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Thermal Mass Flow Sensor Functioning Evaluation and Verification

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Resumo

Este trabalho consiste no estudo, na análise, validação e melhoria do funcionamento do sensor e módulo de vazão de massa térmica desenvolvido pela Innovative Sensor Technology, sediada em Wattwil, Switzerland.

Este estudo servirá como ferramenta para a realização de experimentos e testes práticos com o intuito de melhorar o produto existente.

Primeiramente buscou-se provar, matematicamente, utilizando conceitos de Engenhaira de Controle e Automação, Termodinâmica e Mecânica dos Fluídos, que o objetivo do trabalho é viável e possível. Projetou-se até mesmo um controlador analógico teórico baseados em dados reais de modo a garantir sua viabilidade.

Depois, buscou-se entender e simular o funcionamento do módulo e sensor em estudo. Por fim foram feitas simulações e análise dos resultados fornecendo grande conteúdo técnico e conhecimento teórico para fins de experimentação.

Abstract

This work consists of studying, analyzing, validating and improving the functioning of the thermal mass flow sensor and electronic module developed by Innovative Sensor Technology, based in Wattwil, Switzerland.

This study will serve as a valorous tool for practice tests and experimentations intending to improve the existing product.

At first, one intended to prove mathematically the projects' objectives feasibility, using Control and Automation, Thermodynamics and Fluid Mechanics concepts. A Theoretical analog controller was even designed based upon real data in order to assure the project feasibility.

In a second moment, one intended to understand and simulate the sensor and the module functioning. At last, simulations were made and its results were analyzed providing a very good theoretical base and technical knowledge for practical tests purposes.

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Chapter 1: Introduction

The flow measurement is fundamental to assure safety for several industrial processes. The thermal mass flow measurement technology is the core technology for thermal mass flow meters. It is responsible for indicating the amount of mass per time unit that drains through certain transversal section in a free conduit (such as channel, river or tubing) or a forced conduit (tubing with positive or negative pressure).

In addition to these concepts, the thermal technique is also understood by the use of thermodynamics principles for calculating the thermal mass flow through heat exchange between the fluid and the power dissipation elements.

Thereby, the main objective of this work is to validate theoretically the thermal mass flow sensor technology developed by Innovative Sensor Technology AG, from Wattwil, Switzerland, through theoretical foundation and software simulations, as well as figure out whether is possible or not to assure certain constant temperature differential between two elements in its electronic system.

The methodology used based initially on researching of secondary data sources available in books, published scientific works and websites. In a second moment, simulations were used in order to verify the theoretical development.

The problematic used on this project focused on sustainable and feasible solutions both for IST and for the world since thermal mass flow meters are expensive. Future projects will have very good proved solutions to base on. Experimentation as well implementation will certainly be theme of future projects.

1.1: The Innovative Sensor Technology AG

IST AG is the company this work was developed for and had such an important role supporting with important information about its system.

IST is a company of the Endress+Hauser Group, headquartered in Reinach in north-western Switzerland. The Endress+Hauser Group is among the global leaders in measuring instruments, services and solutions for industrial process engineering.

IST AG has its headquarters in Wattwil in the canton of St. Gallen in the heart of eastern Switzerland in the beautiful area of Toggenburg. Since 1995 IST has a subsidiary in Roznov, Czech Republic, and a sales office in the USA since 1999.

IST AG has been recognized for innovative and high quality sensor technologies since its establishment in 1991. It has more over developed a reputation worldwide as a pioneer of providing application specific solutions for measuring temperature, humidity, flow and conductivity.

IST AG is coming up with an ambitious plan: the setting up of a sales office in Brazil, whose intent is to take advantage of the Brazilian economy growth and its opportunities.

The foundation of all IST products is the thin-film deposition technology. It has given IST a huge expertise on the development of micro-technology.

1.2: Problem Description

The Thermal Mass Flow Sensor is nothing more than two resistors. One is called SENSOR and it is a PT1200, that is, a resistance made of platinum whose resistance value is 1200 ohms at 0^{o}C. Its role is to measure the environment temperature of the fluid in tubing. It is usually placed close to the border of the tubing.

The other resistor is called HEATER and it is a PT45, that is, a resistance made of platinum whose resistance value is 45 ohms at 0^{o}C. The HEATER is important to provide its heat loss rate according to the power dissipation on it so that the flow rate can be calculated accordingly. The picture below is a simple representation of a thermal mass flow sensor. The sensor on the tip is the HEATER and the other one in the middle is the SENSOR.

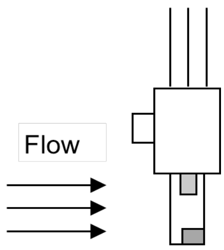


Figure 1 - Thermal Mass Flow Sensor

In order to calculate the flow rate, the HEATER must dissipate such a power so that it is feasible to acquire its heat loss rate. In theory, the HEATER should be kept 30 Kelvin above the environment temperature in order to provide accurate measurements.

For this task IST developed the following electronic module, Figure 2. This module has a Wheatstone bridge able to measure the potential difference between the HEATER and the SENSOR. As the flow rate increases the Wheatstone bridge misbalances. An Operational Amplifier calculates this difference and through a BJT it feeds back current to the HEATER and the SENSOR. As the HEATER way has a lower resistance, more current passes through it and more power is dissipated on the HEATER.

In order to keep a constant temperature differential between the SENSOR and the HEATER, it is believed that it can be done inserting and adjusting an analog PI controller in the electronic module. Placing it after the Wheatstone bridge may allow the circuit to faster deliver the current needed to keep the constant temperature difference. This is the main hypothesis raised for this project. The analog PI seems to be a cheaper way to solve the problem if we consider the average value of U$45 that is charged for this product.

The problem solving process consisted of modeling the physical process and analyzing simulations in order to figure out the theoretical feasibility of the hypothesis raised and which kind of control or analog controller configuration would better solve this problem.

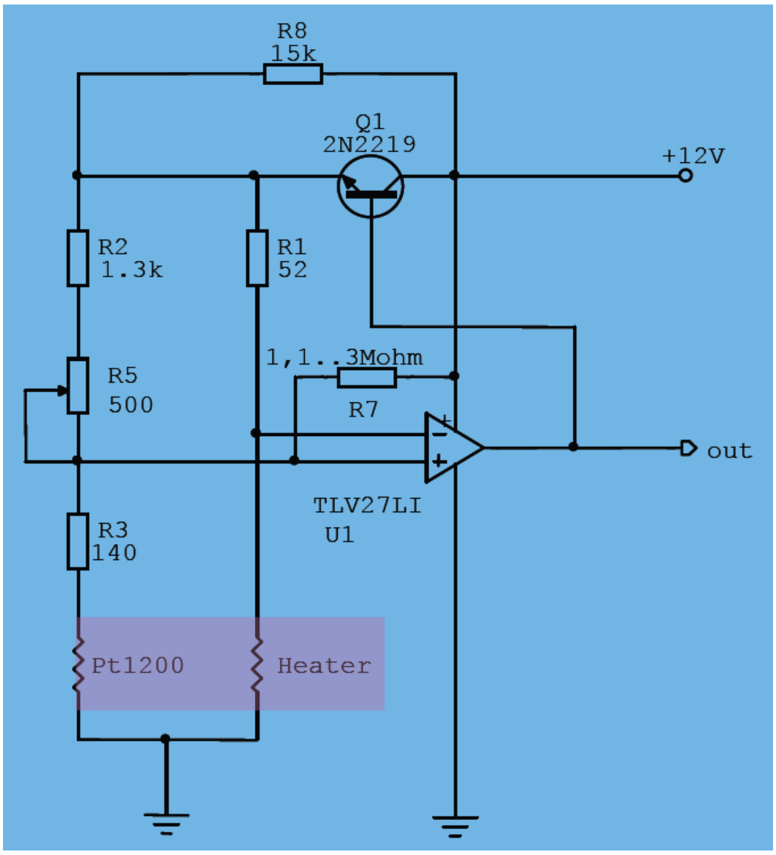


Figure 2 - Electronic circuit scheme

The resistor R5 is used to balance the Wheatstone bridge at the application. According to IST the resistor R3 must be kept at 140 ohms in order to keep 30 Kelvin temperature difference between the HEATER and the SENSOR. However it is really hard to prove without practical activities.

1.3: Objective

The objective of this work is to study and analyze theoretically the electronic module as well as the physical phenomenon behind the thermal mass flow sensor working principle and figure out whether it is possible or not to assure the 30 Kelvin temperature difference between the SENSOR and the HEATER using an analog electronic circuit configuration.

1.4: Context with Control and Automation Engineering

The UFSC Control and Automation Undergraduate Course provided important concepts for the problem understanding and solution proposal, mostly concerning:

- Electronics,

A basic knowledge of electronic circuits is extremely important to understand the working principle of the Electronic Circuit Scheme. The knowledge of Wheatstone bridge, Operational Amplifiers and Bipolar Junction Transistors is fundamental for the problem understanding.

- Feedback Control Systems

The concepts of Feedback Control Systems are very important to the problem solution proposal, mostly regarding PID and its configurations.

- Circuits

The concepts of resistors, current, power, rheostats and DC voltage source are very useful for this problem resolution.

- Instrumentation

Concepts of Instrumentation are very important to understand how the thermal mass flow sensor is supposed to work in the applications it is made for. It helps a lot the simulation process in which it is important to make some considerations based on the real sensor behavior.

- Thermodynamics

Concepts of Convection Thermal Law were extremely useful for the physical phenomenon modeling process and understanding.

- Measurement of Mechanical Magnitudes

A basic knowledge of Measurement of Mechanical Magnitudes is important for practical purposes.

1.5: Subject Importance

This project is very important for IST because it is a real product sold by IST. Keeping a 30 Kelvin temperature difference between the SENSOR and the HEATER is very important to avoid damages in the electronic circuit, to keep low power consumption and also to keep an accurate measurement system.

Many industries in the world may have a better flow measurement system depending on the results of this project contributing to safer and more accurate systems delivering better products for our society. Therefore it is a project whose results will be seen in practice and this is very motivating for engineering students.

1.6: Methodology

- Technical literature revision for project information adequacy;
- Production process analysis
- Physical Phenomenon modeling
- Software modeling
- Electronic circuit validation and improvements
- Documentation of results

1.7: Document organization

This document is structured in five chapters, enunciated as follows:

Chapter 1: Introduction, IST AG Company, Contextualization, Objectives, Subject importance and Methodology.

Chapter 2: Theoretical Foundation in general (Thermodynamics concepts, electronics concepts, Control concepts, Analog PID controllers configurations.

Chapter 3: IST Sensor Technologies, Thermal Mass Flow Sensor Manufacturing Process, Other flow measurement technologies.

Chapter 4: Development, where is shown both the mathematical modeling process and the electronic software modeling process.

Chapter 5: This chapter consists basically of theoretical and simulating results discussion.

Chapter 6: This chapter consists of conclusion taking in consideration the whole process, the objective and the original circuit. In the end there are some suggestions for future projects.

Chapter 2: Theoretical Foundation

Many concepts of Control and Automation Engineering were used in this project in order to model, simulate and validate the electronic circuit one intended to improve. Some concepts of Control Engineering were necessary to suggest a better solution for the problem introduced.

As important as the bibliography revision is getting to know some sensor technologies working principle as well as the electronics knowledge necessary for simulating purposes.

2.1: Thermal Mass Flow Sensors

The flow rate is a relation between physical magnitudes and time. It can be defined as: “the volume or amount of mass per time unit that flows through an specific transversal section of either a free conduit (river, channel, tube under the atmospheric pressure) or a forced conduit (tubing with positive or negative pressure)” (Wikipedia Foundation, Inc., 2012). Therefore, the flow unit is the unit of volume per time unit or the mass unit per time unit. Hence, the volumetric flow is the result of the flow speed multiplied to the tubing section area, whereas the mass flow is the result of the volumetric flow multiplied for fluid density (RIBEIRO, 2003, p. 315).

In practice, temperature and pressure measurements are used to deduce density, because it is very hard to measure the fluid density directly in the process and the gases composition is usually constant.

It is noticeable how broad the flow measurement applicability is. It varies from wastewater treatment to oil refining passing through all its processes.

2.2: Important variables

There are many independent variables in the processes that involve fluids which characterize the material and the outflow.

In the thermal mass flow measurement process it is extremely important to understand some intrinsic variables such as viscosity, temperature, pressure, compressibility, density and flow.

2.2.1: Pressure

Pressure is responsible for a fluid outflow in closed tubing. It assures that fluid occupies the whole transversal section. The pressure variation effect is very well defined concerning fluid density, gravity and compressibility (RIBEIRO, 2003). In terms of energy, the pressure potential energy is turned into kinetic energy. Even though only higher pressure values can affect the measurement system for liquids, pressure must be considered both for the measurement process and for the control process (DIAS, 2009).

2.2.2: Temperature

Temperature is as important as pressure for thermal mass flow measurement. Constant temperature differential assurance is even one of the objectives of this work.

Temperature is the result of sensitive heat. Therefore, two bodies in the same temperature may have different amount of heat and, as a consequence, two bodies with different temperatures may have the same amount of heat (RIBEIRO, 2003).

Temperature influences the fluid density, viscosity and compressibility as well as pressure does. Thereby it is mandatory to compensate temperature in the volumetric gases flow measurement. In some cases it is also important for liquids.

In any instrument specification, there will always be defined the operation, storage and reference temperature. For extreme flow measurement conditions, there will always be some special specifications (DIAS, 2009).

2.2.3: Compressibility

Compressibility is the relative volume reduction caused by an external agent. Whereas the liquids are quite incompressible, the gases are very compressible.

