# Implementation of an Automated System to Measure the Breathability of Different Fabrics

Salustiano Valverde-Forcadell, Herminio Martínez-García
Eastern Barcelona School of Engineering (Escuela de Ingeniería de Barcelona Este – EEBE)
Departamento de Ingeniería Electrónica
Technical University of Catalonia (Universidad Politécnica de Cataluña – UPC), BarcelonaTech
Avda. Eduard Maristany, nº 10 – 14.
E-08019 - Barcelona. Spain
salus.vf@gmail.com; herminio.martinez@upc.edu

*Abstract*—**In this paper the design of an automated measuring system to study and characterize different fabrics in terms of breathability is presented. This system came as a solution to the actual problem in the fabric industry regarding the measurement of breathability. Currently the systems used are not automated, expensive and slow, and the few automated systems used do not often recreate the real sweating conditions. That leads to breathability results that do not match the real performance of the fabrics. This paper presents a system that simulates better the human perspiration. A low-cost system based in Arduino was built and Matlab models were extracted and used to finely tune the PIDs that control the parameters. The software was designed to provide an user friendly operation and to calculate the breathability expressed in commonly used units. This system was proved to be an 80% faster than the current systems in the market, providing a good instrument to perform further studies of different kind of fabrics.**

**Keywords: Breathability, Temperature, Relative humidity, Absolute humidity, Automatic control, PID.**

## I. INTRODUCTION

Products from fabric industry have evolved until limits that require providing some valuable information to allow clients to objectively choose. This is particularly important in sweat management or breathability in sports fabrics. In this regard, a lot of technologies to measure breathability have arisen during the last years, neither of them resulting in objective data to compare products. Breathability is the ability of a fabric to get rid of the sweat on the surface of the skin, by letting it pass trough it and being released to the environment as it is showed in Fig. 1. There is also a gradient in temperature and humidity, which also intervene in this procedure. The wind is also a factor but in this study the assumption of no wind was approached in order to analyze breathability under the worst conditions.

To overcome the breathability problem in sports fabrics, two main strategies are currently used: capillarity and permeability. In capillarity, drops of sweat in the garment are absorbed and driven to th external part, where the moisture spreads and is evaporated by body temperature and dried by the air. In the permeability strategy, the air in the outside

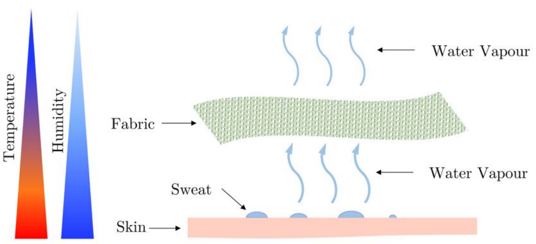


Fig. 1. Schematic explanation of breathability.

and the convection push the vapor outside, thus drying the garment.

Human beings are endotherms. This means that we create our own heat in order to achieve our body core temperature set point of $37^oC$. Brain, liver, heart and the skeletal muscles are the main organs and muscles involved in maintaining our body temperature. Nonetheless, when either emotional[4] or physical stimuli appear, our core temperature usually rises. Despite this, the main fight of the Thermo-regulatory System is against the Ambient Temperature ($T_a$) in order to maintain the Core Temperature ($T_{core}$). Regarding the objectives of this paper, only the mechanisms to decrease the temperature will be mentioned. The human body has 4 mechanisms to reduce the internal temperature; conduction, convection, radiation and evaporation. Our skin acts as an interface. The problem appears when the $T_a$ is higher than the skin temperature. Then, the first three methods get out of the game. In fact, in this case, our bodies gain temperature from the environment by radiation and conduction. Evaporation is the only survivor and we have to trust on it to keep our temperature stable.

