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THERMAL BEHAVIOR OF POLYMERS DURING INTERMITENT HEATING MEASURED BY THERMOCOUPLE AND ARDUINO® MICROCONTROLLER

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Abstract. *The combination of relatively low production costs and a versatility make polymers one of the most used classes of engineering materials. The complexity of their chemical bounds, however, make the thermomechanical processing of these materials a challenge, since thermal flux from manufacturing might significantly alter their properties. In this paper it was evaluated the use of thermocouple with Arduino® compatible hardware for measurement and control of an intermittent heating system for processing of Nylon-6 and polycarbonate thermoplastics. A 2² factorial design was created for using K-type thermocouple for the two polymers at two different surface finishes obtained by sanding with mesh #80 and #600 abrasives. The results indicate that the Arduino interface has satisfactory processing capacity for monitoring heating cycles and temperature logging, making it possible to know how temperature varied and at what level it stabilized for the heating conditions presented. Roughness did not present a significant effect on the material heating. The difference in material specific heat capacity and thermal conductivity affected the observed temperature profile, but not the temperature in which polymers stabilized. The observed behavior indicated that the material thermal conductivity was more important than the specific heat capacity in the conditions tested.*

Keywords: *thermoplastics, thermocouple, Arduino® microcontroller, intermittent heating, MAX31855 module*

1. INTRODUCTION

Polymers have been gaining increasing attention since the XXth century due to their versatility and cheap manufacturing. They are constituted of molecules with high molecular weight, usually containing carbon, oxygen and/or nitrogen in their molecular chains. Although they comprise a huge set of materials, they may be classified as elastomers, thermoplastics and thermosets, according to how their macromolecules behave as temperature changes (Osswald et. al., 2006). Thermoplastics have uncross-linked molecules in such way they flow viscously when heated but solidify as they cool. They present fair resistance at room temperature as solids and do not require much energy when processed by molding, finding several applications in packaging, transportation, and even in construction, since several thermoplastics possess tensile, impact and even heat resistance up to certain ranges.

Although in most applications polymers work well below their melting temperature, they are usually heated in manufacturing process to ease moldability and incorporation of fillers and pigments. It is important for engineers to know the temperature range that the polymer undergoes in these cases because it will affect process efficiency and final material characteristics. The first is because heating the material consumes energy but usually lowers the forces involved and accelerates reactions and mixing with additives. The second relates to different mechanical and physical properties in thermoplastics depending on how fast they cooled.

The temperature measurement and monitoring in these scenarios are accomplished by several ways whereas thermocouples are some of the most applicable choices. They are cheap, simple, robust, and cope with a wide range of temperatures (Ross-Pinnock and Maropoulos, 2016). However, they cannot operate on their own and need a system that not only converts their electric voltage signals to digital data but also calculates the corresponding temperature according to the voltage values and shows the information to the user. In line with the characteristics of simplicity, low cost and robustness, Arduino® compatible hardware and software were used in this work to acquire temperature data for a manufacturing process where a polymer surface experiments constant heating by hot air while being struck by an intermittent flow of compressed air at room temperature.

The dynamics of these interactions cause the material surface to be constantly heated and cooled in short cycles around temperatures high enough to changes bulk material properties. Although these cycles might cause instant temperature variations in polymer most outer surface, an inner surface does not experiment so great oscillations due to thermal damping by the material heat conductivity and specific heat capacity. Overall, if both hot and cold flow are maintained as explained, the material heats up in a rate dependent on the thermal flow conditions up to a certain baseline temperature where it tends to stabilize around. In this work, the influence of material surface and polymer type were investigated regarding this rate of temperature rise and the baseline temperature attained when all other conditions were fixed. The results show that the acquisition system composed by thermocouple and Arduino® are adequate for monitoring the temperature specially in applications where small temperature variations are tolerable. Also, analysis of variance for the results indicated if there were any correlations between the material characteristics and surface roughness against the baseline temperature and polymer heating rate.