2.2.4: Viscosity

Viscosity is a measure of resistance of a fluid that is being deformed by either shear stress or tensile stress. Viscosity describes a fluid's internal resistance to flow and may be thought as a measure of fluid friction. Put simply, the less viscous the fluid is, the greater its fluidity (SYMON, 1971). Thereby, viscosity can be considered as a frictional force between flow layers when one layer is forced to move relatively to another layer.

The viscosity and the other fluid characteristics are very important for the flow meters building process, because it helps to understand which kind of drain the flow meter will be exposed to. The position where the flow meter is placed is also very important, because it has to be placed where the outflow is fully developed. Otherwise the flow measurement will not represent a real value (DIAS, 2009).

The viscosity modifies the outflow, which can be classified as Laminar or Turbulent depending on the Reynolds' number, defined on Equation 11 - Reynolds number equation.

$$R_e = \frac{V.l}{v}$$

$\boldsymbol{R_e}$: Reynolds' number equation;

$\boldsymbol{l}$: System characteristic dimension [m];

$\boldsymbol{V}$: Fluid speed [m / s].

$\boldsymbol{v}$: Kinematic viscosity [m^2 / s];

In a laminar outflow, all the fluid particles have the same trajectory. In contrast, in a turbulent outflow it does not happen. In a turbulent outflow the flow lines are instable.

The Reynolds' number is taken in consideration for flow meters either manufacturing and/or acquisition process because it is possible to evaluate if the equipments specifications are verified. Furthermore, it allows to simplifications on the equations and solutions.

2.2.5: Density

The absolute density is defined as: mass over volume (RIBEIRO, 2003, p. 25). Its unit is expressed as [kg/m^3] or [kg/L]. The relative density is “the substance mass over the equivalent water volume considering the same pressure, temperature and gravity conditions” (RIBEIRO, 2003, p. 35). The relative density is essentially related to the atoms and molecules organization.

The measurement for compressible flow depends on temperature and pressure. In this case, both the absolute and relative densities vary. In order to read accurate values from the system, it is extremely important to compensate temperature and pressure.

2.3: Electronics Knowledge

Some basic concepts of electronics are extremely useful for the project understanding and also for this problem solution.

2.3.1: Operational Amplifiers

> An operational amplifier ("op-amp"), Figure 3, is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output. An op-amp produces an output voltage that is typically hundreds of thousands times larger than the voltage *difference* between its input terminals.
>
> The power supply pins (VS+ and VS−) can be labeled in different ways (See IC power supply pins). Despite different labeling, the function remains the same — to provide additional power for amplification of the signal. Often these pins are left out of the diagram for clarity, and the power configuration is described or assumed from the circuit. (Wikipedia Foundation, Inc., 2012)

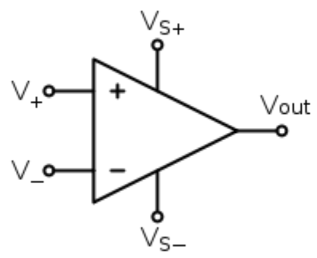


Figure 3 - Operational Amplifier

2.3.1.1: Inverting Configuration

An inverting amplifier inverts and scales the input signal. As long as the op-amp gain is very large, the amplifier gain is determined by two stable external resistors (the feedback resistor R_f and the input resistor R_{in}) and not by op-amp parameters which are highly temperature dependent (Wikipedia Foundation, Inc, 2012).

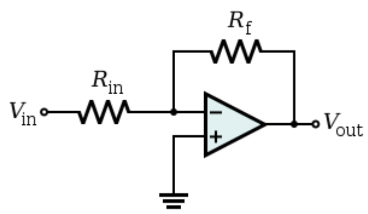


Figure 4 - Inverting Op Amp Configuration

Hence, the amplifier output is related to the input as in

$$V_{out} = -\frac{R_f}{R_{in}} . V_{in}$$

So the voltage gain of the amplifier is

$$A = -\frac{R_f}{R_{in}}$$

Where the negative sign is a convention indicating that the output is 180^o out of phase.

2.3.2: Bipolar Junction Transistors

A bipolar junction transistor (BJT) is a three-terminal electronic device constructed of doped semiconductor material and may be used in amplifying or switching applications.

Bipolar transistors are so named because their operation involves both electrons and holes. By design, most of the BJT collector current is due to the flow of charges injected from a high-concentration emitter into the base where there are minority carriers that diffuse toward the collector, and so BJTs are classified as minority-carrier devices". (Wikipedia Foundation, Inc., 2012)

An NPN transistor can be considered as two diodes with a shared anode. In typical operation, the base-emitter junction is forward biased and the base–collector junction is reverse biased. In an NPN transistor, for example, when a positive voltage is applied to the base–emitter junction, the equilibrium between thermally generated carriers and the repelling electric field of the depletion region becomes unbalanced, allowing thermally excited electrons to inject into the base region. These electrons wander or diffuse through the base from the region of high concentration near the emitter towards the region of low concentration near the collector. The electrons in the base are called minority carriers because the base is doped p-type which would make holes the majority carrier in the base. (Wikipedia Foundation, Inc., 2012)

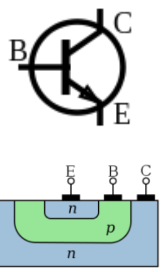


Figure 5 - NPN Bipolar Junction Transistor

2.4: Control Theory

It is growing the role of automatic control and the number of its applications. Nowadays, automatic control is indispensable in the majority of industrial sectors and in applications which demand a higher level of specialization such as military systems, airspace devices and robotics (ESPIGA, 2012).

There are two fundamental concepts for characterizing a control system: the magnitude measured, known as *controlled variable*, which one desires to control; and the *manipulated variable*, which is modified by the controller intending to influence the *controlled variable* (ESPIGA, 2012).

2.4.1: Feedback Control

Feedback control or closed loop control, Figure 6 is one type of control that uses the difference between the *reference signal* and the *controlled variable,* known as error, to calculate the action needed over the *manipulated variable* in order to keep the system desired behavior. In this kind of control system, it is possible to lead the system error to zero. Besides, it also rejects disturbances that might happen in different points of the closed loop controlled system.

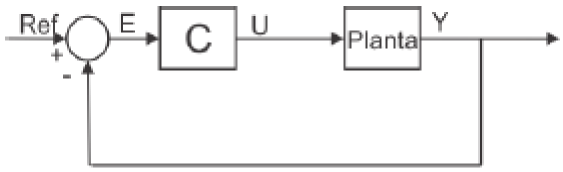


Figure 6 - Feedback Control System

Figure 6 depicts a simplified structure of a feedback control, in which the reference signal is represented by Ref, the error by E, the controller by C, the control signal by U and the controlled variable by Y.

2.4.2: State Equations

> The state equation is a first-order linear differential equation, or (more precisely) a system of linear differential equations. Because this is a first-order equation, it is possible to use results from Ordinary Differential Equations to find a general solution to the equation in terms of the state-variable *x*. Once the state equation has been solved for *x*, that solution can be plugged into the output equation. The resulting equation will show the direct relationship between the system input and the system output, without the need to account explicitly for the internal state of the system". (Whiteknight, 2007)

$$\dot{x} = a \,.\, x + b \,.\, u + q$$

This equation is used in this project to determine the process equation.

2.4.3: Analog PID Controllers

Throughout this century, many diverse analog controllers emerged. The pneumatics emerged first and launched the modern era of automatic industrial control for temperature, flow and level. Hydraulic controllers were also very important for controlling speed and position. However, as time went by, the electronic technology was developed and improved, and as a consequence, the digital controllers emerged. Nowadays, most of applications use analog or digital controllers (Pinto, 2005).

The current analog controllers utilize an active component named Operational Amplifier. Due to its versatility it is possible to assemble many different analog controllers' configurations. Some of this configurations follows on Figure 7 - Analog Proportional Controller, Figure 8 - Analog Integrator Controller, Figure 9 – Analog PI Configuration, Figure 10 - Analog PD Configuration Con and Figure 11 - Analog Derivative Integrator Proportional Configuration. (BARBOSA, DOS SANTOS, LIMA, & BATISTA JÚNIOr, 2010)

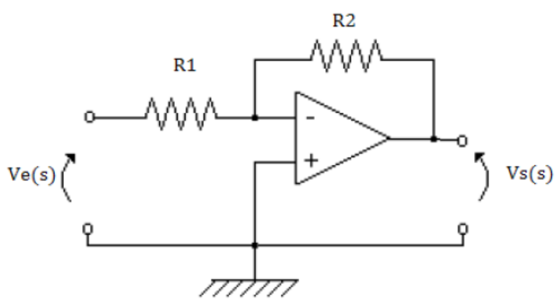


Figure 7 - Analog Proportional Controller

The proportional configuration is proportional to the voltage difference between the HEATER and the SENSOR at the Wheatstone bridge. The higher the error, the stronger the action.

The transfer function for this configuration is according to the inverting configuration of Op Amp's on page 19.

$$\frac{V_O}{V_I} = -\frac{R_2}{R_1}$$

In which

V_O : Output Voltage

V_I : Input Voltage

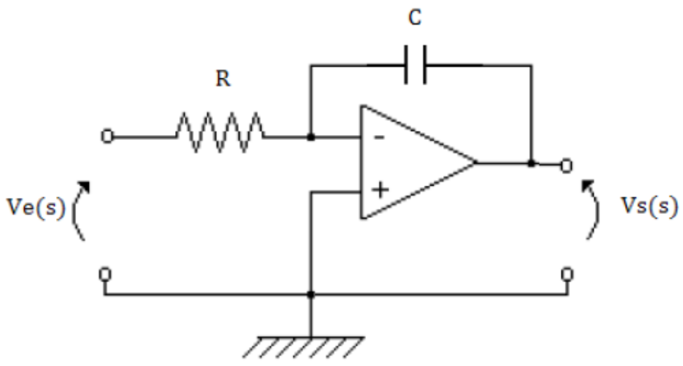


Figure 8 - Analog Integrator Controller

The Integral action aims to assure null error in order to faster balance the Wheatstone bridge in steady state.

The transfer function for this configuration is

$$\frac{V_O}{V_I} = -\frac{1}{RCs}$$

Equation 1 - Analog I Controller

The PI configuration had the best simulating results. Two different configurations are presented on Figure 9 – Analog PI Configuration.

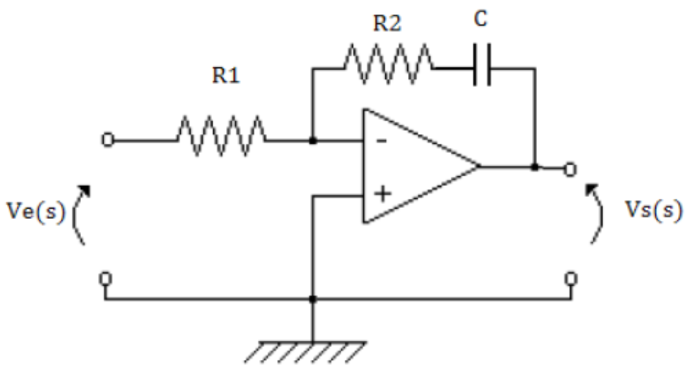


Figure 9 – Analog PI Configuration

The transfer function of this PI configuration is

$$\frac{V_O}{V_I} = -\frac{R_2}{R_1}\left(\frac{R_2Cs + 1}{R_2Cs}\right)$$

Equation 2 - Analog PI Controller

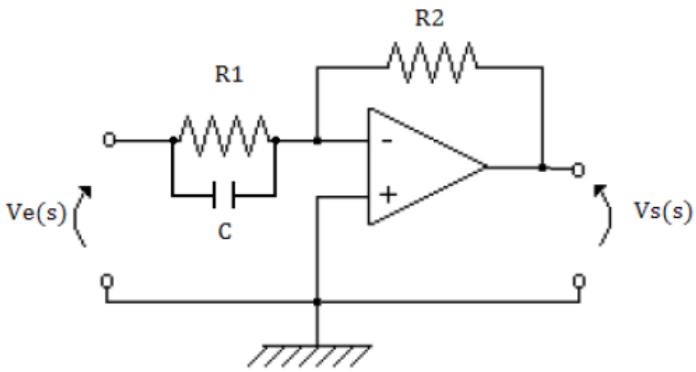


Figure 10 - Analog PD Configuration Configuration

The transfer function is

$$\frac{V_O}{V_I} = -\frac{R_2}{R_1}(R_1Cs + 1)$$

Equation 3 - Analog PD Controller

The Derivative action aims to faster respond to any input signal. It somewhat predicts the error and faster deliver a control action. For second order systems, the derivative action may result in over shooting depending on the derivative gain.

Many different configurations are displaced below and analyzed in chapter 5.

The PID controller, Figure 11 - Analog Derivative Integrator Proportional Configuration, sums all the other characteristics mentioned above (eCircuit Center, 2002).

- The proportional action KP reduces a large part of the overall error;
- The integrative action KI reduces the final error in steady state to zero;
- The derivative action KD helps to reduce the overshoot and ringing, however it has no effect on final error. It somewhat counteracts the KP and KI terms when the output changes quickly.

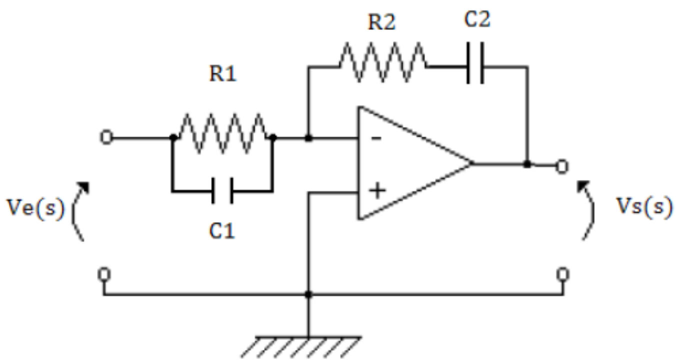


Figure 11 - Analog Derivative Integrator Proportional Configuration

The transfer function of this analog PID is as follows:

$$\frac{V_O}{V_I} = -\frac{R_2}{R_1}\frac{(R_1C_1s+1)(R_2C_2s+1)}{R_2C_2s}$$

Equation 4 - Analog PID Controller

2.4.4: Transfer function

The transfer function is a convenient representation of a linear time invariant dynamical system. Mathematically the transfer function is a function of complex variables. Transfer functions are commonly used in the analysis of systems such as single-input and single output filters, typically within the fields of signal processing, communication theory, and control theory. The transfer function can be obtained by inspection or by simple algebraic manipulations of the differential equations that describe the systems.

