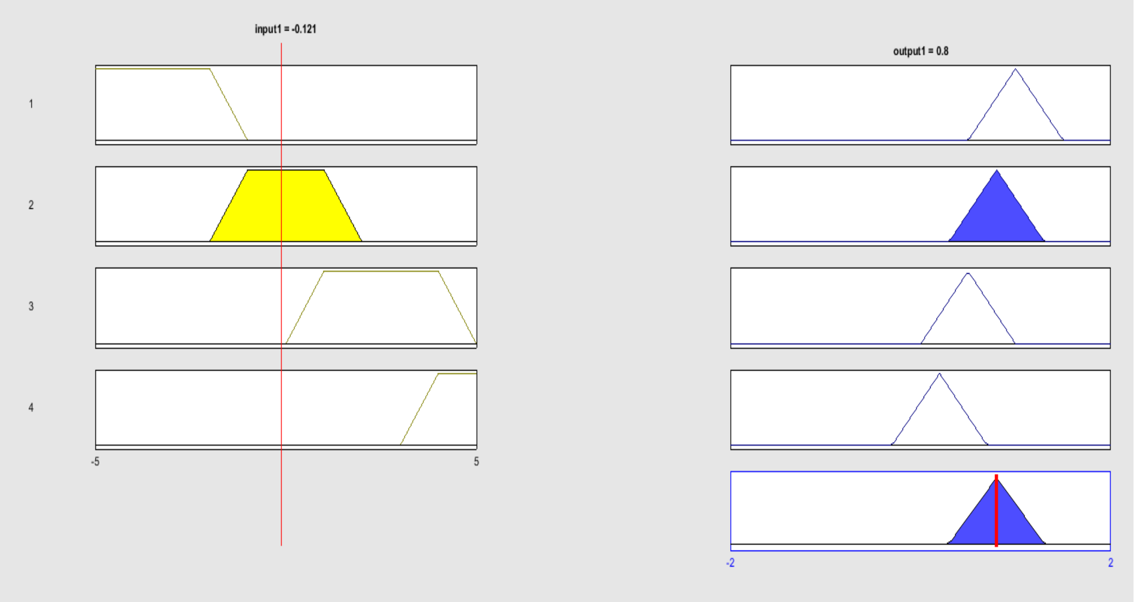


Figure 38: Fuzzy stepper

In fuzzy controller of stepper valve (Figure 39), if heat exchange temperature is bigger than set point temperature, no restrictions are made in the valve, but if it is smaller, depending on the value, the restriction is bigger or smaller. The input in this fuzzy is subtraction between temperature of heat exchanger and setpoint temperature.