2. THERMOCOUPLE AND ARDUINO® COMPATIBLE HARDWARE AND SOFTWARE

Thermocouples are the most common sensors for temperature measurements. Its working principle is based on the Seebeck effect. When two distinct homogenous materials are connected in a closed circuit and the two junctions experience different temperatures, electrons will diffuse across the circuit generating an electric potential difference. With a proper device to measure this small voltage, the signal can be correlated with the temperature difference between the two junctions (Oliveira et. al., 2020). The cold junction is kept away from heat sources, usually at room temperature, because it is the point of connection with the electronic devices that measure the small voltage and convert it to digital data. It is important to determine its temperature for compensating the voltage signal read by thermocouple. This is usually done through a thermistor or resistance temperature detector (RTD) built in the acquisition system as close to the cold junction as possible.

Regarding the acquisition system, Arduino® is an open-source electronic prototyping platform that allows users to create interactive electronic objects using a low cost programmable logic microcontroller. Although they are not trustworthy and precise enough for monitoring and controlling sensitive industrial processes, they may be used for data logging over short time periods or in process that do not require an extremely precise monitoring of data (Vasconcelos Neto et. al., 2018). The compatible boards were chosen mostly due to its price and the constant risk of damaging other more sensitive equipment by dust and humidity around the manufacturing site.

Type K thermocouple was used, whose wires are made of Nickel-Chromium and Nickel-Aluminum alloys. They can be used from -200 °C up to 1250 °C as long as the wire coatings do not degrade (Omega Engineering, 2015). An Arduino® compatible module with chip MAX31855 was employed, which has an in built thermistor to automatically compensate for the cold junction temperature. The 14-bit module reads and converts analogic signal to digital data and sends it to the ATMEGA 2560 microcontroller through SPI communication, where temperature is calculated with 0.25 °C resolution. Their combination yields a sensitivity of about 41 μV/°C and their maximum error varies between ±2 °C and ±6 °C depending on the temperature interval being measured (Maxim Integrated, 2015). Compressed air line pressure was also registered through a piezoelectric pressure transducer from TMOEC. With operating range of 0 to 12 bar, it sends corresponding signals of 0.5 V to 4.5 V to the microcontroller, which calculates and register pressure values with a 1.5 % precision.

3. METHODOLOGY

3.1 Calibration of thermocouple and module

Every measuring system possess errors and therefore requires calibration. Especially in the case of thermocouples, an adjustment curve must be calculated to show the correspondence between the actual temperatures measured by a more precise instrument and values indicated by thermocouple based system. This way, a correction is applied in order to reduce the offset error. For this, the measuring system was used in a serious of temperature-controlled water baths within a refractory container and electric resistance with potentiometer. The bath was allowed to stabilize for an hour before a 5 min acquisition. The procedure was carried out in 5 different conditions and results are shown in Fig. 1. It was employed a bulb thermometer with 0.2 °C resolution and range of 0 to 200 °C whose readings were considered as the actual correct values, since they did not vary during measurements. The equation resultant from a linear regression shown in Fig. 1 is adequate for correcting the measured temperature during the actual manufacturing process, since the variations are within the calibrated values and type K thermocouple is fairly linear in this range (Nicholas and White, 2001).