Based on the previous work of J.Werner[6], K.Kanosue[1] showed that the $T_{core}$ acts as a manipulated variable and as a negative feedback, while the Skin Temperature ($T_s$) acts as a feedforward disturbance variable (see Fig. 2)[3]. When the temperature is sensed by the skin, the sweating system acts with a delay. That is easy to understand if the composition of our body is analyzed. Water is a precious resource for our body and it is wasted during the sweating process. While this

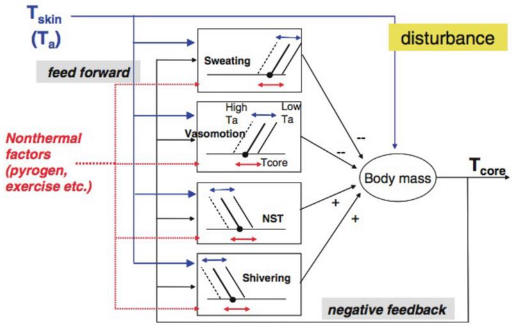


Fig. 2. Thermoregulatory System. Abbreviations: NST, Non-Shivering- Thermogenesis[6].

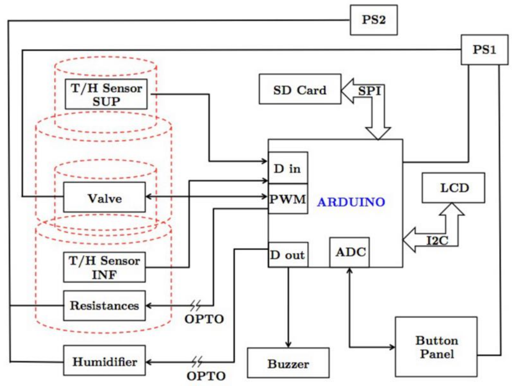


Fig. 3. Hardware block diagram. Abbreviations: Power Source (PS), Serial Peripheral Interface (SPI), Secure Digital (SD), Pulse Width Modulation (PWM), Liquid Crystal Display (LCD), Inter-Integrated Circuit (I2C), Temperature and Humidity (T/H), Analog to Digital Converter (ADC).

strategy of delay may be less effective for maintaining the optimal value of the regulated variable $T_{core}$, it is likely to be more beneficial for overall survival[1].

Given the complexity of our body to maintain temperature, designing a reliable test method that mimics the real case becomes a problem for industries. Currently, there are two different main conceptions of the tests: some measure the Water Vapor Transmission Rate (WVTR) and others measure the Water Vapor Diffusion Resistance (WVDR). Nonetheless, both of them have weaknesses in different aspects. Normally, sampled textiles are given in tiny pieces[3] of cloth that barely simulate the real case. In garments, there are wrapped parts and wrinkles that affect severely the final performance. There are several methods regulated by the Standard Test Methods for Water Vapor Transmission of Materials (ASTM 1999), ISO 11092 and the (ASTM F 1868). The advantages and disadvantages of the most common methods used by industry are summarized in Table I [2].

TABLE I
SUMMARY OF THE MENTIONED METHODS

| **Upright cup** | **Sweating Guarded Hot Plate** |
|---|---|
| + Simple<br>- Slow<br>- Wind tunnel needed<br>- Operator reliance<br>- Manual | + Operator reliance<br>+ Real<br>+ Automated<br>- Slow (>1 h 30')<br>- Sample wetting avoided |
| $g/m^2/24h$ | $m^2\Delta Pa/W$ |

## II. Description of the System

In order to create an easy system, able to simulate the behavior of a sweating body, and at the same time, able to fit a fabric sample and measure what is happening, the system was assembled like follows.

The main part are the two chambers made of PVC, one controlled in terms of temperature and humidity, i.e. with sensors and actuators for both variables, and the other only with sensors. The controlled chamber, where the conditions are created, is the lower one and the reading chamber is the upper one. The sample fabric of interest is fit between the two chambers.