In its simplest form for continuous time input signal $\boldsymbol{x(t)}$ and output $\boldsymbol{y(t)}$, the transfer function $\boldsymbol{H(s)}$ is the linear mapping of the Laplace transform of the input, $\boldsymbol{X}(\boldsymbol{s}) = \boldsymbol{L}\{\boldsymbol{x}(\boldsymbol{t})\}$, to the Laplace transform of the output $\boldsymbol{Y}(\boldsymbol{s}) = \boldsymbol{L}\{\boldsymbol{y}(\boldsymbol{t})\}$.

$$\boldsymbol{Y}(\boldsymbol{s}) = \boldsymbol{H}(\boldsymbol{s})\boldsymbol{X}(\boldsymbol{s})$$

Or

$$\boldsymbol{H}(\boldsymbol{s}) = \frac{\boldsymbol{Y}(\boldsymbol{s})}{\boldsymbol{X}(\boldsymbol{s})} = \frac{\boldsymbol{L}\{\boldsymbol{y}(\boldsymbol{t})\}}{\boldsymbol{L}\{\boldsymbol{x}(\boldsymbol{t})\}}$$

Chapter 3: Sensor Technologies Understanding

The development process consists of all IST sensor technologies understanding. It is very important to get to know the working principle of this micro technology in order to figure out all the influences it may have on the sensor behavior. For the same reason, it is described in this chapter the manufacturing process of the thermal mass flow sensor.

Even though the Thermal Mass Flow Sensor is one of the best technologies for gas flow measurement, there are many technologies for flow measurement which are also described in this document. All these technologies are application specific and are worth to quick overview.

3.1: IST Sensor Technologies

3.1.1: Resistance Temperature Detectors

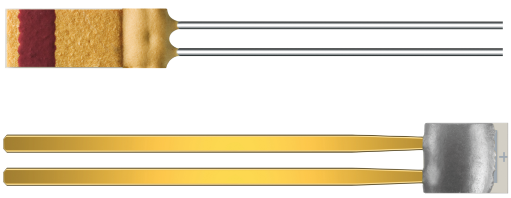


Figure 12 – Some Pt and Ni Temperature Sensors

Figure 13 – Surface Mounted Device Configuration

Figure 14 – Pt10,000

3.1.1.1: Measurement Principle

Resistance Temperature Detectors (RTD) functions on the principal that a material's electrical resistance changes with temperature.

Platinum and Nickel are the materials commonly used on IST products. The platinum is a noble metal and has the highest resistivity which means measurement integrity and linearity. For such reason Platinum is used in wide temperature range applications. Nickel has a lower resistivity, is quite non-linear and tends to drift over time. For such reasons it is used in applications of limited temperature range.

Another temperature sensor IST develops and manufactures is the Temperature Sensor Integrated Circuit (TSic). The TSic product family consists of chip-integrated and calibrated temperature sensors with an integrated signal converter for analog or digital signal output. It offers measurement accuracy and high signal resolution for optimal temperature control. Due to its low power consumption (typical 30 Microampere), it is well suited for data logger, digital thermometer, temperature monitoring and measurement applications.

3.1.2: Humidity

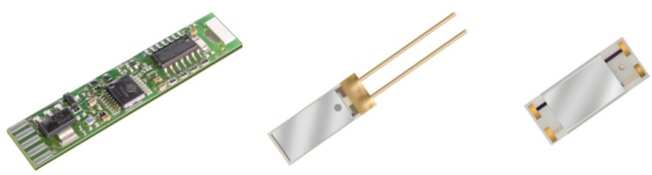


Figure 15 – Humidity Sensor. A lot of different configurations such as SMD Wire and Digital modules with analog and digital output signal

Figure 16 – Brand new humidity module. Temperature and humidity sensor in one device

3.1.2.1: Measurement Principle

Capacitive RH (of Relative Humidity) sensors consist of a ceramic substrate on which a thin film of polymer is deposited between two electrodes.

The sensing surface is coated with a micro porous metal electrode, allowing the polymer to absorb moisture while protecting it from contamination and exposure to condensation.

As the polymer absorbs water, the dielectric constant changes incrementally and is nearly directly proportional to the relative humidity of the surrounding environment. Thus, by monitoring the change in capacitance, relative humidity can be derived.

IST thin-film capacitive relative humidity sensors are capable of measuring 0-100% relative humidity and operating at temperature ranges of -80^{o}C to +190^{o}C.

3.1.3: Flow

Figure 17 – Flow sensors

3.1.3.1: Measurement principle

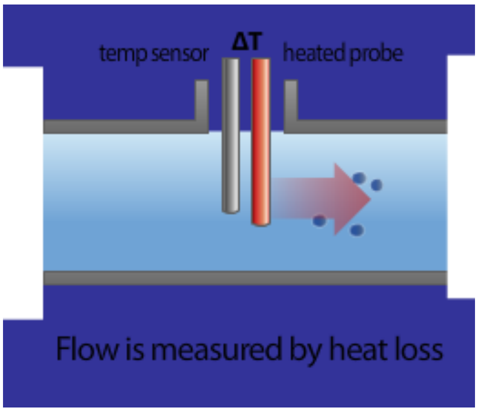


Figure 18 - Thermal Mass Flow Meters

Thermal mass flow sensors utilize heat transfer principles to determine the flow velocity of a fluid. As flow increases, so does the amount of heat that is transferred. By knowing medium temperature, the flow rate can be determined from the amount of voltage compensation needed to maintain a constant temperature differential.

IST flow sensors are applicable in both gas and partially in liquid, have an operating temperature range of -30°C to +450°C, and can measure flow rate and direction from 0.001m/s to 100m/s in gases and from 0.1 m/s to 10m/s in liquids. In addition to measuring flow rates, IST liquid sensors can detect the presence of a liquid, biofilm, or bubbles, as well as indicate liquid level.

3.1.3.2: Brazilian demand for Thermal Mass Flow Sensors

In Brazil there is only one manufacturer of thermal mass flow sensors. Many traditional companies do not believe there is a good potential for this technology and for such reason are not willing to risk and invest in R&D. On the other hand, many companies forsee a good future for this technology and are demanding samples and investing in the development of a thermal mass flow meter. These companies believe they can profit more than 30% with a nacional technology. The thermal mass flow meters found in Brazil are brought form Mexico, USA and Europe and they cost about R$1200,00.

3.1.4: Thermal Mass Flow Sensors Manufacturing Process

The manufacturing process understanding of thermal mass flow sensors is very important to get to know the materials used in it and also to figure out some systematic error intrinsic to the process.

3.1.4.1: Thin Film Coating

Figure 19 - Thin Film Coating

Platinum or Nickel is coated onto a substrate (Zirconium) through sputtering. This process coats all the substrate with a thin layer of platinum. This is such an expensive process due to the high costs of Platinum.

3.1.4.2: Photo Lithography

Figure 20 - Photolithography

Each meander design is imprinted on the substrate using photolithography, and then etched away. After the Thin Film Coating Process the substrate is coated with a light sensitive polymer. After that a photo mask is used to transfer a geometric pattern to the substrate. A series of chemical treatments then either engraves the exposure pattern into the material underneath the photo resist.

3.1.4.3: Trimming / Passivation

Figure 21 – Trimming

Trimming alters the meander to achieve custom values for resistance, capacity, etc. A high tech machine measures each resistance of the flow sensor, there are two, and with a laser it reaches the right resistance value for them.

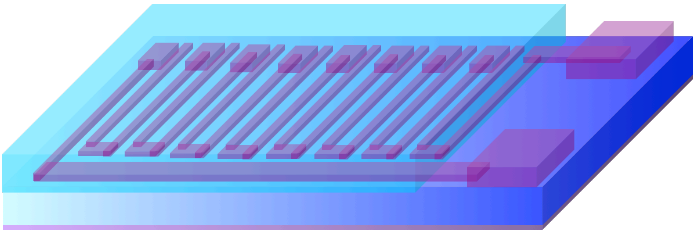


Figure 22 – Passivation

A protective glass passivation layer is used to protect the meander. The layer material was specially developed to match the substrate and the platinum. This passivation layer is made screening the passivation material onto the substrate.

3.1.4.4: Assembly

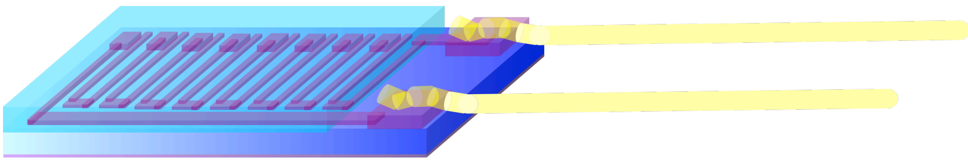


Figure 23 – Assembly process

The sensors are separated from each other through a high speed dicing process, and leads are automatically welded on.

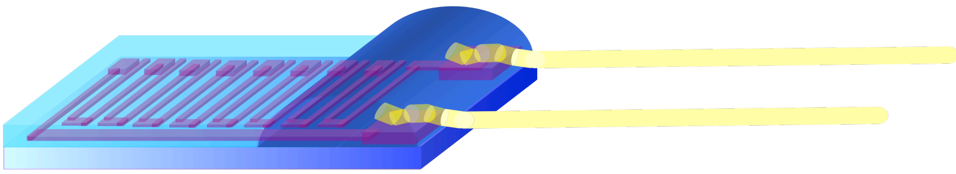


Figure 24 – Special glob top added

A special glass glob top is put above the wire connections to protect, among other things, against mechanical strain. The junction of the leads and the sensors are very brittle.

3.1.4.5: Test & Measurement

Figure 25 – Test & Measurement

All IST sensors are measured, tested, and inspected. The measurement is an automatic process which ensures quality of IST sensors.

3.1.4.6: Calibration Laboratory

Figure 26 – Calibration

Most of IST sensors are calibrated according to internal reference standards with certified calibration tools. The flow sensors must be calibrated on the application so that the right values can be taken out of the process.

3.2: Different Flow Measurement Technologies

3.2.1: Variable Area Flow meters

Variable area flow meters measure flow by allowing the flow stream to change the opening within the flow meter by moving an internal part. When the flow increases, the fluid generates more force and moves the internal part farther (Flowmeters.com LLC, 2003).

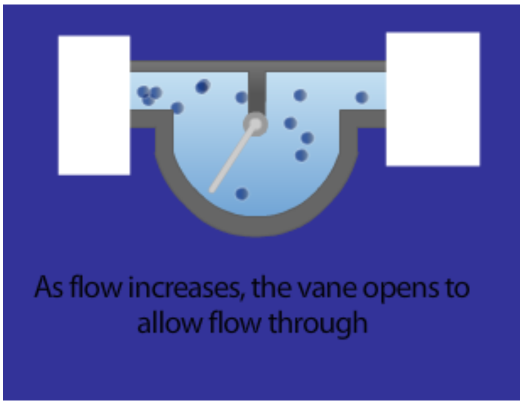


Figure 27 - Variable Area Flow meters

Vane-style variable area flow meters have a spring-opposed vane that moves in relation to the flow rate. Similarly, piston variable area flow meters use a spring-opposed piston that moves in relation to the flow rate and are less sensitive to viscosity than vane-style variable area flow meters. Both vane-style and piston variable area flow meters can be connected to an indicator or transmitter (Flowmeters.com LLC, 2003).

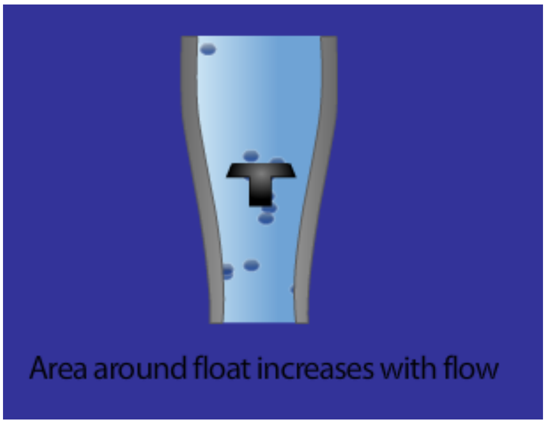


Figure 28 - Variable Area (Float Style)

One variable area flow meter measures flow in a vertical metering tube by balancing the downward weight of a float with the upward force of the flowing fluid. Spring-opposed float designs allow this type of flow meter to be installed in horizontal pipes, because the functioning of the float is not dependent upon gravity. These flow meters can be read locally because their glass or plastic metering tubes have markings that relate the height of the float (that can be seen) with the flow rate of the fluid. Flow meters with remote signals are typically constructed with metal tubes, and include a transmitter that senses the height of the float to determine fluid flow (Flowmeters.com LLC, 2003).

3.2.2: Laminar Flow Element Flow Meters

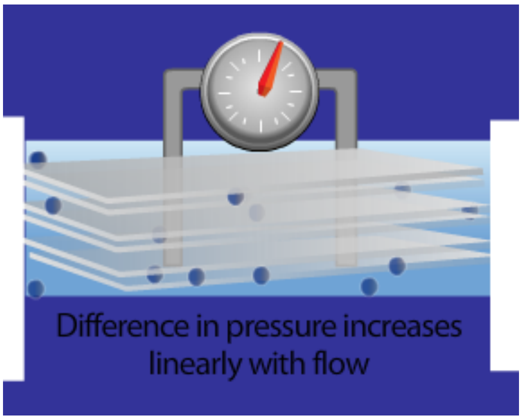


Figure 29 - Laminar Flow Element Flow meters.