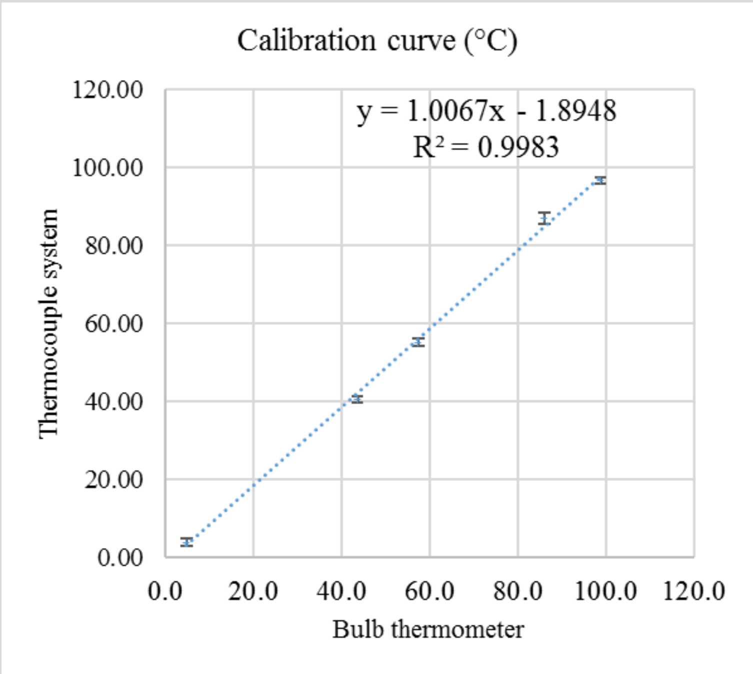

Figure 1. Thermocouple calibration with error bars showing twice the standard deviation for each temperature.

3.2 Materials and design of experiments

The materials used were Nylon 6 (Ny) and polycarbonate (PC), cut in samples of 30 x 20 x 4 mm. For each material, one sample was grinded with mesh 80 sandpaper and the other was grinded with 600 sandpaper, ensuring controlled surfaces. Table 2 shows the average and standard deviation for five measurements of Rq in each sample. This variable might influence the convection coefficient and therefore it is important to verify its influence.

Table 2. Roughness parameters (values in μm) for the grinded samples (average-AVG and standard deviation-STD).

Roughness - Rq				
Material	**Ground in sandpaper**	**Cut-off**	**AVG (μm)**	**STD (μm)**
Nylon 6	# 80	2.5 mm	7.61	1.17
Polycarbonate	# 80	2.5 mm	5.49	0.45
Nylon 6	# 600	0.8 mm	0.31	0.04
Polycarbonate	# 600	0.8 mm	0.73	0.15

Distinct polymers have different thermal properties such as specific heat capacity *cp* and thermal conductivity *k*, which are temperature dependent. They will affect heat distribution, maximum temperature (baseline temperature after stabilization) and rate of increase in temperature. This are important parameters since the thermal flux on the polymer might modify sharply its mechanical and physical properties. Osswald et. al. (2006) provide reference values for *k* and *cp*, which were interpolated for an arbitrary temperature of 70 °C and yielded the values in Tab. 3.

Table 3. Thermal properties of Nylon 6 and polycarbonate interpolated from reference values by Osswald et. al. (2006).

Thermal properties		
Material	Specific heat capacity *cp* (kJ / kg . K)	Thermal Conductivity *k* (W / m . K)
Nylon 6	1.75	0.29
Polycarbonate	1.35	0.26

This way, a factorial design of experiments of the type 2^2 is attained, considering the two different roughness and two materials as input variables. The output was the baseline temperature and rate of temperature rise up to steady state, starting observation when temperature reaches 50 °C and acquiring data over 5 minutes. It is important to highlight that the heat flux is not constant and therefore the term "steady state" is not appropriate, but in this work, it refers to the condition in which temperature reaches a plateau that represents the maximum possible within the given parameters.

3.3 Experimental setup

The hot air source used was a heat blower gun BOSCH GHG630DE with up to 2000 W and temperature adjustment through electronic thermostat. Gun temperature was fixed and was constantly hitting the sample. Compressed air line pressure was regulated at about 2 bar in regulator-filter set and was directed to the sample by a jetting pistol. The compressed air was released in a cyclic manner, being automatically opened and closed in regular determined times. When opened, the compressed air jet dislocated the smaller hot air flow and absorbed heat from the sample.

Thermocouple, module, pressure transducer and microcontroller were connected to a protoboard. The Arduino® based PLmC was connected to a laptop via USB cable for data logging in text file at rate of 5 Hz. In this configuration, the system is subject to oscillations resultant from electromagnetic fields generated by near machines, WiFi signals or others. Although there might be other causes, this might explain the noise observed, which is present even in temperatures measured in the isothermal mix of water and ice.

Figure 3 shows the equipment, while Figure 4 shows the schematics of the thermocouple fixed to sample with epoxy resin. Since this device measures temperature by contact, it is very important to position it similarly during all the experiments. In this configuration, it is probing the temperature of the sample at 1 mm below the surface hit by hot air. Meanwhile, the other side of the sample rests on a stainless steel plate holder.