An Arduino MEGA 2560 was used as a controller of the whole system, actuating over the temperature actuator, made of 4x18 Ωx10 W resistors in parallel, through an own designed board that introduced a galvanic isolation between the controller and the actuator using optocouplers (4N35), called interface board. The resistances are driven by a MOSFET (IRF520N) at 12 V providing a maximum power of 32 W. MOSFET has very low on-resistance, a good property for the desired circuit, in which a considerable amount of current through the electronic switch was expected and the least power dissipation in the electronics circuit was desired. It is controlled using a 8-Bit PWM output of the Arduino, which provides a 0 to 5 V square signal, with 490 Hz and a duty cycle that varies from 0 to 100 %

Regarding the humidifier, as it is implemented using a bottle cap ultrasonic humidifier with a slow behavior and a low drain of current, the control through the interface board was made using a BJT transistor (BC548B). It is controlled using an own code implemented PWM routine that provides a rectangular 5 V signal with 3 s period.

TABLE II
TECHNICAL SPECIFICATIONS OF THE DHT22 SENSORS.

| Spec | Humidity [%] | Temperature [$^oC$] |
|---|---|---|
| Operating Range | 0 to 100 | -40 to 80 |
| Resolution | 0.1 | 0.1 |
| Relative Error | ±2 | ±0.5 |

The sensors implemented in both chambers are the well-known among the "makers" DHT22. In this case provided by DFRobot, which include the decoupling capacitors, the pull-up resistors and a connector to make the things easier. These sensors provide temperature and RH readings every second with the specifications showed in Table II. They communicate with the Arduino using a dedicated protocol called MaxDetect-1Wire Bus.

Another feature added to the system was an SD card reader. This is a module called Itead SD Shield V3.0, connected to the Arduino using an SPI communication protocol. This device allowed to store every test that the machine performed, creating a Data-log. Regarding the Human Machine

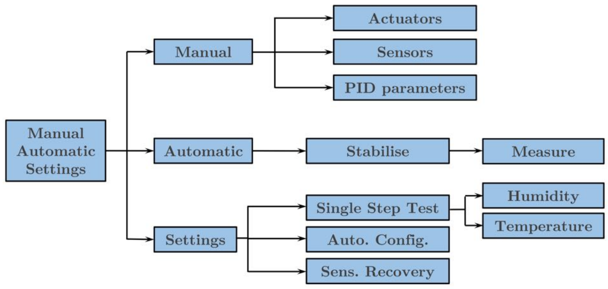


Fig. 4. Software structure of the system.

Interface (HMI), a 20x4 LCD screen, a button panel and a buzzer were used. The LCD screen is controlled using an I2C driver. The button panel is made of resistors and buttons in a way that they provide a different analog value that is read by the Arduino ADC. It consists of four arrows representing the 4 directions, an OK button and a BACK button. Nonetheless, the latter mentioned is independent to the rest to act as a trigger of the external interruption. In addition, a buzzer was also included to provide sound notifications to the operator. A wide picture of how the software looks like to the operators is shown in Fig. 4.

The software is designed in a way that provides 2 operating modes and the settings adjustments. The manual mode provides a way to read and actuate with any sensor or actuator of the system.It also allows to read the configured values for both PID, in order to check the proper functioning of every part of the system.

The automatic mode is basically the main operating mode, since it is the mode that provides the breathability value. It implements a routine that creates and controls the temperature and humidity conditions at the bottom chamber, guides the operator to perform the test properly, reads and calculates the final breathability value providing the result and it is foolproof designed to warn of every abnormality during the process. To measure the final breathability value in $g/m^2/24h$, an approximation to the $H_{ABS}$ from the RH was used, as described previously[5].

The setting mode allows to configure the measuring parameters of the automatic mode. It also includes the Sensor Recovery routine, which basically dries out the sensors to elongate their lifespan according to the manufacturer. Finally, the Single Step Test routine in both, temperature and humidity, performs a sudden change in the set point of one of the variables in open loop just after having regulated the other one to the normal working values. This routine provided the data to know the behavior of the system in both, temperature and humidity, allowing then to finely tune the PID.