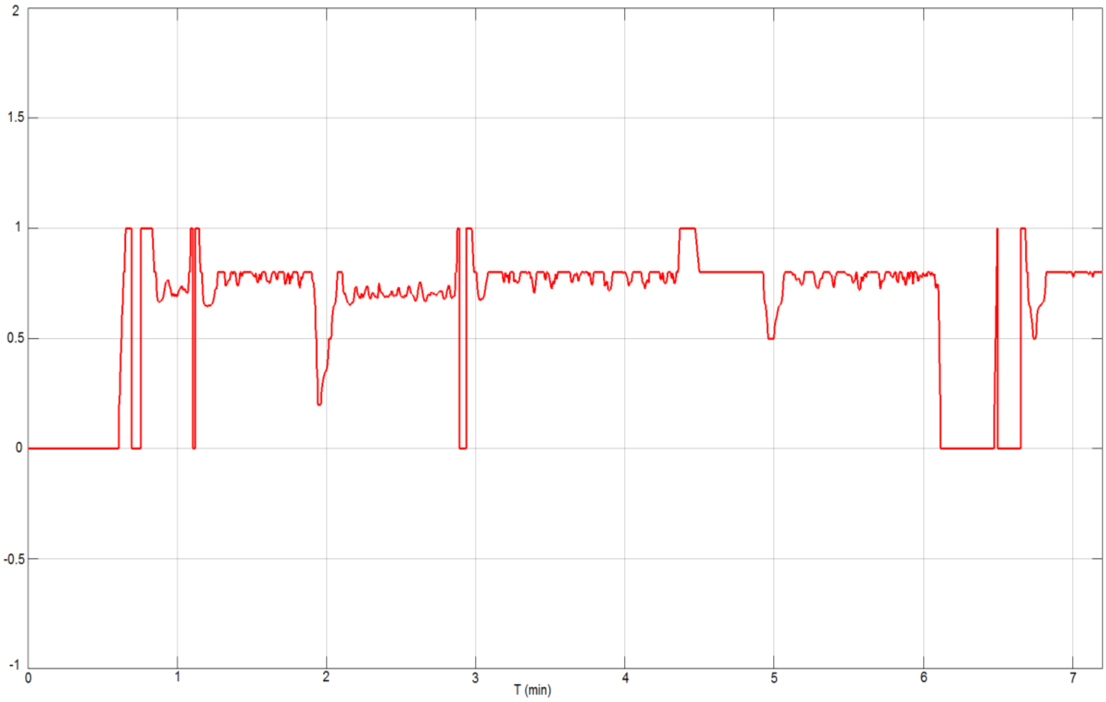


Figure 39: Results of fuzzy control of stepper.

Fuzzy controller of bypass valve is different. When Outlet temperature is bigger than set point temperature, the fuzzy controller opens the valve more, depending on the value. If it is smaller, it restricts the valve until reaching the values. This controls overshoots and undershoots so that the user doesn´t feel the change for a better comfort.

In figure 40, it is represented the input and output memberships of fuzzy control of bypass valve and represent the input and output value too.

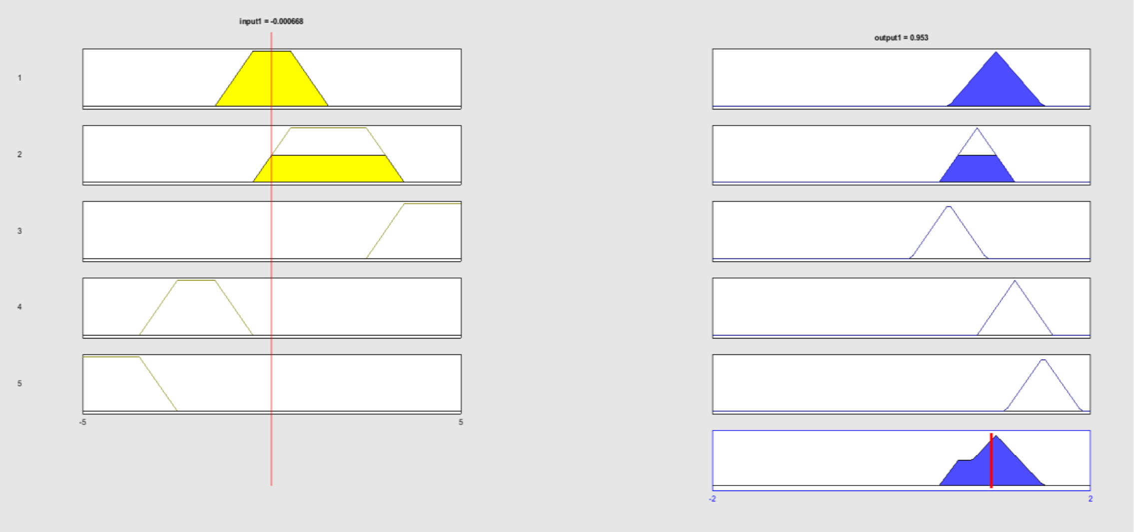


Figure 40: Fuzzy bypass.