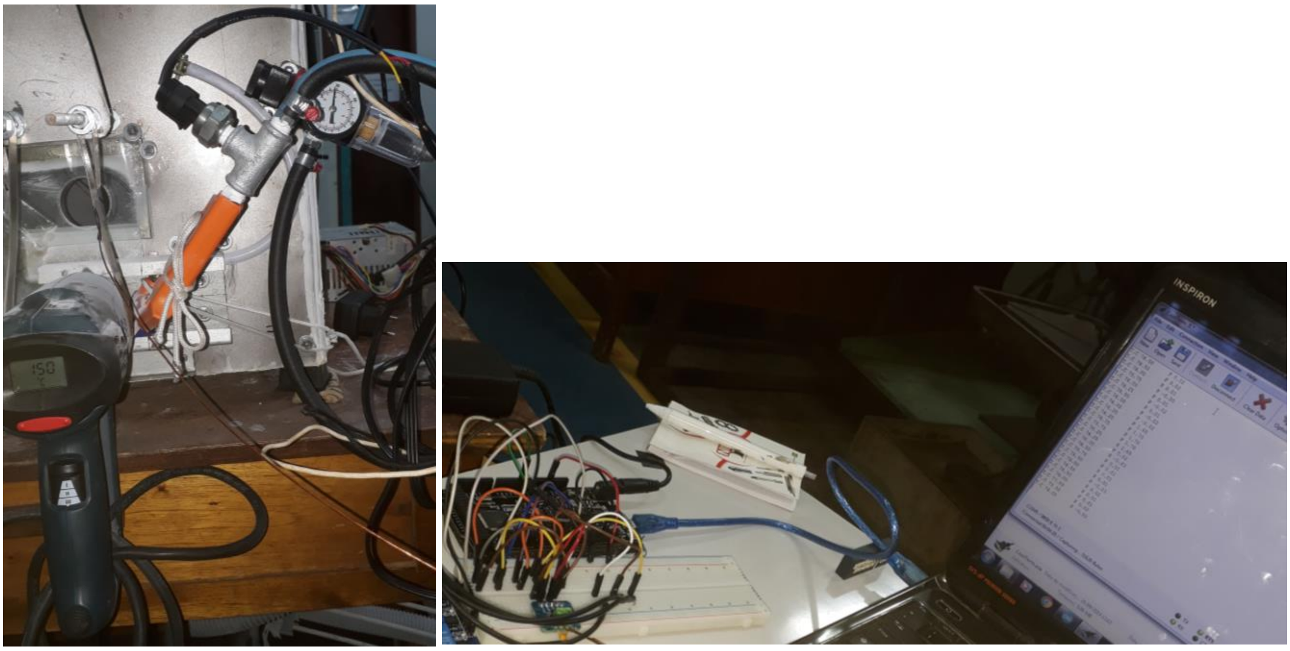

Figure 3. Heat blower gun and compressed air pistol at left. Arduino® based PLmC, protoboard, USB and laptop, at right.

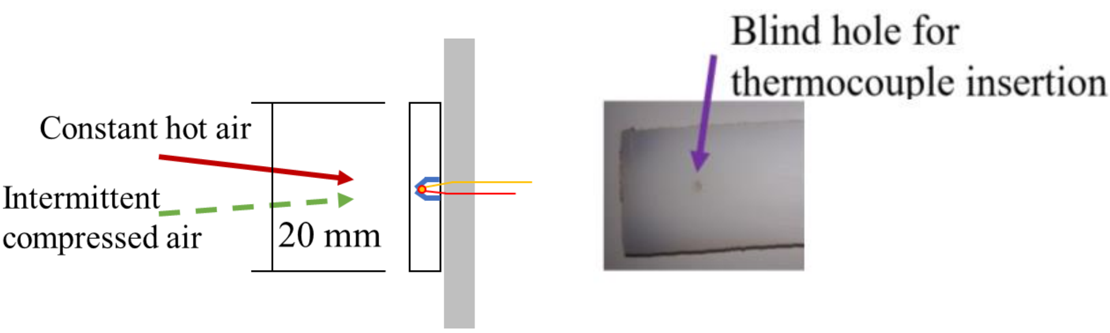

Figure 4. Schematics of hole for thermocouple positioning and sample placement.