Differential pressure flow meters use Bernoulli's equation to measure the flow of fluid in a pipe. Differential pressure flow meters introduce a constriction in the pipe that creates a pressure drop. When the flow increases, more pressure drop is created. Bernoulli's equation states that the pressure drop across the constriction is proportional to the square of the flow rate. Laminar flow elements, however, present a special case wherein the fluids are in a laminar regime (low Reynolds number) and the pressure drop is linear in relation to the flow rate. That makes very useful for reading the low end of the scale and increases the "turn down" from the usual 10:1 to 100:1. This technology is optimal for clean gas flows. The flow is calculated by measuring differential pressure and making corrections with data from temperature and absolute pressure sensors (Flowmeters.com LLC, 2003).

3.2.3: Coriolis Mass Flow Meters

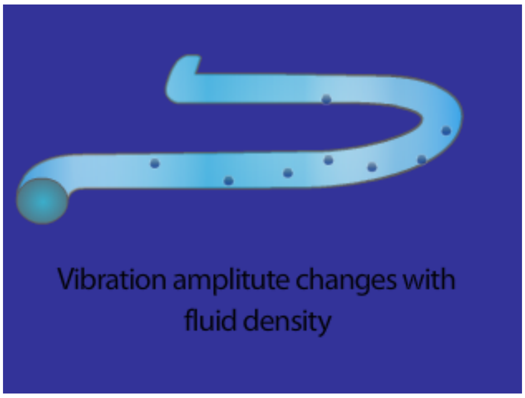


Figure 30 - Coriolis Mass Flow Meters

Coriolis mass flow meters measure the force resulting from the acceleration caused by mass moving toward (or away from) a center of rotation. In a Coriolis mass flow meter, the “swinging” is generated by vibrating the tube(s) in which the fluid flows. The amount of twist is proportional to the mass flow rate of fluid passing through the tube(s). Sensors and a Coriolis mass flow meter transmitter are used to measure the twist and generate a linear flow signal (Flowmeters.com LLC, 2003).

3.2.4: Turbine Flow meters

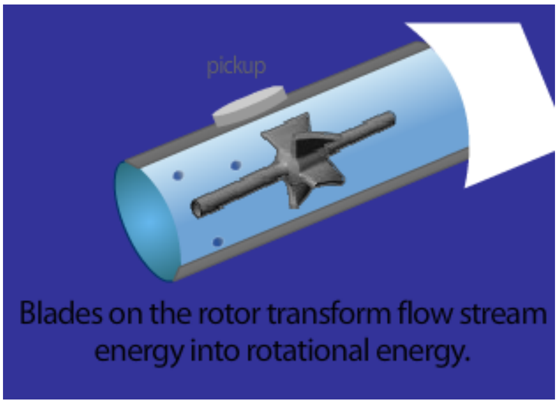


Figure 31 - Turbine Flow meters

Turbine flow meters use the mechanical energy of the fluid to rotate a “pinwheel” (rotor) in the flow stream. Blades on the rotor are angled to transform energy from the flow stream into rotational energy. The rotor shaft spins on bearings. When the fluid moves faster, the rotor spins proportionally faster (Flowmeters.com LLC, 2003).

3.2.5: Ultrasonic Flow meters

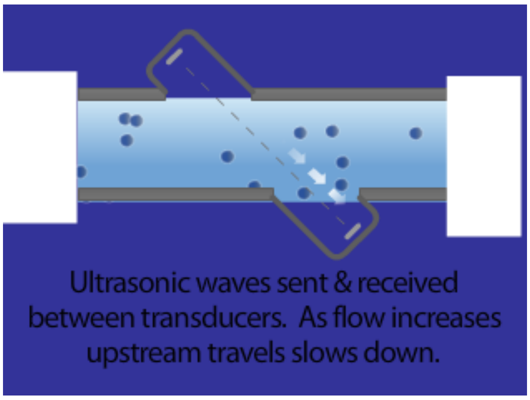


Figure 32 - Ultrasonic Flow meters

Ultrasonic flow meters use sound waves to determine the velocity of a fluid flowing in a pipe. At no flow conditions, the frequencies of an ultrasonic wave transmitted into a pipe and its reflections from the fluid are the same. Under flowing conditions, the frequency of the reflected wave is different due to the Doppler Effect. When the fluid moves faster, the frequency shift increases linearly. The transmitter processes signals from the transmitted wave and its reflections to determine the flow rate (Flowmeters.com LLC, 2003).

Chapter 4: The Project Development

This chapter has the objective of describing what was in fact accomplished. It is important to emphasize that due to a secrecy agreement with IST, this chapter will present just a project overview, not even showing important issues such as the complete electronic circuit, some parameters, variables and the circuit manufacturing technologies.

The development is based on the project of an analog PI controller to the Thermal Mass Flow Sensor of IST aiming to assure the maintenance temperature differential. The physical model was obtained in order to prove that such a proposal is logical and applicable for this project.

The process of comparing practical solutions with theoretical solutions using simulations is very hard. At first because it is extremely important to reproduce the practical solutions exactly the way it is. And secondly, it is hard to propose a new solution using only simulations because it is not known every application it will be subject to.

For such reason, in this project both the practical and theoretical solutions were treated the same way, theoretically. It was tried to reproduce the same electronic circuit even using the same components. Even though the circuit is simple, it was hard to find the right elements. Some similar components had to be used in this designing process due to the LT Spice IV restrictions.

For this project it was used two simulation softwares: LTSpice IV and Solvelec. Both are very good softwares depending on the project purposes. For elementary school purposes, Solvelec is such a good tool. It can emulate many simple circuits and even provide some analysis, graphs, transfer functions, equivalent circuits and equations. For academic and design purposes there is a student version for free download of LTSpice IV. This software has been very useful with many different features providing very accurate simulations.

4.1: Physical Phenomenon Modeling Process

In order to test and validate the thermal mass flow sensor working principle it is important to figure out if the constant temperature differential can be physically proved through mathematical modeling.

This flow measurement system is based upon the electric power needed to keep one Resistance Temperature Detector (RTD) in a temperature higher than the environment temperature. The representation of such a system considers two RTD's. One is placed along with the tubing border (called SENSOR) and the other placed in the middle of this tubing (called HEATER).

Some considerations had to be done so that an approximate relation between the Power Dissipation on the HEATER and the flow speed as well as the Voltage Differential between the HEATER and the SENSOR could have been achieved. The SENSOR is supposed to be placed in the fluid temperature and the power it dissipates is inconsiderable. The HEATER is supposed to receive power from the electronic system. Therefore, the HEATER is responsible for every heat exchange taking place in this system. One part of the energy HEATER receives is lost to the outflow and the other part is converted into heat.

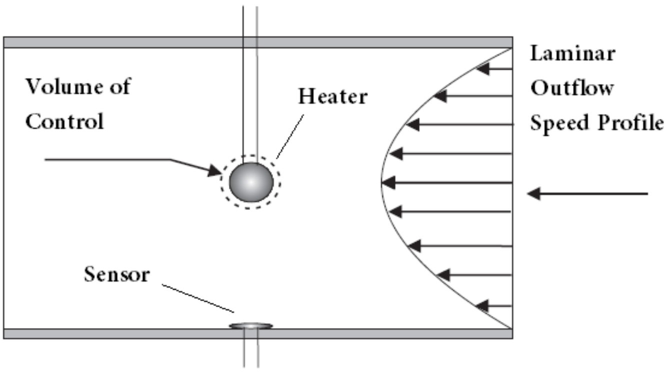


Figure 33 - Laminar Outflow Speed Profile

The analytical process considered the micro system shown above as Volume of Control. At first, it was analyzed considering the energy balance with the surroundings.

Considering uniform temperature on the entire tubing extension, the volume of control shown above, Figure 33, exchanges heat with the surroundings according to the Convection Thermodynamics Law, Equation 5. This micro system is

$$q = h. A_s. (T_{(t)} - T_{amb})$$

Equation 5 - Convection Thermodynamics Law

In which:

$\boldsymbol{q}$: Instantaneous heat exchange rate $[W]$;

$\boldsymbol{h}$: Convection heat exchange coefficient $[W / m_2 {}^oC]$;

$\boldsymbol{A_s}$: The superficial body area which exchanges heat [m^2];

$\boldsymbol{T_{(t)} - T_{amb}}$: The temperature differential between the fluid and the HEATER [^oC].

The energy balance on the HEATER is such as

$$\sum in - \sum out = 0$$

Equation 6 - Energy Balance

Then the energy gets into the system through power dissipated on the HEATER. This energy is lost to the fluid under the Convection Thermodynamics Law and also serves to heat the HEATER leading it to a higher temperature.

$$P_{(t)}. dt - h. A_s. \left(T_{(t)} - T_{amb}\right). dt = m_s. c. dT$$

$\boldsymbol{P_{(t)}}$: Power dissipation on the HEATER, the micro system analyzed [W];

$\boldsymbol{m_s}$: Heater mass [Kg];

$\boldsymbol{c}$: Thermal Mass Flow Sensor material specific heat [J / kg . K];

$\boldsymbol{dT}$: Temperature differential [^oC];

$\boldsymbol{dt}$: Time differential [s].

$$\frac{dT}{dt} = \frac{-h.A_S}{m_S.c} . T_{(t)} + \frac{1}{m_S.c} . P_{(t)} + \frac{h.A_S T_{amb}}{m_S.c}$$

$$\dot{x} = a\,.\,x + b\,.\,u + q$$

Equation 7 - HEATER Dynamics

The Equation 7 - HEATER Dynamics shows the HEATER dynamics according to both the entry signal u or $P(t)$ and the disturbance signal $Tamb$. The convection coefficient h concerns the system geometry, its properties, the flow speed and the type of outflow.

Knowing that on the equilibrium the derivative of constant values is equal to zero, that is,

$$0 = \frac{-h.A_s}{m_s.c}.T_{eq} + \frac{1}{m_s.c}.P_{eq} + \frac{h.A_s}{m_s.c}.T_{amb}$$

And that,

$$T_{eq} = \Delta T + T_{amb}$$

The following equation is reached:

$$0 = \frac{-h.A_s}{m_s.c}.\Delta T - \frac{h.A_s}{m_s.c}.T_{amb} + \frac{1}{m_s.c}.P_{eq} + \frac{h.A_s}{m_s.c}.T_{amb}$$

$$\frac{h.A_s}{m_s.c}.\Delta T = \frac{1}{m_s.c}.P_{eq}$$

$$h.A_s.\Delta T = P_{eq}$$

Equation 8 - Power dissipation on Equilibrium

Notice on Figure 34 how the profile of an outflow is. It is noticeable there are two regions, one laminar and another turbulent.

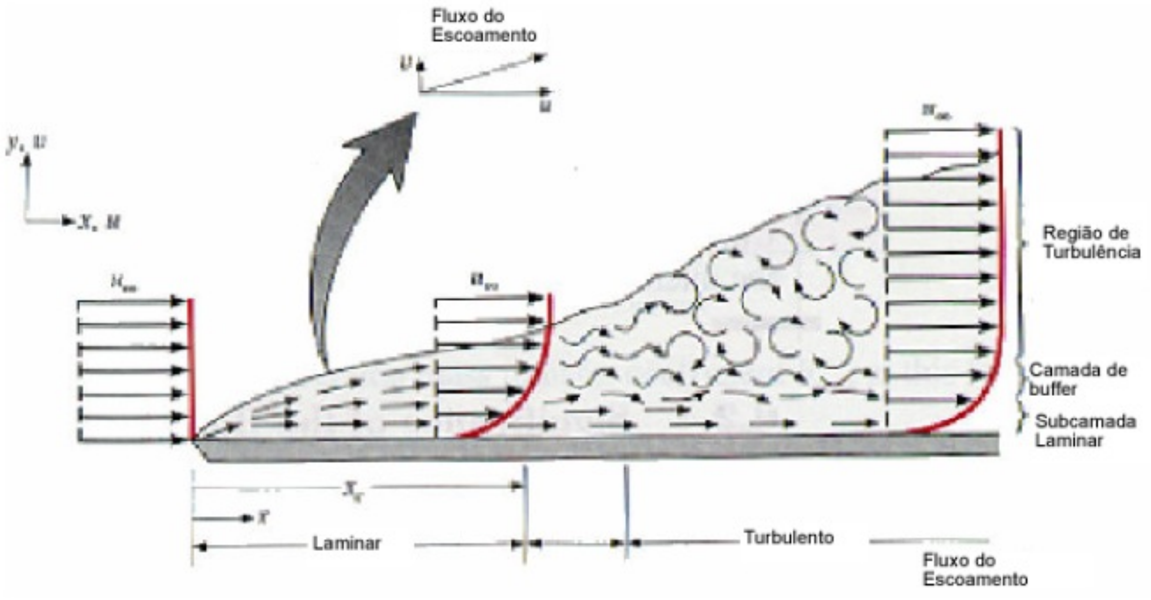


Figure 34 - Outflow Profile

The following table shows the film coefficient magnitudes (**h**) for different mediums.

PROCCESSES	
Free convection h(W/m^2 K)	
Gases	2 - 25
Liquids	50-1000
Forced convection h(W/m^2 K)	
Gases	25 - 250
Liquids	100-20000
Boiling and Condensation	**2500-100000**

Table 1 - Heat exchange coefficients for different mediums

In order to make this modeling process easier it was considered a laminar outflow. The convection coefficient ***h*** is related to with the system geometry and properties and with the flow speed.