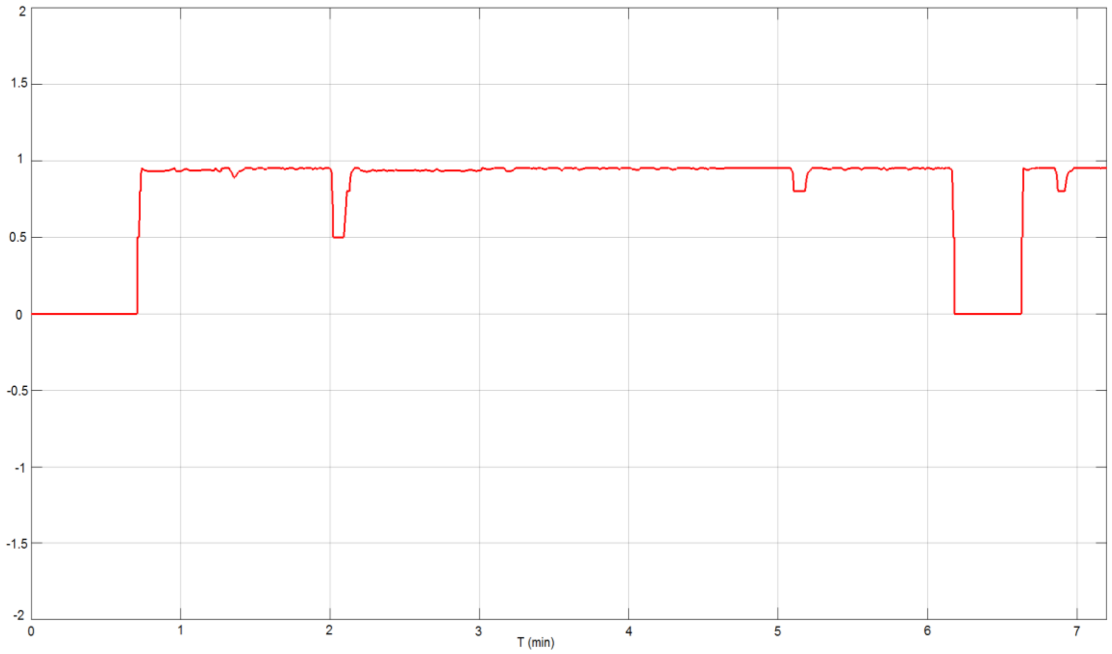


Figure 41: Results of fuzzy control of bypass valve

In figure 41, it is possible to see the output of fuzzy control to bypass valve. In most of time, output is very close to one, less between minute six and seven, because there it appens an undershoot in temperature of heat exchanger and close the bypass valve to doesn’t lower the temperature more.

4.4 Pressure losses

Pressure is important because one of the parameters of bypass valve is inlet pressure and output pressure. And with losses in pipes or stepper valve, the model knows the pressure in all parts of the system; it also knows the input valve pressure and pressure in the pipe after bypass valve. So with this pressure, the bypass valve model controls and measures the water flow better.

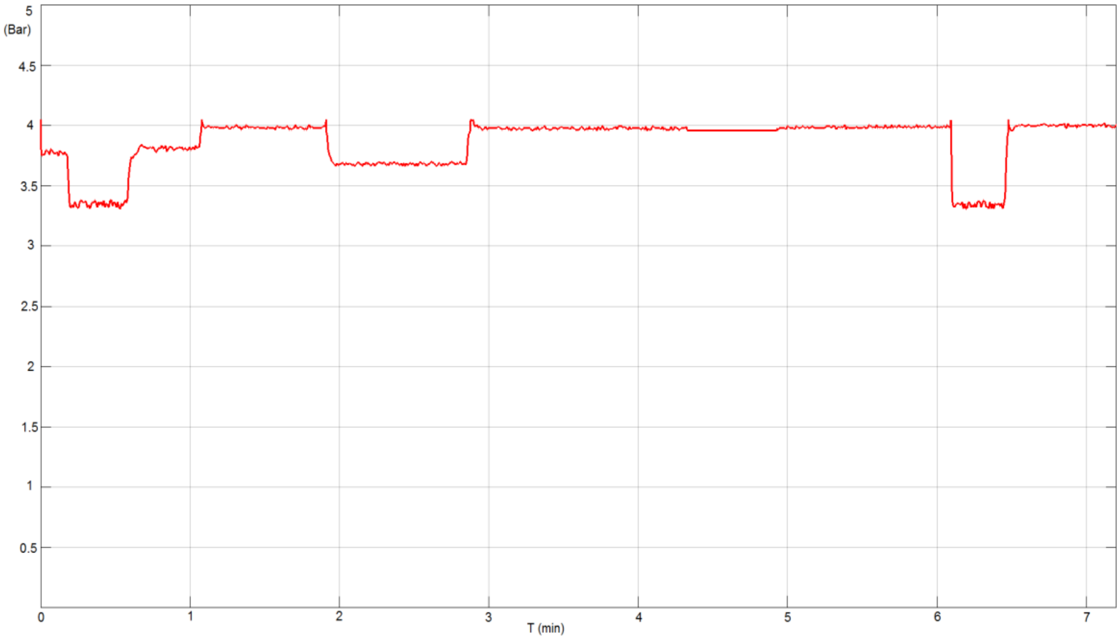


Figure 42: ΔP in stepper valve

In this graphic (figure 42) the pressure losses of stepper valve is represented. It is where the major loss of the entire system occurs because there is a bigger flow separation and there are more obstacles.