4. RESULTS

The temperature and pressure data was obtained during 5 minutes for each sample, starting acquisition after they reached 50 °C. Before analysis, the collected temperature data was corrected by applying the equation from the linear regression in Fig. 1. The signals presented an intense variation as displayed in Fig. 5, part of which is related to electromagnetic noise since these fluctuations also occurred in the controlled baths where temperature stable. However, as compressed air hits the sample, its temperature is also expected to vary at about the same frequency of the blown compressed air, due to the corresponding change in heat flux. Inherently, the thermal capacity of the polymer and the distance from thermocouple to polymer surface dampens and delays the heat flux arriving at the thermocouple, in such way that it is not possible to distinguish the contribution of the intermittent airflow from the noise.

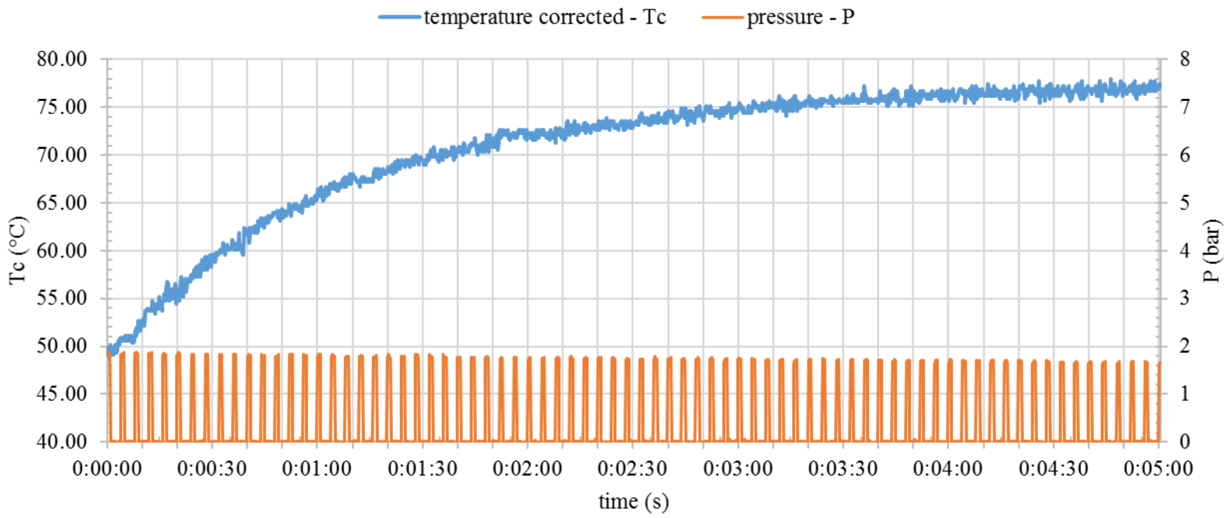

Figure 5. Temperature signal corrected by the equation from the linear regression from Fig. 1. Pressure data shows the intermittence of the compressed air blows in between heating cycles.

In all cases the temperature increased rapidly at first, with rate *rT* (°C/s) that diminishes progressively. This is due to the lower temperature difference between sample and hot air, since the heat flux for convection at the surface is proportional to this difference. There is a clear stabilization in the temperature signal towards the end of the acquisition, which characterizes the baseline temperature *Tss* (°C). In order to separate both regimes, a reference temperature *Tr* (°C) had to be calculated, however, due to the high fluctuations an average moving filter was applied first just to smoothen the curve and provide a better separation of the regimes. *Tr* (°C) was then determined as 95 % of the highest observed value during the 5 minutes, above which the system was considered as being in steady state. *Tss* (°C) is then the average from the points after *Tr* (°C), while *rT* (°C/s) is the average slope of the curve calculated through a linear regression of the points before *Tr* (°C). These calculations use the signal before attenuation by the filter. This procedure is exemplified in Fig. 6 and Fig. 7 for polycarbonate mesh 600.