- *How are the variables kept under control?*

In order to lead the variables to the desired values as fast as possible and keep them stable afterwards, 2 independent PIDs were created using the software. In order to test the things in a faster way, a model of the system and then some simulations were performed using MATLAB R2014b, see Fig. 3. The behavior of both systems were modeled using 1, a first order differential equation adding also a time delay. The temperature system behaved similarly to a second order system, however, the first order approximation was good enough for the purpose of the study.

$$G(s) = \frac{K}{1 + T_{P1}s} e^{-T_D s} \tag{1}$$

For the compensator, a non-interacting PID was designed and tunned. In order to tune the compensator, the root-locus diagram was used. Over it, the poles and zeros of the plant were plotted as well as the specifications in terms of maximum overshoot and stabilization time. It is precisely the intersection of this two lines what it was looked for. The compensator in 2 was used to bend the root-locus path of the system and make it pass over this intersection point. Then, the values of the proportional, integral and derivative gains were calculated to place the compensator just over this point as shown in Fig. 5.

$$G_C(s) = K_P \left(1 + \frac{K_i}{s} + K_D s\right) \tag{2}$$

In the graph represented in Fig. 5 the diagonal lines represented a 4% overshoot, while the vertical line delimited the desired 600 s to reach the stability.

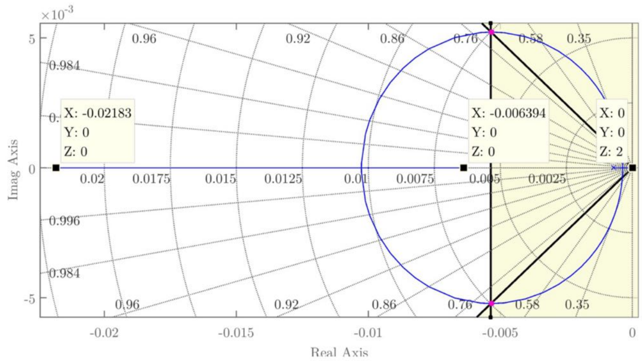


Fig. 5. Root-Locus PID design with the specifications plotted on it.

Although this routine allowed to find a tunned PID, it did not guaranteed in any case the stability of the system. To know whether the systems were convergent or not, the Nyquist's Stability Criterion was used. Equation 3 states this simple criterion, where the Z is the number of zeros of $1 + G_C(s)G(s)$ on the right side of the S-plane, the N is the number of clockwise circumscriptions around the point $-1 + j0$ and P is the number of poles of $G_C(s)G(s)$ on the right side of the S- plain.

$$Z = N + P \tag{3}$$

In case 3 is accomplished, the stability of the design can be assured. This procedure was followed to design both controllers, the one for the temperature and the one for the humidity.

## III. SIMULATION RESULTS

### A. The assembled system

The first thing to show is the physical system assembled according to the theoretic design, see Figures 6 and 7.

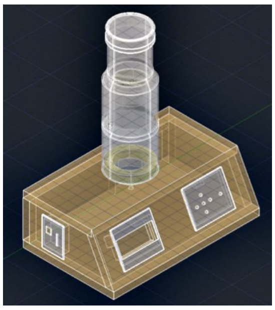

Fig. 6. Theoretic 3D design in AutoCAD.

Fig. 7. Real assembled system.

As it can be seen, the reality was pretty close to the desired aspect of the prototype.

### B. The Temperature Model and its PID

The Table. III shows the values used to create the model and extracted from it to design the compensator.

The Fig. 8 shows how good it was the theoretical approximation to the temperature system without any need to perform fine tunning of the PID.