Now, in the next graphic (figure 43) pressure losses for a random pipe are represented. All the pipes have losses that differ from pipe to pipe due to several factors like length or diameter. Where in figure 46 has peaks, is when water flow changes, up or down respectively. There aren´t losses like in a valve because there aren´t so many obstacles like in a valve.

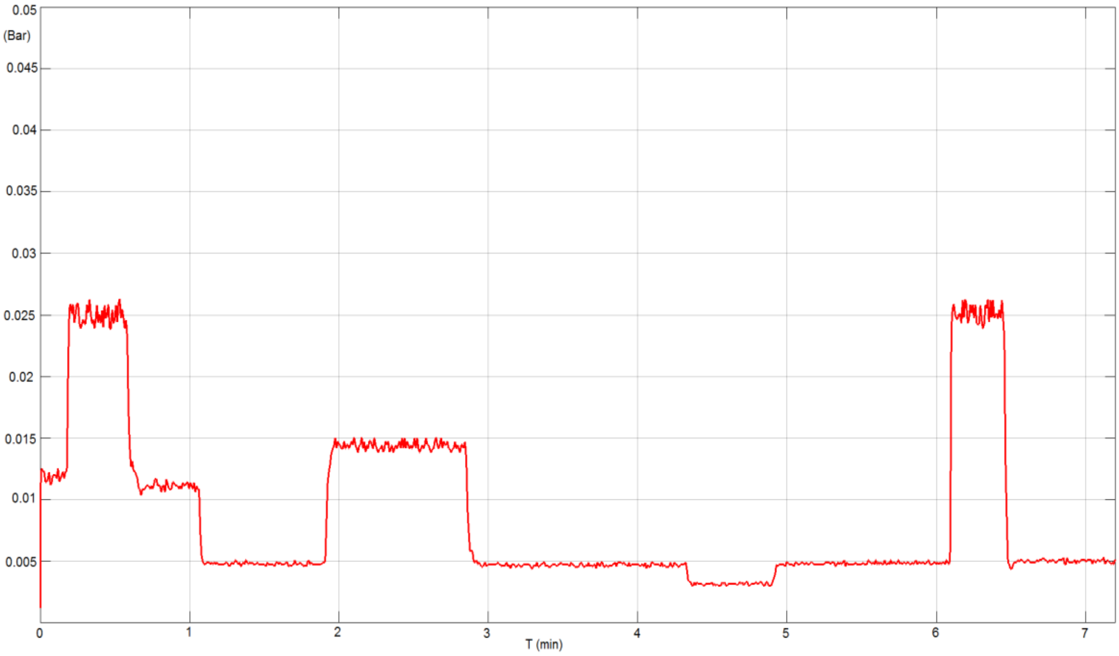


Figure 43: ΔP in a random pipe

4.5 Final Results

To ensure control algorithms with dynamic response, it is important to verify if the modeled system has the same dynamic response as the real system, and the better way to verify this is by undergoing many experimental tests. Three different measurements were made, one with set point of 55ºC and a referent flow, other with 40ºC and another with 50ºC, both with different flow.

After assembling all modeled parts, an all in one system was constructed and a comparison between experimental data acquired directly from the appliance and the modeled system was made. The main variables were water inlet flow, water outlet temperature, setpoint temperature and experimental data from water outlet temperature.