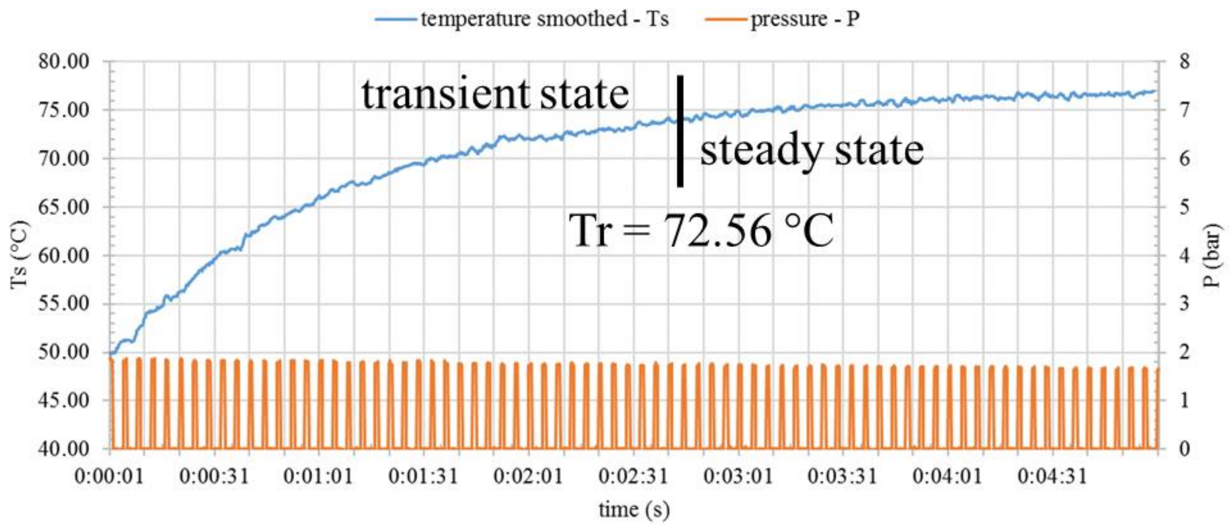

Figure 6. Temperature smoothened by an average moving filter of N = 7.