In order to determine the convection heat exchange coefficient based on the dimensional analysis, it was used the Nusselt number. Physically speaking, the Nusselt number represents the relation of convection heat transfer of a fluid (that is, by convection and conduction. Nusselt number is also function of Reynolds' number as well as of Prandtl number. It is commonly expressed as follows.

$$N_u = C.R_e^n.P_r^m$$

Equation 9 - Nusselt number formula

$\boldsymbol{N_u}$: Nusselt number;

$\boldsymbol{C, n, m}$: These are constant values and should be determined experimentally.

The Nusselt number is directly related to the convection coefficient $\boldsymbol{h}$ as follows:

$$N_u = h.\frac{l}{\lambda}$$

Equation 10 - Nusselt equation with convection coefficient h

$\boldsymbol{l}$: System characteristic dimension [m];

$\boldsymbol{\lambda}$: Fluid thermal conductivity [W / m.K].

In fluid mechanics, the Reynolds number is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. It is commonly represented by the following equation.

$$R_e = V.\frac{l}{v}$$

Equation 11 - Reynolds number equation

$\boldsymbol{R_e}$: Reynolds' number equation;

$\boldsymbol{l}$: System characteristic dimension [m];

$\boldsymbol{V}$: Fluid speed [m / s];

$\boldsymbol{v}$: Kinematic viscosity [m^2 / s].

In the formulas of this project, the characteristic length is the horizontal length of the HEATER on the flow sensor (DIAS, 2009).

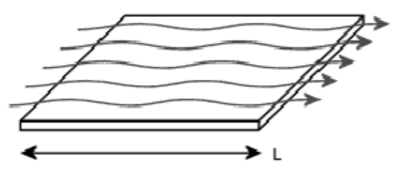


Figure 35 - Laminar outflow over a flat surface

Regardless of the fluid and the outflow, the system can be represented as follows:

$$N_u = C.R_e^n$$

Using Equation 10,

$$h = \frac{N_u.\lambda}{l}$$

$$h = \frac{C.R_e^n.\lambda}{l}$$

Using Equation 11

$$h = \frac{C.\left(V.\frac{l}{v}\right)^n.\lambda}{l}$$

Equation 12 - Convection coefficient equation

Going back to Equation 8

$$P_{eq} = \frac{C.\left(V.\frac{l}{v}\right)^n.\lambda}{l}.A_s.\Delta T_p$$

$$P_{eq} = \frac{C.l^{n-1}.\lambda.A_s.\Delta T_p}{v^n}.V^n$$

Equation 13 - Final relation Ph x V

Knowing that ΔT_p is equal to 30 K which was the objective of this project and that the only variable in this equation is V^n, the equation above, Equation 13 - Final relation Ph x V, can be seen as follows:

$$P_H = k.V^n$$

Equation 14 - Relation between Power and Flow Speed

P_H : Power dissipated on HEATER

Therefore, depending on the **flow speed, surface geometry, fluid properties and the type of outflow,** this relation can be even linearly proportional.

It is extremely important to notice on Equation 13 - Final relation Ph x V, that $\boldsymbol{\Delta T_P}$ (30 Kelvin temperature difference, the objective of this project) is also a constant value and is included on the constant $\boldsymbol{k}$ on Equation 14 - Relation between Power and Flow Speed.

This

Considering the Voltage applied on HEATER the relation gets to:

$$\frac{U_H^2}{R_H} = k.V^n$$

$$U_H^2 = R_H.k.V^n$$

$$U_H = \sqrt{R_H.k.V^n}$$

$\boldsymbol{U_H}$: Voltage applied on HEATER [V];

$\boldsymbol{R_H}$: HEATER resistance value [Ω].

In this case, the HEATER resistance value varies depending upon the flow speed. And if the $\boldsymbol{n}$ variable is 2, there is a **linear relation** such as:

$$U_H = k_2.V$$

Equation 15 - Voltage applied on the HEATER

As long as

$$k_2 = \sqrt{R_H.k}$$

Therefore, there are some cases that the Voltage value on the Heater varies linearly with the flow rate and that the environment temperature is a disturbance in this system. The constant values such as $\boldsymbol{k}$, $\boldsymbol{k_2}$ and $\boldsymbol{n}$ depends on the

- flow speed;
- surface geometry;
- fluid properties;
- And the type of outflow.

All these constants are usually determined on the flow meters calibration process.

4.2: A Basic Approach of Control Engineering

According to State Equations and to:

$$\dot{x} = a\,.\,x + b\,.\,u + q$$

And with Equation 7 - HEATER Dynamics

$$\frac{dT}{dt} = \frac{-h.A_s}{m_s.c}.T_{(t)} + \frac{1}{m_s.c}.P_{(t)} + \frac{h.A_sT_{amb}}{m_s.c}$$

The following relation is reached

$$\dot{T} = -aT + bu$$

$$s\dot{T} + aT = bu$$

$$T(s + a) = bu$$

$$\frac{T(s)}{U(s)} = \frac{b}{s + a}$$

$$\frac{T(s)}{U(s)} = \frac{\frac{b}{a}}{\frac{1}{a}s + 1}$$

Looking at Equation 7 - HEATER Dynamics, it is easy to recognize that,

The controlled variable is the temperature

$$x_{(t)} = T_{(t)}$$

$$a = \frac{hA_s}{m_sc}$$

$$b = \frac{1}{m_sc}$$

The control action is

$$u = P_{(t)}$$

And the disturbance is

$$q = \frac{h.A_s}{m_s.c}.T_{amb}$$

Therefore, ideally speaking it is possible to assure a constant temperature differential according to the equations above and a first order system is obtained.

The following equation is the process equation considering an ideal scenario (that is, no power is dissipated on the SENSOR).

$$G(s) = \frac{K_p}{\tau s + 1}$$

$$G(s) = \frac{h.A_s}{\frac{m_s c}{h.A_s} s + 1}$$

Equation 16 - Ideal Process Transfer Function

As can be seen on Equation 16 - Ideal Process Transfer Function,

$$\tau = \frac{m_s.c}{h.A_s}$$

And

$$K_p = h.A_s$$

Therefore, the time constant of this system depends on the flow speed since the convection coefficient depends on the flow speed.

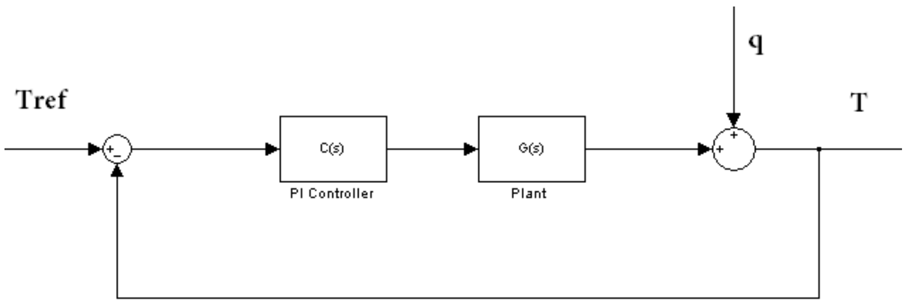
$$\tau = \frac{m_s.c.v^n}{C.l^{n-1}.\lambda.A_s} \cdot \frac{1}{V^n}$$

4.2.1: PI Controller Project

In addition to measure flow, this system is required to reject disturbances, such as environment temperature changes, and to follow the reference temperature so that a constant temperature differential can be achieved and the system accuracy assured.

The controller configuration that best fit on these requirements is the Proportional Integrator Controller due to its characteristics of disturbance rejection and reference following.

So, it was used for this project the analog PI configuration shown on Figure 9 – Analog PI Configuration. The system was modeled using a feedback control architecture using the error calculated by the difference between the controlled variable and the reference value. In the development of this activity it was used the softwares Matlab and Simulink.



Equation 17 - Closed loop system

The equation for the analog PI controller is as on Equation 2 - Analog PI Controller and placed in serie with an operational amplifier inverting configuration it gets to the following equation,

$$C(s) = \frac{R_4}{R_3}\frac{R_2}{R_1}\left(\frac{R_2Cs + 1}{R_2Cs}\right)$$

Renaming some constant values to make the modeling process easier,

$$K_{PI} = \frac{R_4}{R_3}\frac{R_2}{R_1}$$

$$\tau_i = R_2C$$

The controller equation becomes as follows

$$C(s) = K_{PI}\left(\frac{\tau_i s + 1}{\tau_i s}\right)$$

The denominator of C(s) has the integrator coefficient which assure reference following and disturbance rejection.

The disturbance rejection can be better seen looking at the closed loop for disturbances entries,

$$T(s) = \frac{\tau_i s.(\tau_i s + 1)}{\tau\tau_i s^2 + \tau_i(1 + K_P K_{PI})s + K_P K_{PI}}$$

Equation 18 - Closed loop for disturbances

It is clear the presence of a zero in zero assuring disturbance rejection.

One table, Table 2 - System Equation Coefficients with the system equations coefficients such as τ and K_P as well as h was made for different values of flow speed in order to verify graphically the zero-pole diagram and best analyze the step response and the disturbance rejection.

Considering some reasonable numerical values for the constants it is possible to even estimate some Plant transfer functions.

Flow Speed	Tal	h	Kp
1	0.1386	33644.56068	0.0336
2	0.0980	67289.12136	0.0673
3	0.0800	100933.682	0.1009
4	0.0693	134578.2427	0.1346
5	0.0620	168222.8034	0.1682
6	0.0566	201867.3641	0.2019
7	0.0524	235511.9248	0.2355
8	0.0490	269156.4854	0.2692
9	0.0462	302801.0461	0.3028
20	0.0310	672891.2136	0.6729
50	0.0196	1682228.034	1.6822

Table 2 - System Equation Coefficients

The table above, Table 2 - System Equation Coefficients, was created according to the following table.

Constants	Values
ρ	1.18
μ	0.0000183
c_{air}	1.0035
λ_{air}	0.025
C	0.66
n	0.5
l	0.001
A_s	0.000001
v	1.55085E-05

Table 3 - Constant Values

According to (Ogata, 2002), the transient response basic characteristic of a closed loop system depends essentially on the poles location under closed loop system.

Therefore, it is important to know how these poles behave on the plane S in order to project a controller according to the specifications.

These results are analyzed on Results.

4.3: The Flow Electronic Module Modeling Process

The modeling process of this electronic module was hard. It was necessary to figure out the right components in order to make an accurate simulation.

The first challenge was to find out the Operational Amplifier used in this module, the TLV27LIU1. This is a module made by Texas Instruments and has theses characteristics:

- Rail-To-Rail Output
- Wide Bandwidth . . . 3 MHz
- High Slew Rate . . . 2 .4 V/⌠s
- Supply Voltage Range . . . 2.7 V to 16 V
- Supply Current . . . 550 A/Channel
- Input Noise Voltage . . . 39 nV/Hz
- Input Bias Current . . . 1 pA
- Specified Temperature Range
- 0°C to 70°C . . . Commercial Grade
- −40°C to 125°C . . . Industrial Grade
- Ultra small Packaging
- 5 Pin SOT-23 (TLV271)
- 8 Pin MSOP (TLV272)
- Ideal Upgrade for TLC27x Family

The Operational Amplifier, Figure 36, used in this simulation is made by Linear Technology and the characteristics are similar to the Texas Instrument’s used in the original circuit (Linear Technology, 2007).

The characteristics of the Op Amp used follows bellow, Figure 36.

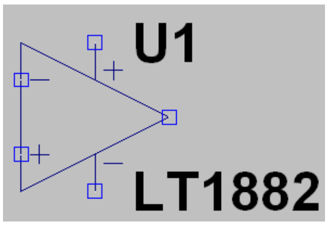


Figure 36 – Op Amp LT1882

- Offset Voltage: 50µV Maximum (LT1881A)
- Input Bias Current: 200pA Maximum (LT1881A)
- Offset Voltage Drift: 0.8µV/°C Maximum
- Rail-to-Rail Output Swing
- Supply Range: 2.7V to 36V
- Operates with Single or Split Supplies
- Open-Loop Voltage Gain: 1 Million Minimum
- 1mA Maximum Supply Current Per Amplifier
- Stable at $A_V = 1$, $C_L = 1000pF$
- Standard Pin outs
- Wide Operating Temperature Range: –55°C to 125°C (LT1882)

The searching process for the BJT used, the Q12N2219 was easier. The LT Spice data bank has the same element used in the real project. The element is the Bipolar Junction Transistor Q12N2219A, Figure 37, made by Phillips and has pretty much the same characteristics (Phillips, 1997).

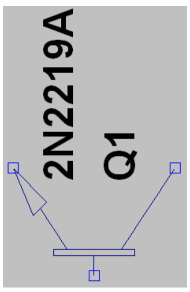


Figure 37 - BJT Q1 2N2219A

It also used common resistances and a 12V DC Supply Voltage Source.

LT Spice has a very intuitive interface as it can be seen on Figure 38.

Figure 38 - LTSpice IV Interface

Common components are on the task bar for easy handling. Complex components can be accessed through clicking on the icon as in Figure 39.

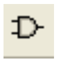


Figure 39 - Complex Component Icon

Through this icon it is possible to access all the complex components available in this version, such as in Figure 40.