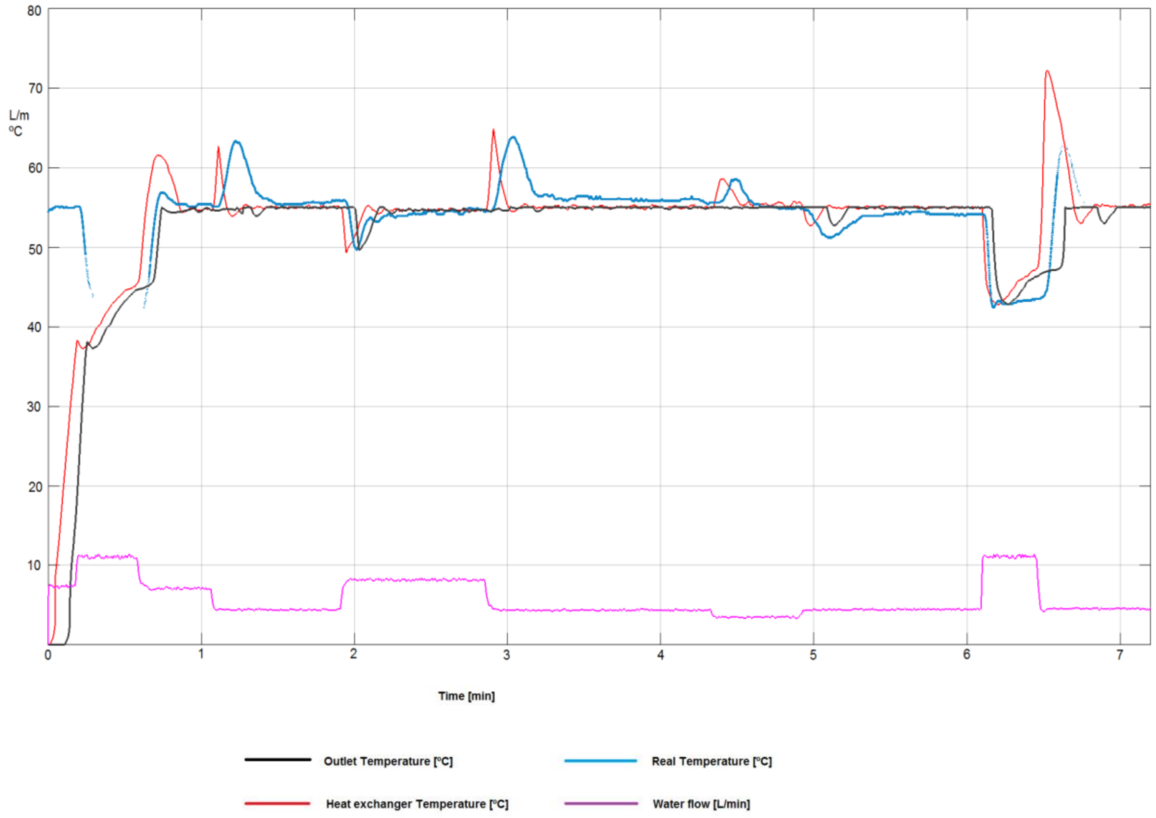


Figure 44: Comparison with a measured value in a setpoint of 55ºC.

In this comparison (figure 44) are represented outlet temperature, heat exchanger temperature, measured temperature and inlet water flow in a simulation of seven minute and fifteen minutes for a setpoint of 55ºC, and compare outlet temperature of model with a measured temperature of gas water heater. It is possible to see when water flow rises, heat exchanger temperature and Outlet temperature falls. It occurs because of system inertia. The burner is to provide energy for a given flow rate, and if that flow rises, system needs more energy for heating the water to set point temperature. This is the reason why temperature drops and it will rise when the system compensates that flow rise with more energy from the heat exchanger.

Now, when water flow falls, the system takes up the temperature to above set point temperature because with less water flow, the burner doesn’t require so much energy, thus the system takes a while to get the necessary energy for this new flow. This delay time exists because dynamic response of the burner. Burner has this delay time to heat because thermodynamics rules of material that composes the burner.