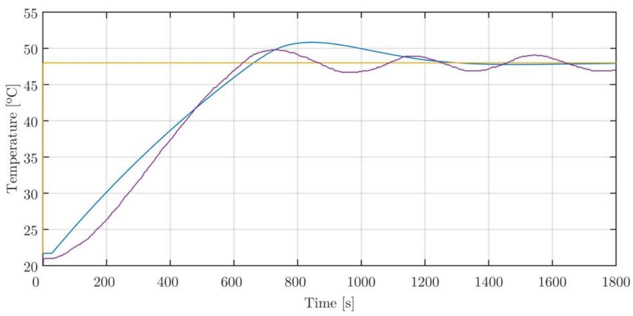


Fig. 8. Temperature stabilization in closed-loop. Yellow: Setpoint. Blue: Model + Compensator simulation. Violet: Real Plant.

TABLE III

PARAMETERS OF THE TEMPERATURE MODEL

| Parameter | Value |
|---|---|
| System Gain (K) | 5.6768 |
| System Time Constant ($T_{P1}$) | 1413.7 s |
| Time Delay ($T_D$) | 30 s |
| Proportional Gain ($K_P$) | 36.1051 |
| Integral Gain ($K_i$) | 0.0049 |
| Derivative Gain ($K_D$) | 35.4272 |

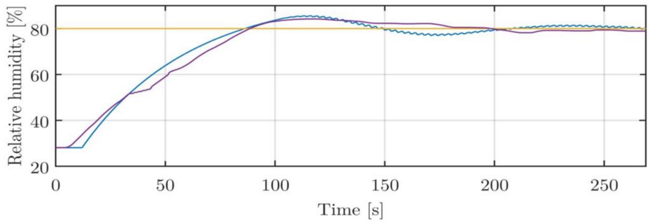


Fig. 9. Humidity stabilization in closed-loop. Yellow: Setpoint. Blue: Model + Compensator simulation. Violet: Real Plant.

### C. The Humidity Model and its PID

The Table. IV shows the values extracted an used to simulate the humidity system.

The Fig. 9 shows how accurate the model was compared to the real system.

TABLE IV

PARAMETERS OF THE HUMIDITY MODEL

| Parameter | Value |
|---|---|
| System Gain (K) | 13.4987 |
| System Time Constant ($T_{P1}$) | 49.8689 s |
| Time Delay ($T_D$) | 12.035 s |
| Proportional Gain ($K_P$) | 152.0971 |
| Integral Gain ($K_i$) | 0.0327 |
| Derivative Gain ($K_D$) | 2.4402 |

## IV. CONCLUSIONS

The development of this project has proved the possibility to develop a low-cost electronic system able to measure the breathability of different sports fabrics in an automated manner. This electronic system, not only allowed to measure the breathability, but also proved to be an $80\%$ faster than the current existing methods.

This system is the first step to perform further studies over different fabrics, over different PID tunning strategies, over different ways to extract the breathability, and it also could be modified to measure other parameters, e.g. thermal isolation of the fabrics, dynamic moisture management, etc.

## REFERENCES


[1] Kazuyuki Kanosue, Larry I. Crawshaw, Kei Nagashima, and Tamae Yoda. Concepts to utilize in describing thermoregulation and neurophysiological evidence for how the system works. *European Journal of Applied Physiology*, 109(1):5–11, 2010.

[2] Elizabeth A McCullough, Myoungsook Kwon, and Huensup Shim. A comparison of standard methods for measuring water vapour permeability of fabrics. *Measurement Science and Technology*, 14(8):1402–1408, 2003.

[3] P.W.Gibson. Factors Influencing Steady-State Heat and Water Vapor Transfer Measurements for Clothing Materials. pages 749–764, 1993.

[4] Marieke van Dooren, J. J G Gert Jan de Vries, and Joris H. Janssen. Emotional sweating across the body: Comparing 16 different skin conductance measurement locations. *Physiology and Behavior*, 106(2):298–304, 2012.

[5] W. Wagner. The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use. *Journal of Physical and Chemical Reference Data*, 31(2):387, 1999.

[6] J. Werner. The concept of regulation for human body temperature. *Journal of Thermal Biology*, 5(2):75–82, 1980.