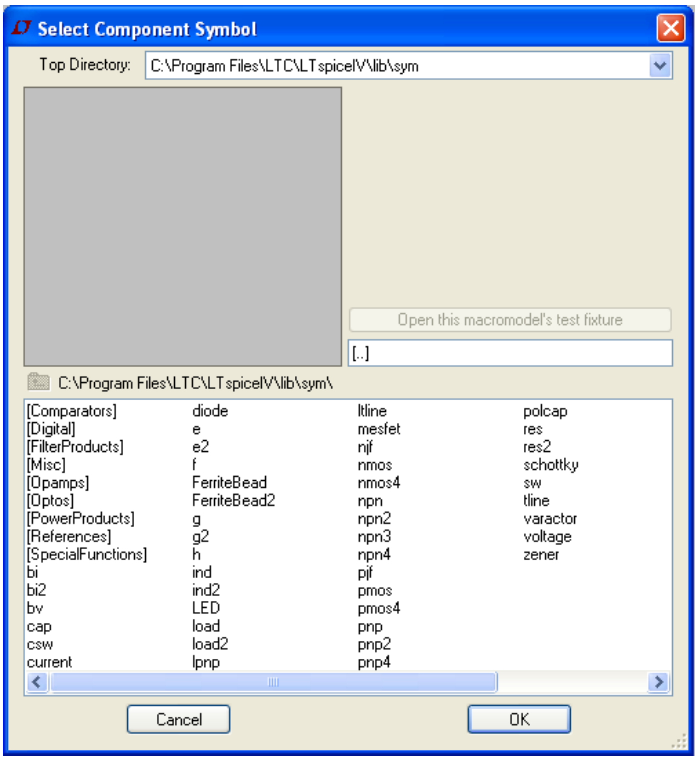


Figure 40 - Complex Components Available on LTspice IV

After modeling the whole electronic module scheme, the main characteristics can be simplified by the following circuit, Figure 41. Some considerations had to be done in order to simulate some hypothesis.

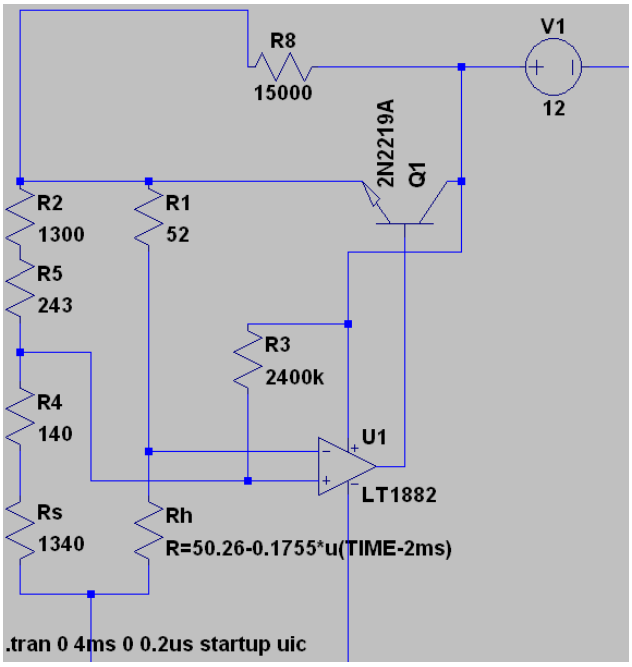


Figure 41 - Original Circuit Simplified

Looking at Figure 41, it is presented Rh and Rs which represent the Thermal Mass Flow Sensor. The Rs represents the SENSOR and the Rh represents the HEATER.

According to IST the simulations should be done considering the environment temperature of 25^{o}C. Knowing that the resistivity coefficient for Platinum is 0.0039 at 25^{o}C, the following formula, Equation 19 - Metal Resistivity, was used to calculate the resistance value of the SENSOR and the HEATER at this temperature. The following formula considers the resistance value dependent upon temperature variation.

$$R = Ro.(1 + \alpha.\Delta T)$$

Equation 19 - Metal Resistivity

The SENSOR resistance value is 1317 ohms at 25^{o}C and the HEATER resistance value is 49.4 ohms also at 25^{o}C.

Considering ΔT equal to 30 Kelvin or Celsius, the system was taken to the operational point of 55^{o}C and its output signal (3.5 Volts) can be seen on Figure 43. This value represents 2m/s flow speed according to Figure 42. The output signal of 3.5 Volts validates the simulation system according to Figure 42.

This output signal was reached for the Rh (HEATER's resistance) value of 55 ohms. It is important to notice from the graphic below, Figure 42, which from 2 m/s on, the system responds with great linearity.

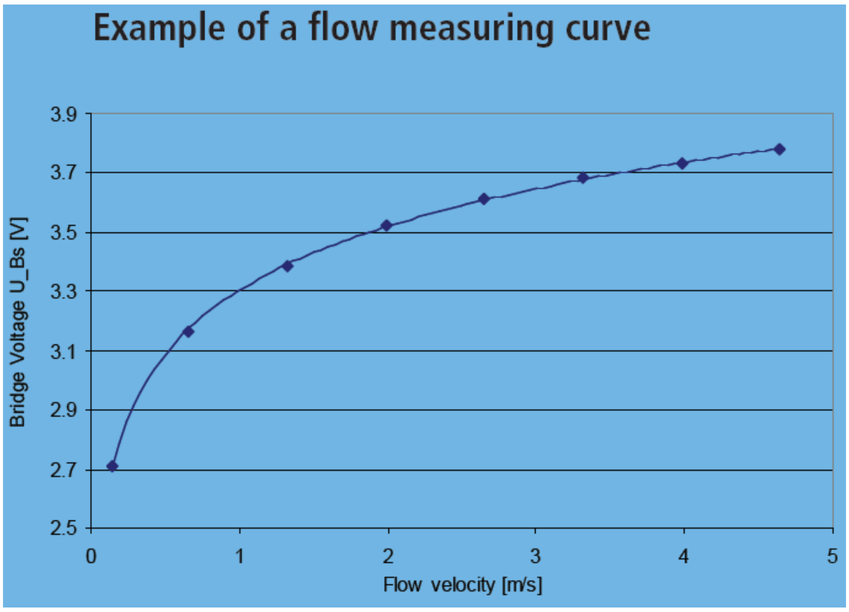


Figure 42 - Example of a flow curve

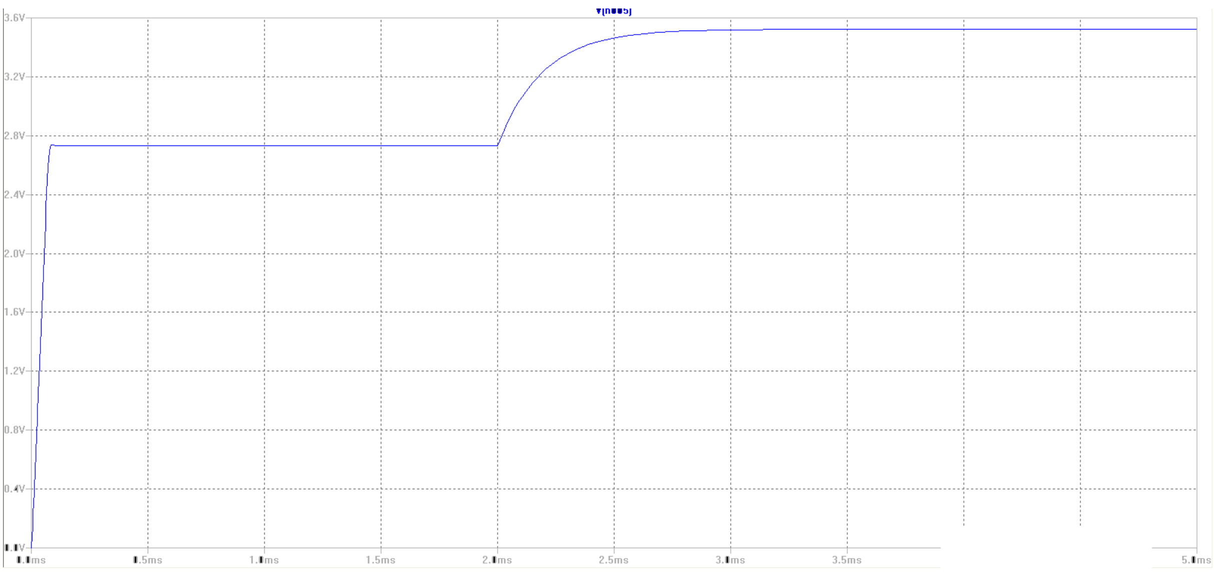


Figure 43 - Graphic Output signal for 2m-s

Rh [ohms]	I(Rh) [mA]	Vout	Ph [mW]
56.1260577	0.75860502	2.677991	32.299512
55.4743014	0.98554816	3.471158	53.882476
55.3030371	1.04411134	3.66445	60.289628
55.2591531	1.10442715	3.872645	67.402867
55.2675255	1.16007869	4.055466	74.378073

Table 4 - Rh x Vout and Ph

Due to practical issues it was not possible to simulate and even to verify the temperature difference of 30 Kelvin. However it was obtained a table, Table 4 - Rh x Vout and Ph

, which validates the electronic circuit modeled according to Figure 42. Some values were simulated and some correlation was noticed between the resistance value and the output signal. For such reason IST suggested to analyze some system whose power dissipation remains constant when the HEATER resistance value changes.

Therefore, some analog PI, PID controllers were suggested due to its integration action, null error in steady state and very good accuracy. They were important to faster deliver the current needed to keep a constant temperature difference.

4.4: Suggested Analog Controllers

All the analog controllers suggested are described and depicted below. They were modeled in the circuit aiming to faster and accurate deliver the current needed to keep a constant temperature differential between the HEATER and the SENSOR.

It is very important to make clear that the analog controllers proposed in this project do not aim to control the electronic system. The electronic module itself is already a feedback system and the configurations proposed here just aim to improve the current system. Due to R&D and financial issues, the suggestions made in this project could not be tested yet. IST is focused on releasing new products such as Ammonia and CO sensors. Thereby no practical result will be shown here.

According to control theory, just I, PI and PID controllers' configurations are able to serve the systems' requirements. For such reason, the simulating processes reported here are just the ones that might help this project.

The IST Flow Electronic Module is a real product and there is power dissipation on the SENSOR.

The null error requirement can be assured by measuring 0V on the Wheatstone bridge. However, as the flow speed increases, the error is no longer zero because the Wheatstone bridge will be misbalanced since more heat will be taken out of the resistor and it will decrease its temperature.

The following configurations, Figure 44 - Analog I Configuration and Figure 45 - Analog PI Configuration, were drawn according to Figure 8 - Analog Integrator Controller and Figure 9 – Analog PI Configuration.

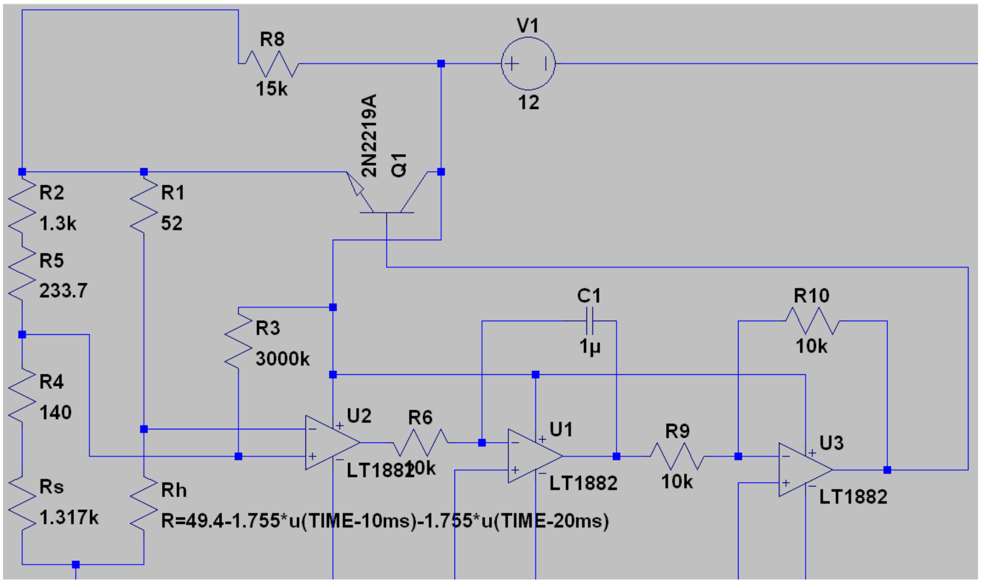


Figure 44 - Analog I Configuration

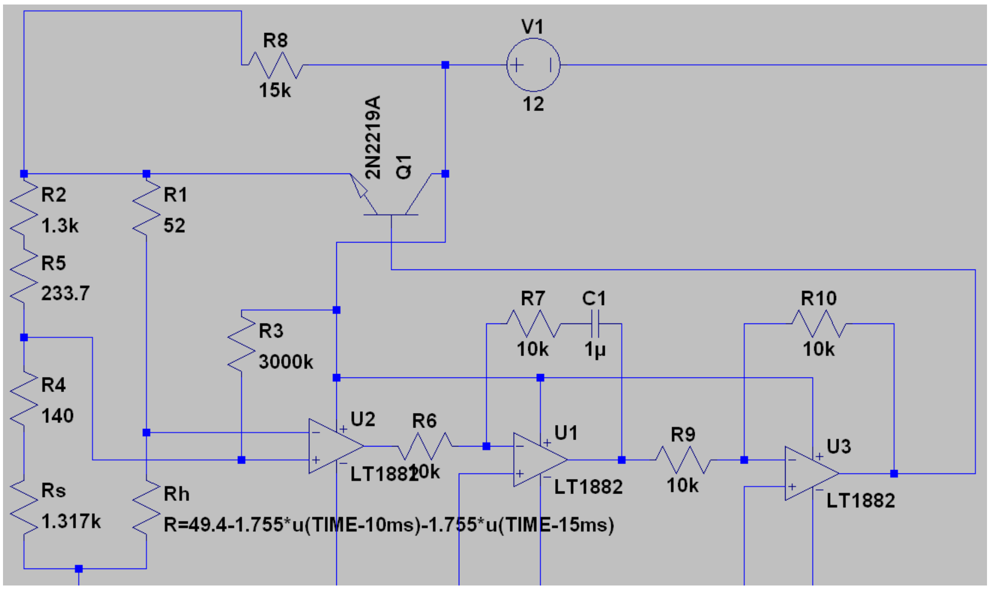


Figure 45 - Analog PI Configuration

The results can be seen on Simulating Results.