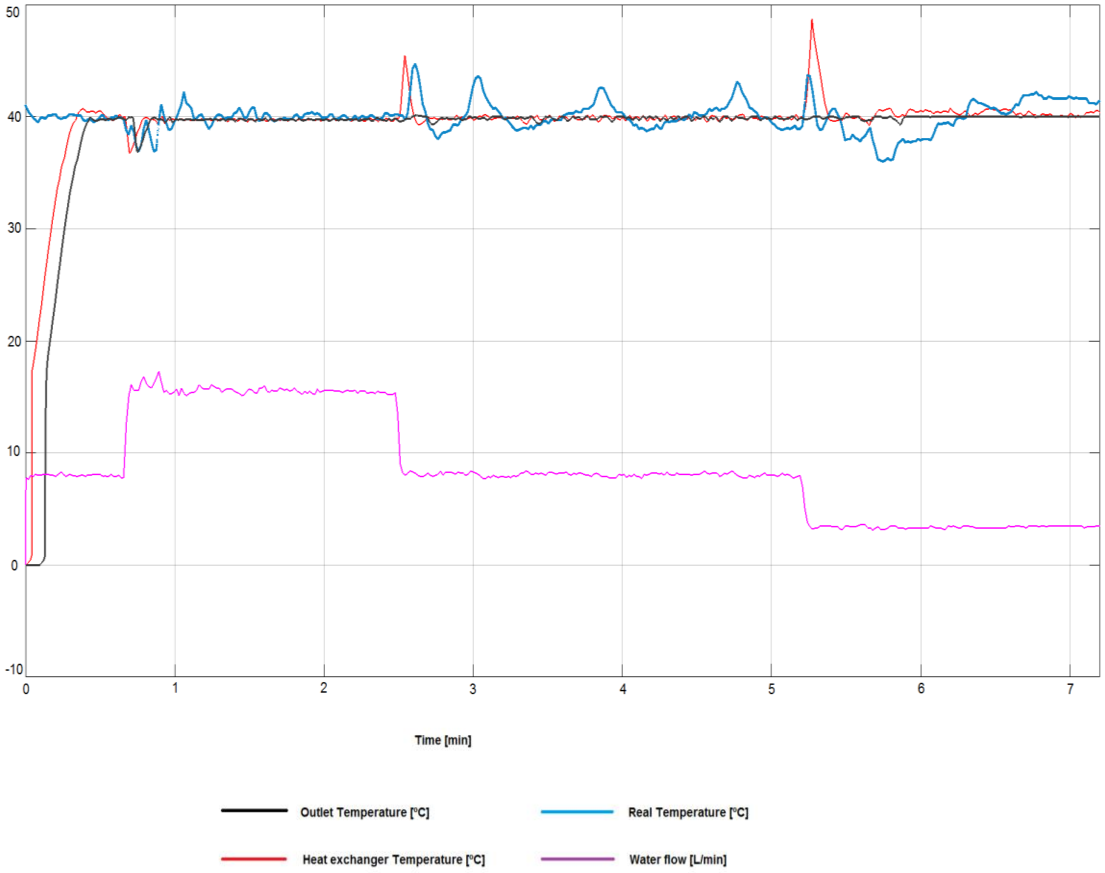


Figure 45: Comparison with a measured value in a set point of 40ºC.

In figure 45 it is represented outlet temperature, heat exchanger temperature, measured temperature and inlet water flow. This is a model response with set point of 40ºC.

To set point temperature, this model reacts better than previous experimental data because it there aren´t so many abrupt flow changes. By comparing with experimental data, this model has a better response; it is more stabilized when there is no flow change. But when there is flow change, the models reaction approaches with the real appliance.

