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**EXPERIMENTAL STUDY AND SIMULATION MODEL FOR  
DETERMINING THE RESPONSE TIME OF THERMOCOUPLES WITH  
DIFFERENT INSULATION THICKNESSES**  
**27<sup>th</sup> COBEM**

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**Abstract.** *The aim of this paper is to determine the temporal response of T-type and K-type thermocouples with different coating thicknesses. In applications with high thermal gradients, the thermocouple can experience thermal fatigue caused by its exposure to high temperature levels and severe thermal cycling involving heating and cooling of the sensor. Repeated expansions and contractions can lead to the appearance of micro-cracks, affecting the accuracy of temperature measurements and eventually causing sensor failure. In these circumstances, thermocouples with greater sheath thicknesses are more suitable. However, thicker thermocouples have a high response time, so that, in processes under transient conditions, the delay will generate a temperature error at every instant of time. The present study focuses on how different coating thicknesses affect the thermocouple's ability to accurately measure temperature changes over time, especially in transient conditions. Experimental tests were carried out with a T-type thermocouple, with a 0.5 and 1.5 mm sheath, and K-type thermocouples of thickness 6mm and 8mm sheath. An equation for prediction of delay time of thermocouples is presented and validated experimentally with mean error of 3.57%.*

**Keywords:** *Thermocouple, temporal response, mathematical modeling, time constant.*

## 1. INTRODUCTION

Obtaining temperatures in order to determine the heat flow in real time is essential information to ensure quality in manufacturing processes, providing control and time optimization. Likewise, the estimation of transient heat flux in real time, and the consequent compensation of delay in reading thermocouples, extends to several industrial and laboratory segments that require analysis of temperature transients, such as applications in heating and cooling systems, tribological analysis (Nosko and Tsybrii, 2021), determination of flame temperature (Jiménez and Luna, 2022), vapor phase welding (Alaya et al., 2020), combustion engine exhaust systems (Augustin, et al., 2013), electronic packages (Shaukatullah and Claassen, 2003), among other applications. Straubinger investigated the influence of parameters such as uninsulated wire length, insulating material (PFA, PVC, PTFE and fiberglass fabric), insulation thickness, and hot spot diameter in thermocouples type K, T and J and the results show that most parameter and geometry changes, most significantly, the not isolated wire end, can result in non-negligible temporal variation, in the 100 ms range, between different sensors (Straubinger et al., 2022).

Thermocouples have an intrinsic response time that can dampen the temperature gauges, in this way Oliveira (2022) recently proposed the correction of the temperature signal for a precise calculation of the heat flux in inverse heat conduction problems, through a model that allows the reconstruction of the temperature signal of a fast thermocouple using the measurements of a slow thermocouple (Oliveira et al., 2022). Thermocouples are quite versatile in these engineering applications because of their fast response time, on the order of a millisecond or less (~0.1 ms) (Manjhi and Kumar, 2019).

In view of the above, the choice of thermocouple type and the thickness of its sheath is decisive for the accuracy of the results. The ideal would be a thermocouple with a thin sheath, however, exposure to high temperature gradients can cause thermal fatigue, reducing its useful life and the quality of its measurements. The solution is to use thicker sheath thermocouples, which naturally minimize thermal variation, but just as it minimizes the effects of thermal fatigue, it delays the real-time reading. (Caldwell, 1962)

Thermal fatigue in thermocouples is caused by their exposure to elevated temperature levels and severe thermal cycling involving heating and cooling of the sensor. Repeated expansions and contractions can lead to micro-cracks appearing in the thermocouple wire, affecting the accuracy of temperature measurements and eventually causing sensor failure. Failure occurs due to mismatched thermal expansion between the various thermocouple materials, which causes high tensile stresses in the thermocouple wires during exposure to elevated temperature. In these circumstances, thermocouples with greater sheath thicknesses are more suitable. However, thicker thermocouples have a slower response time, so in processes under transient conditions, the delay will generate a temperature error every instant of time (Kumar et al., 2023).

The objective of this study is to determine the temporal response of thermocouples in the temperature range between 0°C to 100°C, as well as suggest a delay transfer function that can be applied to the control system to predict the temperature in real time. The transfer function has as input variable the temperature variation, considering the thickness of the thermocouple sheath and the thermal delays. Experimental tests permitted to validate the proposed model, use type K and T thermocouples with coating thicknesses of 0.5 mm, 6.0 mm, and 8.0 mm for type K and compare these results with type T thermocouples of with thicknesses of 0.5 mm and 1.5 mm.