Chapter 5: Results

5.1: Theoretical Analysis

The root locus method and the step responses relative to disturbance and to reference are very good graphics to analyze this system and figure out if the controlled system will reject disturbances and follow the reference.

5.1.1.1: Root Locus for Flow Speed equal to 1 m/s

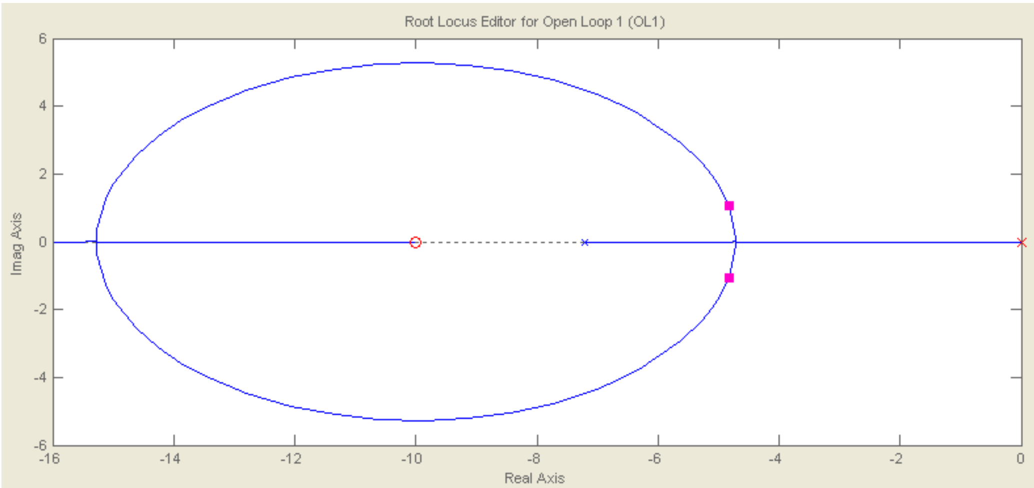


Figure 46 - Root Locus for V = 1 m/s

5.1.1.2: Root Locus for Flow Speed equal to 2 m/s

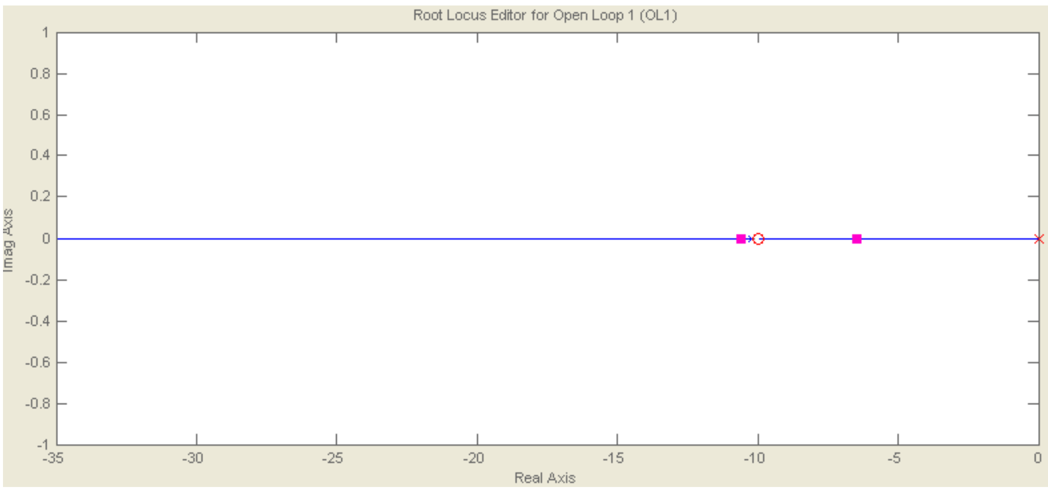


Figure 47 - Root Locus for V = 2 m/s

5.1.1.3: Root Locus for Flow Speed equal to 5 m/s

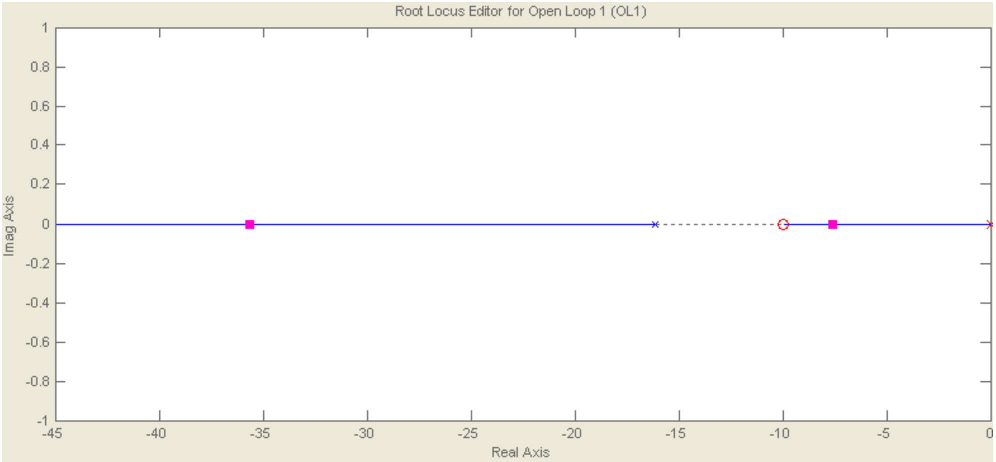


Figure 48 - Root Locus for V = 5 m/s

5.1.1.4: Root Locus for Flow Speed equal to 20 m/s

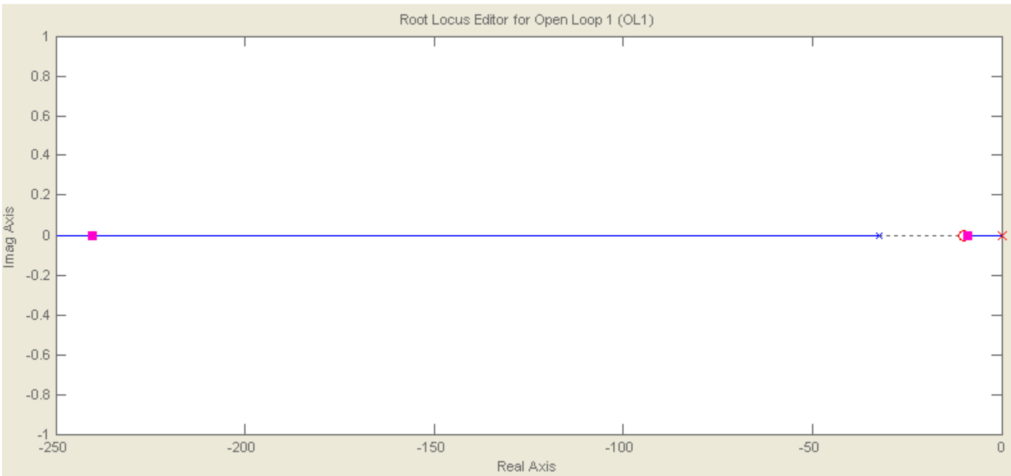


Figure 49 - Root Locus for V = 20 m/s

5.1.1.5: Root Locus for Flow Speed equal to 50 m/s

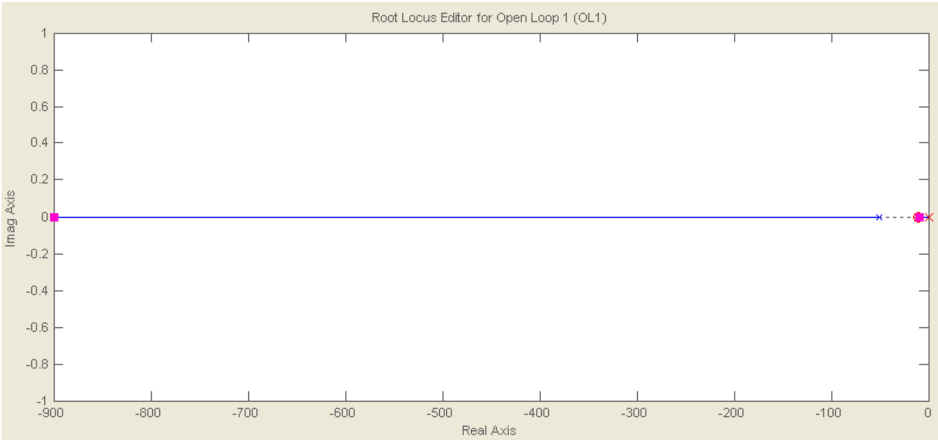


Figure 50 - Root Locus for V = 50 m/s

Obviously, the entire root locus is on the left side of the semi-plane S which means the closed loop system is stable. It is also possible to conclude that as the flow speed increases, the time constant τ decreases because they are inversely proportional as can be seen on the following equation,

$$\tau = \frac{m_s . c . v^n}{C . l^{n-1} . \lambda . A_s} \cdot \frac{1}{V^n}$$

It is important to notice that the controller configuration was kept the same for all flow speed values.

R_4	R_3	R_2	R_1	C
10kΩ	10kΩ	100kΩ	10kΩ	1µF

Table 5 - Controller Parameters

The formula is

$$C(s) = \frac{R_4}{R_3}\frac{R_2}{R_1}\left(\frac{R_2Cs + 1}{R_2Cs}\right)$$

The controller configuration is as follows

$$C(s) = 1000\left(\frac{0.01s + 1}{s}\right)$$

Equation 20 - PI Controller adjusted

The values were chosen based upon real resistance values and considering that this adjustment is supposed to be done using the potentiometer R2.