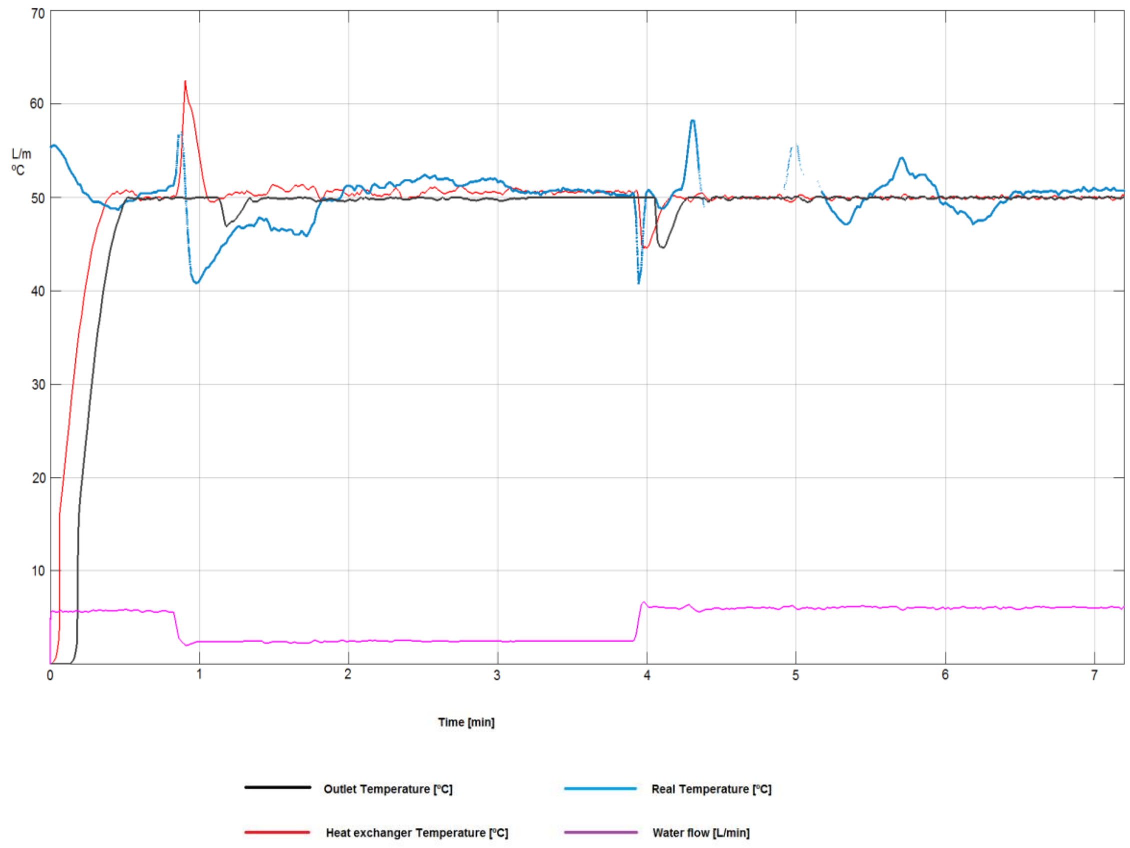


Figure 46: Comparison with a measured value in a set point of 50ºC.

For this comparison with a set point of 50ºC (figure 46), it is represent the model response through outlet temperature, heat exchanger temperature and water flow and comparing outlet temperature with a measured temperature. Water flow is lower than in the other two experimental tests; which can lead a response to a more unsteady response. In a system like this, it is difficult to work with small flows because of burner characteristics and thermodynamic rules. A method to control this is to restrict the minimum water flow to 2 liters per minute. If water flow is lower than 2 liters per minute, the whole system doesn’t start.

Even in relation to figure 46, the response in flow changes is proportional to other tests and more stabilized than real test on appliance.

Now, relative to figure 57, it shows heat exchanger temperature, required power and water flow. It can be seen that when water flow rises, required power also rises and when water flow falls, required power falls too. And with these two changes, an overshoot or an undershoot in heat exchanger temperature occurs, through it water flow falls or rises respectively. Seeing that the system has a bypass control, these overshoots are cancelled, and are thus not felt by the users, an innovation in user’s comfort.