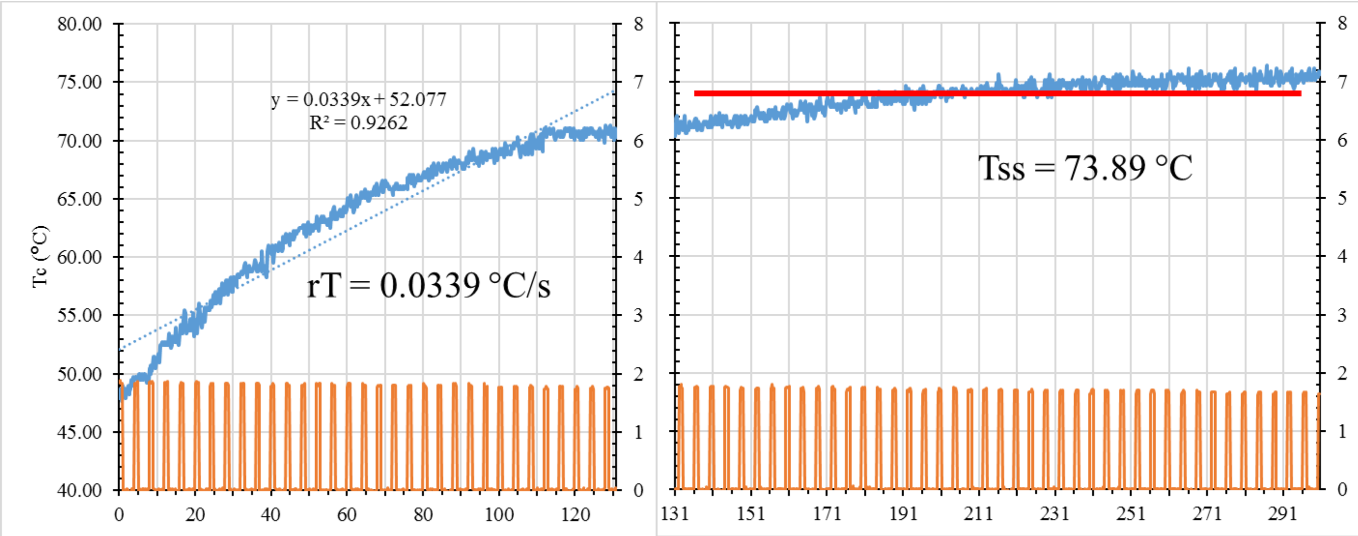

Figure 7. Determination of *rT* (°C/s) through linear regression of points before *Tr*, and *Tss* (°C) by the average of points after *Tr*.

Table 4 shows the results for all samples, for which analysis of variance was carried. The baseline temperature for Nylon 6 was slightly higher than for polycarbonate. Although the higher specific heat for Nylon 6 would lead to a lower temperature considering the same heat flux, this could be related to the higher thermal conductivity that makes that more heat arrives at the point where thermocouple is fixed. Nevertheless, this can not be affirmed because the analysis of variance from Fig. 8a showed there is no significant difference for the *Tss* (°C) between the two materials. Regarding Rq, it did not have any clear effect on the baseline temperature. Although a greater roughness could favor heat exchange due to increased surface area, this effect was not perceived for the tested conditions, neither in the steady state temperature nor in the rate of increase during transient state.

Table 4. Baseline temperature and rate of increase for the two materials and two surface conditions.

Material	Mesh	*Tss* (°C)	*rT* (°C/s)
PC	600	73.89	0.0339
PC	80	74.68	0.0311
Ny	600	76.21	0.0518
Ny	80	75.36	0.0547

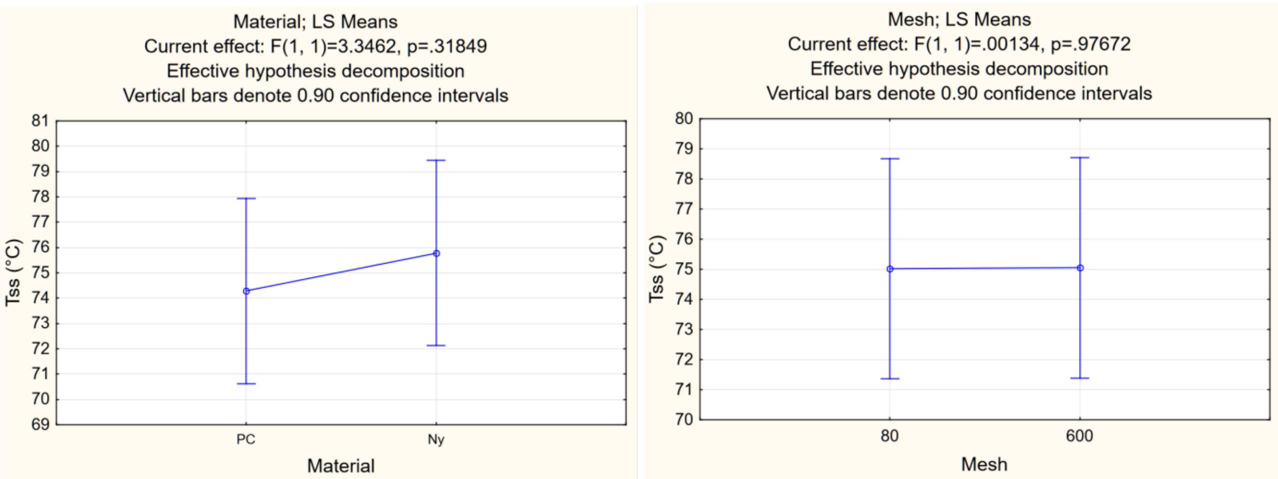

Figure 8. a) Effect of material in *Tss* (°C). b) Effect of surface roughness in *Tss* (°C).