5.1.1.6: Step response to disturbance and reference for flow speed of 1 m/s

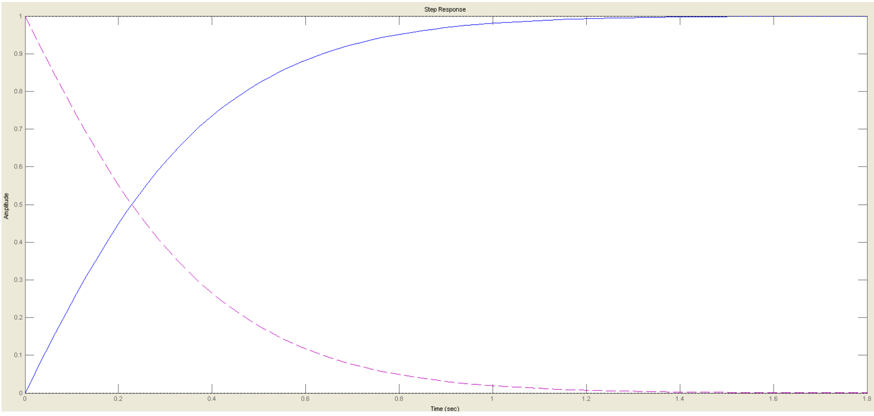


Figure 51 - Step Responses to V = 1 m/s

5.1.1.7: Step response to disturbance and reference for flow speed of 2 m/s

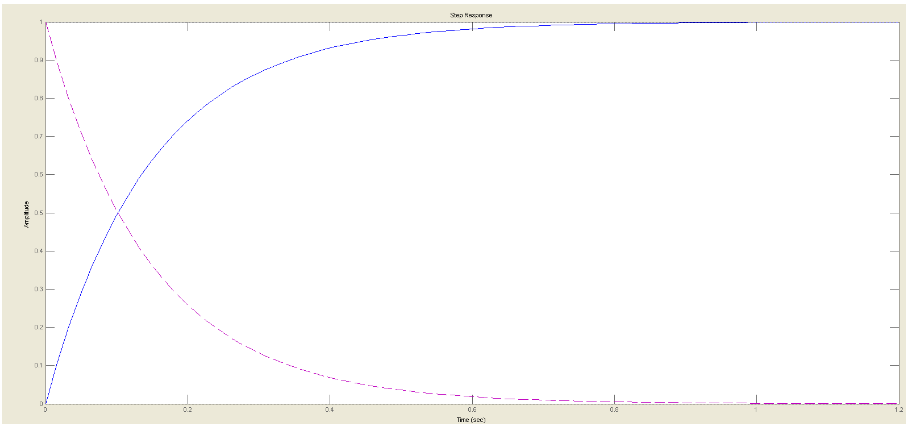


Figure 52 - Step Responses to V = 2 m/s

5.1.1.8: Step response to disturbance and reference for flow speed of 5 m/s

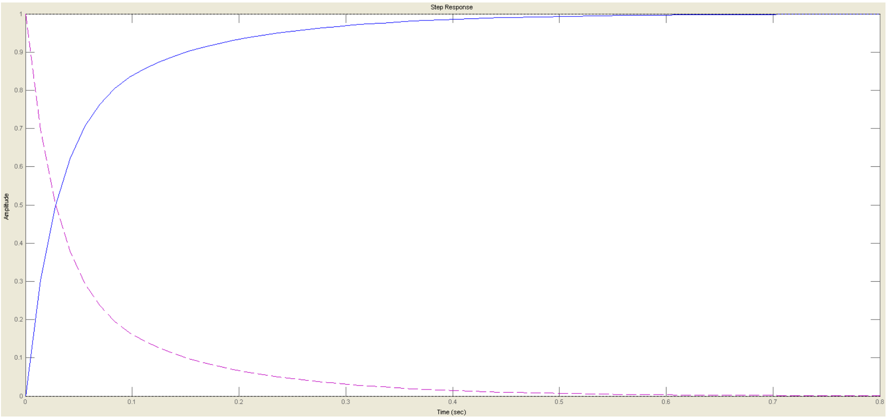


Figure 53 - Step Responses to V = 5 m/s

5.1.1.9: Step responses to disturbance and reference for flow speed of 20 m/s

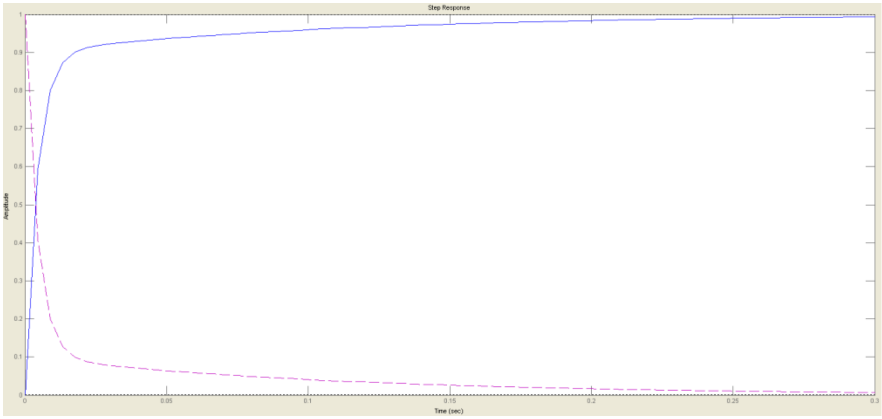


Figure 54 - Step Responses to V = 20 m/s

5.1.1.10: Step responses to disturbance and reference for flow speed of 50 m/s

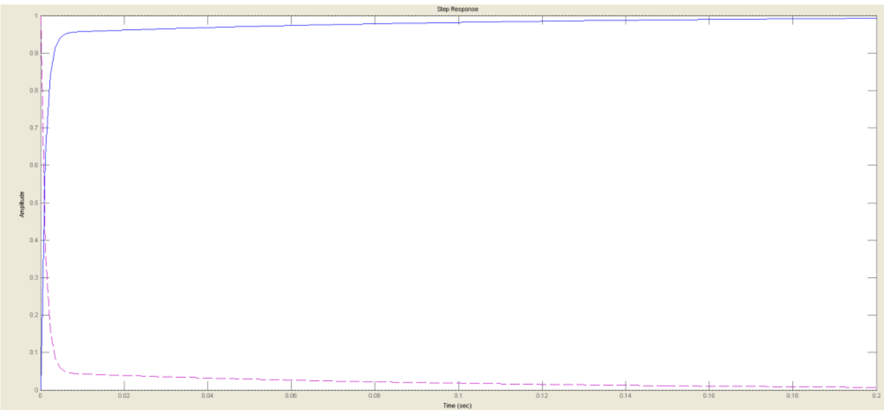


Figure 55 - Step Responses to V = 50 m/s

The step response graphic is another evidence that as flow speed increases, τ decreases. The graphics evidence faster responses both for reference signals and for disturbance signals.

It is very important to remark that the intent with these graphics is to prove the system stability, the reference following and the disturbance rejection characteristics.

Therefore, the controller proposed serves these requirements.

Physically thinking, as flow speed increases, heat is faster exchanged with the fluid and more power is needed to keep a constant temperature differential requiring a faster response.

5.2: Simulating Results

The theoretical results of this project were very well received by IST and they will be taken in consideration for future projects.

All the graphics generated from the circuits in Suggested Analog Controllers on Chapter 4 are displaced in this subsection aiming to find out which configuration would best solve IST’s problem.

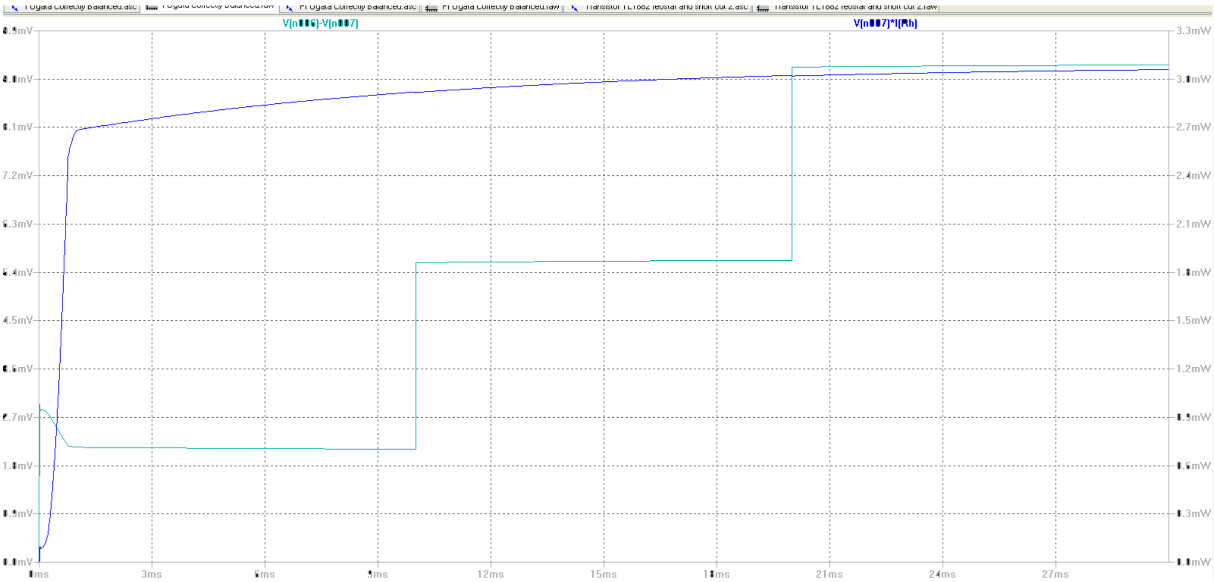


Figure 56 - Error and Power Dissipation on HEATER - I Configuration

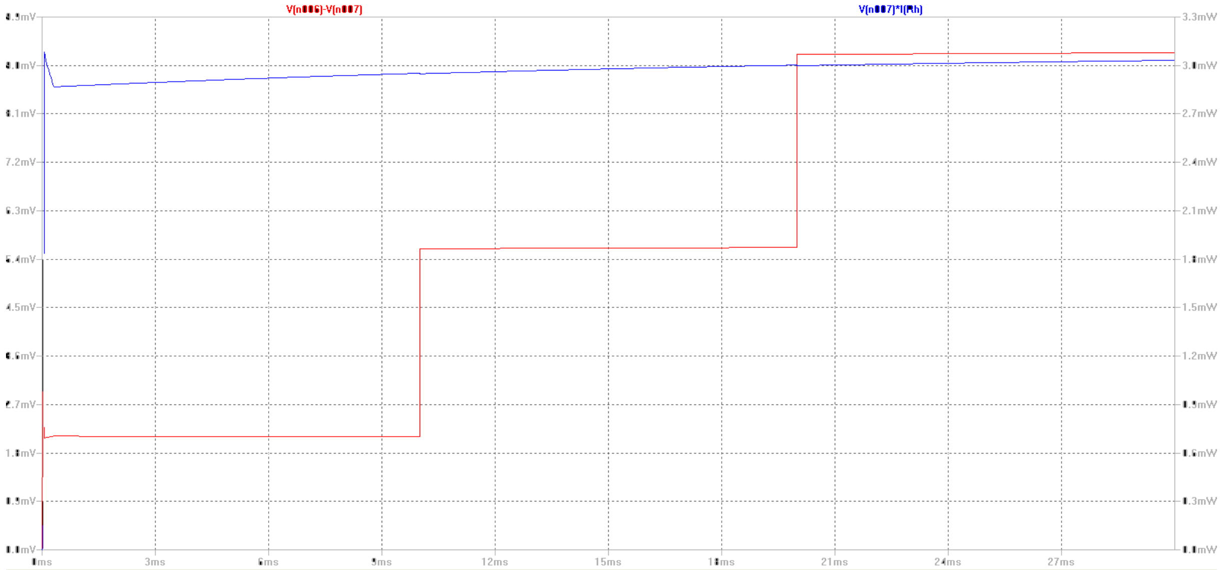


Figure 57 - Error and Power Dissipation on HEATER - PI Configuration

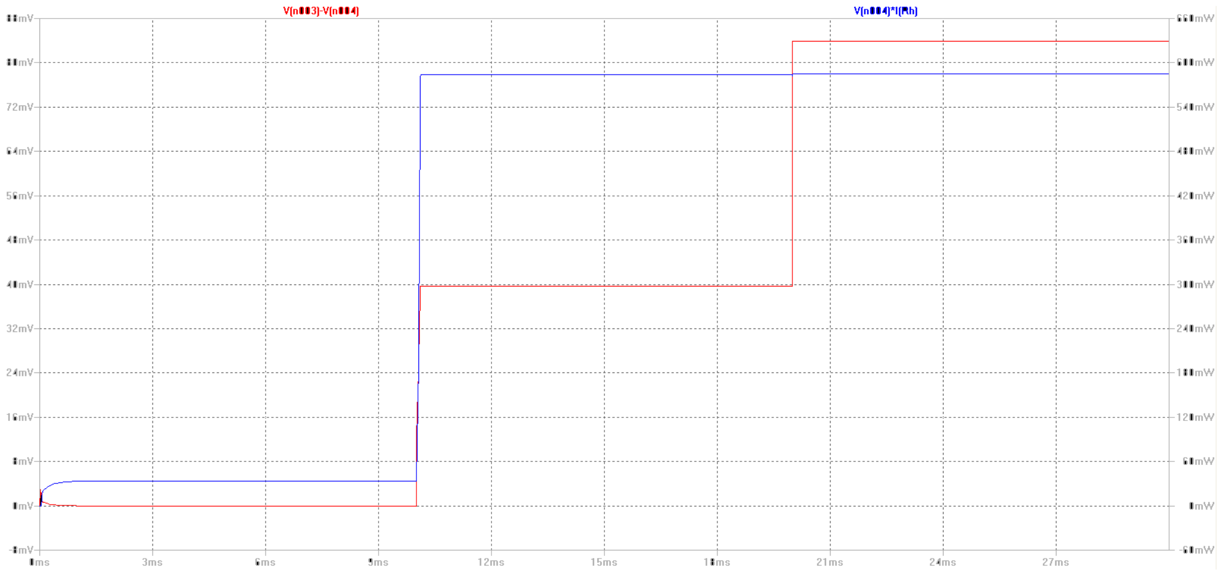


Figure 58 - Error and Power Dissipation on HEATER - Original Configuration

At first, it is extremely important to remark that all the simulating parameters such as sample time as well as simulating time were kept the same for all circuits configurations. The same step amplitudes were aplied to all circuits.

Looking at the graphics above, Figure 56, Figure 57 and Figure 58, it is clear that the error changes as the resistance value on the HEATER changes.

It is possible to see that the error on the Wheatstone bridge is zero for the original configuration, Figure 58.

It is noticeable that both the PI config and the I configurations has pretty much the same behavior. They even dissipate the same power on the HEATER, around

3mW. They also have pretty much the same values for the error on the Wheatstone bridge. The only difference is that the PI configuration, due to the proportional action, better respond and better reaches the operating point.

The power dissipation remains constant in all configurations, since the current feeded increases as the resistance value on the HEATER decreases.

The main difference between the circuits suggested and the original circuit is relative to the power dissipation on the HEATER and to the error on the Wheatstone bridge. The power dissipation on the HEATER on the original circuit is 200 times bigger than in the suggested circuits. This fact can be explained somewhat by the the additional circuit added which contains higher resistance values that consume much more power. It might be very good if this system is able to assure the constant temperature differential because lower power consumption saves energy and contributes to a better system operation. Besides higher power dissipation may damage the electronic circuit.

The original circuit does not consume too much power when operating with the wheatstone bridge balanced. So it is excelent for applications with smaller flow range and for applications with operating temperature close to the temperature the system is calibrated for.

It might happen that suggested systems needs other components in order to deliver the power needed to keep the constant temperature differential.

Undoubtedly, the I and PI configurations are reference followers and reject disturbances. However it is extremely necessary to test and validate the simulations proposed in this project. The simulating results are not enough to validate any theory.

In general, the PI configuration keeps the power dissipation constant It faster reaches the operational point with very short overshoot.

In summary, simulating results shows that the original system is a very good solution and experimentations are necessary in order to compare each configuration and its performances.

Chapter 6: Conclusion and Future Projects Perspectives

The thermal mass flow sensors have undoubtedly broad applicability in the industry. It is applicable in many different industry areas, ranging from medical, HVAC to military and oil and gas industries. Depending on the industry, it may has more or less importance concerning safety and process accuracy. Even though it is expensive, it is a very fast and accurate system when correctly calibrated and its benefits far compensate its price.

Based on Fluid Mechanics and Mathematical modeling it was possible to prove ideally speaking the constant temperature differential requirement. Regardless of the ideal scenario considered, it is easy to adjust the parameters through calibration which would give a real approach to the mathematical model achieved.

Looking at the electronic process, it is possible to conclude at first that the original system operates very well and has very good simulating results. It is necessary to experiment the suggestions presented here and verify its electronic feasibility. It might happen that the PI configuration very emphasized in this project needs a better electronic understanding than the knowledge presented in this document. Therefore, experimentations and the comparison of its results are very good themes for future projects and they will certainly be in a near future.

Another very good suggestion for future projects is the development of a digital system for data acquisition. This system could be controlled by a PIC microcontroller by Microchip Technology, and it could make temperature measurement and power delivery on the HEATER at pretty much the same time. It would certainly be more expensive for IST, however more accurate. Such device is simple, yet requires qualified personnel. Outsource this technology, since it is not the IST's core competence is an excellent alternative.

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