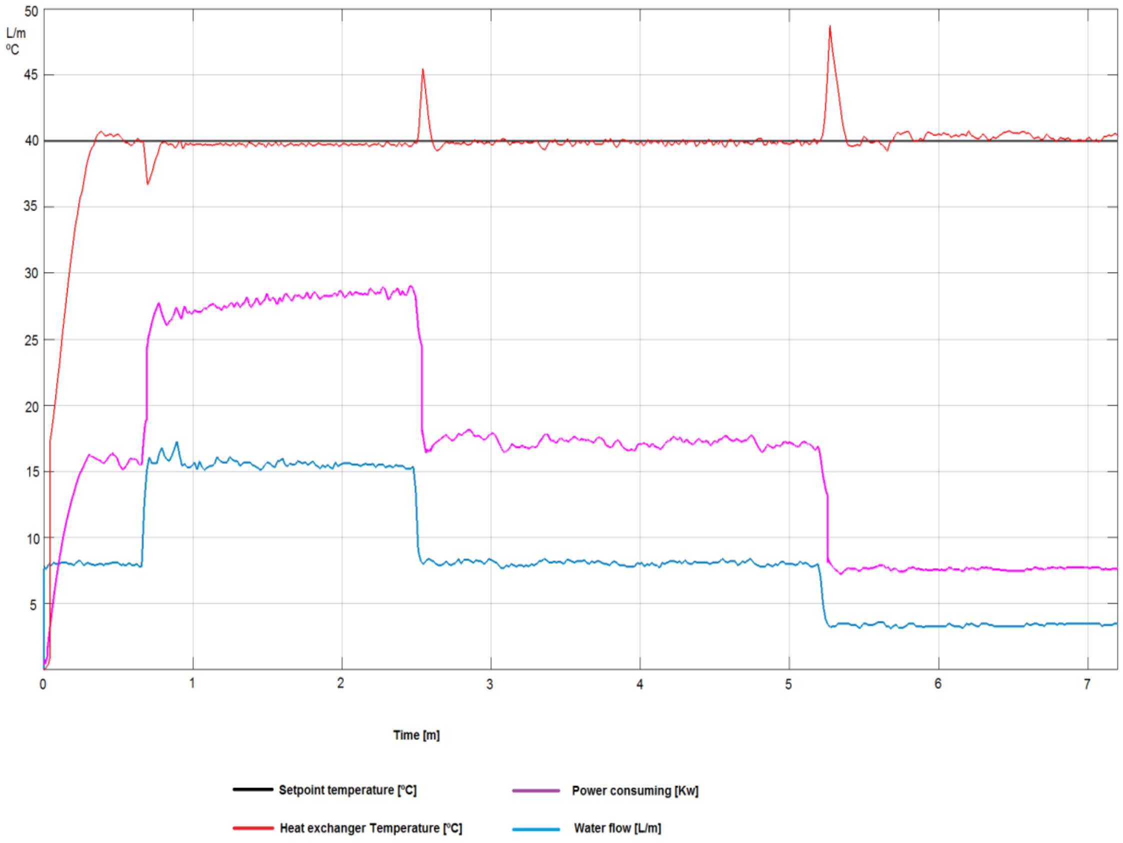


Figure 47: Diagram shows the Temperature of heat exchanger, and required power and water flow to a setpoint of 40ºC.

This figure 47 shows Power consuming. Adjusting somehow burner gains, power consuming would be less. To increase burner gains, power consumption would be lower which causes the device to be more economical.

In conclusion, this system is able to simulate the real appliance but with some improvements. The bypass control by the coefficient flow is not present in real appliance and that is the reason why this model is better than the real appliance.

The system has a good dynamic response like the real appliance, which can guarantee a good simulator for testing new improvements. Dynamic response is not better because of physical limitations on actuators, like burner for example.

With an upgrade of more pressure sensor, in junction with a bypass valve with pipe that comes from heat exchanger, it is possible to have a better accuracy on bypass control. A temperature sensor in the same place helps in accuracy of mixing rate calculation.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis, a model of a smart hydraulic controller was designed and implemented. Model design is described and simulation results are shown in comparison between simulation and real appliance followed by a discussion of the same results.

The main goal of this thesis was to implement an overall model of a gas water heater with hydraulic control and this goal was implemented with success.

As the main goal of this work was to develop a gas water heater model with bypass, bypass control had a greater focus. In a hydraulic control for a gas water heater, bypass control is the most important.

Other aspects taken into account were gas valve, blower, pipe delays, pressure losses and sensors position. With these aspects, overall system is complete.

Regarding to overshoots, all overshoots disappeared with bypass implementation. From the point of view of comfort, suppress overshoots is the most important. These dynamics appear when a quick negative flow change exists. Water temperature overshoot occurs because of slow response of system components, mostly blower and gas valve.

As the water flow suddenly decreases, combustion cannot instantly reduce heat energy necessary for that flow. Overshoot time is the time that the system needs to reach the new heat energy necessary. To overcome these overshoots implemented a new actuator was implemented, bypass valve.

Bypass control is considered the best solution because it is capable to suppress all overshoots and its implementation is not so expensive. It is composed by a valve, some pipes and a fuzzy control, that are implemented in controller programing. To further improve the bypass control, a new pressure sensor in bypass valve output can be added.

Undershoots are also present in the system. Like overshoots, undershoots appear when a flow change occurs, but differently from overshoots, they occur with an increase of water flow and have the same problem than overshoots.

In order to prevent this dynamic response a fuzzy control that restricts the water flow when an undershoot appears, was implemented. This is a method to control this dynamic but there are more. We could also implement an improvement in actuators delay time or water tank working as accumulator.

Taking into consideration these possibilities, the best option is the fuzzy control restricting water flows because this method only inserts some codes in the controller, and the others have large production investments.

Pipe losses implementation is necessary because of lack of pressure sensor. For pipes and valves we calculate the pressure loss in order to have the pressure in junction between bypass valve output and the pipe that comes from the burner. Instead of this implementation, a new pressure sensor must be installed.

In fuzzy control, two fuzzy controllers were designed. The controllers are relatively simple, one of them with five rules and ten memberships, five as input and 5 as output; and the other controller with four rules and eight memberships, half as input and the other half as output.

In spite of being simple, controllers work very well and for restricting or increasing the bypass valve aperture, a very complex controller is not required, which was also not possible because of lack of memory in water heater controller.

5.2 Future work

There are still some work that can be done in order to improve this model and this appliance. For appliance, one improvement is adding new pressure sensors for a better precision in pressure control of bypass valve. In other way, it can be changed the bypass valve for one that pressure does not affect its functioning like one equal to stepper valve. After this implementation in appliance, for a better Simulink model, it is missing change the pipe losses block by reading the pressure sensor; and change bypass valve implementation too.

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