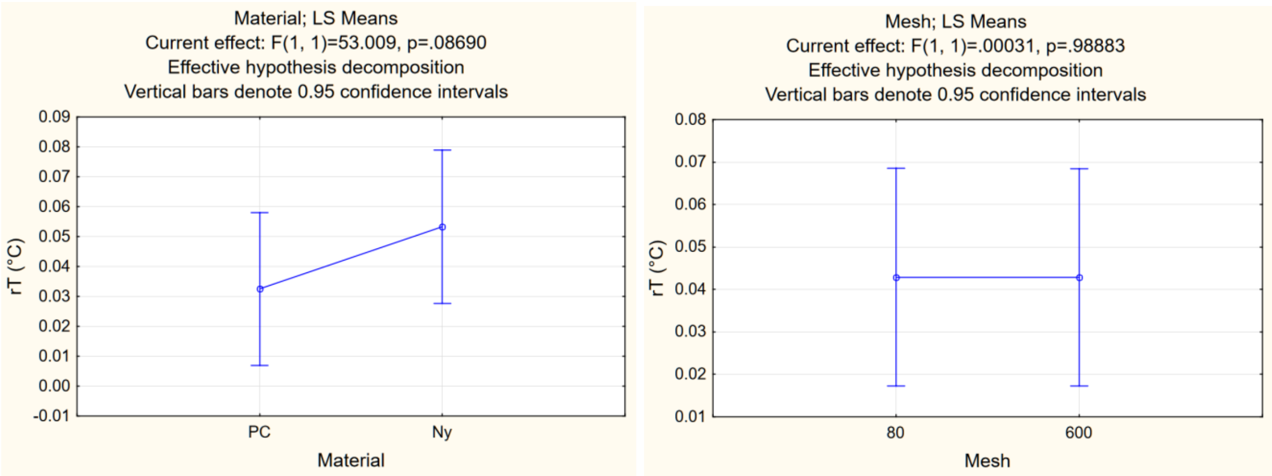

Figure 9. a) Effect of material in *rT* (°C/s). b) Effect of surface roughness in *rT* (°C/s).

From Tab. 4 it is evident that the rate of temperature increase up to steady state was higher for Nylon 6. According to the analysis of variance, there was a significant higher rate for this material considering a significance level of 10 %. This is likely due to the higher thermal conductivity, which is about 10 % higher than that of polycarbonate. But again, the *cp* from Nylon 6 is almost 30 % higher than for polycarbonate, which would lead to a lower temperature considering the same heat flux for the two samples. This means that for the conditions essayed the effect of *K* superseded the effect of *cp*., probably because of the high thermal load provided by the heat gun in comparison with the low heat capacity from the samples since they are very small.

5. CONCLUSIONS

Temperature measurements with thermocouple and Arduino compatible hardware were carried in polymers subject to intermittent heating from a manufacturing process. To simulate this condition, a heat gun and compressed air were used to heat and cool down the polymer surface in a cyclic manner. The thermocouple was positioned 1 mm below the surface and captured the temperature evolution, from which the following conclusions can be drawn.

- Although there was some noise in the signal, the data acquisition system based on Arduino proved to be a reliable and very cost efficient acquisition system specially when applied to situations that do not require very precise monitoring and control of process temperature.
- The position of the thermocouple creates a thermal dampening effect in which the flow temperature variations are not sensed by the thermocouple right way. Furthermore, any possible fluctuation due to the varying thermal load is not easily distinguishable from the noise.
- The air came out of the heat gun at a temperature of almost 150 °C, the maximum baseline temperature the polymers reached was about 76 °C. Although the distance of samples is enough to cool down the hot air by some degrees, this also shows that even a small layer of polymer shielding the thermocouple creates a considerable heat resistance.
- According to the analysis of variance the temperature reached by both polymers after 5 min of intermittent heating had no significant difference, which indicates it has more to do with the air temperature and flow then with the materials used, which do not differ substantially in its thermal properties.
- There was a significant higher rate of increase in temperature for Nylon 6 during the transient state, indicating that the slightly better conductivity of this material allowed the heat to diffuse to the thermocouple more efficiently. This shows that this thermal property was the most important in our work, probably because of the small size of the samples.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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