## 2. EXPERIMENTAL METHODS AND TESTS

### 2.1 Experiment apparatus

In order to ensure the repeatability of the phenomena of interest to be analyzed, a retrofit was performed on a prismatic robot with three degrees of freedom, from Mettler Toledo®, which had all its micro processed electronics redone. The robot allows a linear displacement with controlled time, the variation of the immersion depth of the thermocouples, as well as the circular movement of the thermocouples in order to increase the convection, all actions carried out through G code. Figure 1 shows the experimental setup developed for standardization of experiments. A graduated beaker with water varying between room temperature and the boiling point was placed next to another beaker with melting ice and isolated surface, as shown in Figure 2. A pneumatic actuator connected to the robot's Z axis, with support for fixing the sets of thermocouples, was activated to carry out the dip periodically and alternately in the two containers. The depth of immersion of the thermocouples was controlled through G-code commands to activate the motors, allowing the experiments to be repeated. A T-type thermocouple with a sheath thickness of 0.5 mm was used as a reference in the measurements, which has the best accuracy among base metal thermocouples, with a continuous use range from -270°C to 370°C and error limit between  $\pm 1^\circ\text{C}$  or  $\pm 0.75\%$  (Drebushchak, 2015). The interval between readings taken is 0.4 seconds.

The digitization of the signal read by the thermocouples and the cold junction compensation was performed by the MAX31856 acquisition module. This module can provide output data formatted in degrees Celsius, with its cold junction compensation temperature range from  $-55^\circ\text{C}$  to  $125^\circ\text{C}$  for both types of thermocouples used. The module works in the measuring range of  $-200^\circ\text{C}$  to  $+1372^\circ\text{C}$  and in the range  $-200^\circ\text{C}$  to  $+400^\circ\text{C}$  for type K and T thermocouples, respectively. Its analog-to-digital conversion resolution is 19 bits, equivalent to a resolution of  $0.0078125^\circ\text{C}$ . According to the manufacturer's Datasheet, the measurement accuracy of the module is  $-0.13^\circ\text{C}$  and  $+0.12^\circ\text{C}$  for K-Type thermocouples and  $\pm 0.07^\circ\text{C}$  for T-type thermocouples (Alldatasheet, 2023). Of the eight types of thermocouples that the MAX31856 module can work with, these being types K, J, N, R, S, T, B and E, T-type thermocouples are the ones with the lowest reading error in data acquisition (Alldatasheet, 2023). The reading standard adopted in the module was the Auto conversion mode, conversions 2 through n (60Hz) which has a 90ms response for each thermocouple, automatic cold junction compensation and linearization. If the thermocouple wires make contact with different metals, usually on connectors or at the solder joint of a Printed Circuit Board (PCB), a "cold junction" is created at the site and its temperature must be measured and compensated for. This is done with the internal precision temperature sensor, which is accurate to better than  $\pm 0.7^\circ\text{C}$  from  $-20^\circ\text{C}$  to  $+85^\circ\text{C}$  (Alldatasheet, 2023).

The K-type thermocouples and T-type used are of the special class, that is, they have a reading error of the order of  $+1.1^\circ\text{C}$  or  $+0.4\%$  and  $+0.5^\circ\text{C}$  or  $+0.4\%$  respectively, depending on the manufacturer (Ecil, 2023). For this reason, the T-type Thermocouple (TJC50-CPIN-020U-S) with a sheath thickness of 0.5 mm, manufactured by Omega, was adopted as

a reference standard for data analysis (Omega, 2023). As the temperature test range was the liquid phase of water, the error added to the T-type thermocouple was  $+0.5^{\circ}\text{C}$ , a more conservative value in the measurement range used.

The signal captured by the MAX31856 data acquisition module was sent to a programmable platform *open source*: Arduino Due, 32-bit and 84MHz clock, and Arduino Leonardo, 8-bit and 16MHz clock, both have native USB on the AT91SAM3X8E and ATmega32U4 microprocessors, respectively, which allows direct publication of data in an open spreadsheet on a computer connected to USB. Data were taken from 2 to 6 thermocouples simultaneously. With the reading performed in two thermocouples, added to the data processing and their publication in a spreadsheet, the acquisition time between data was 0.4 seconds. Data were acquired for periods of two hours or more to generate graphs.

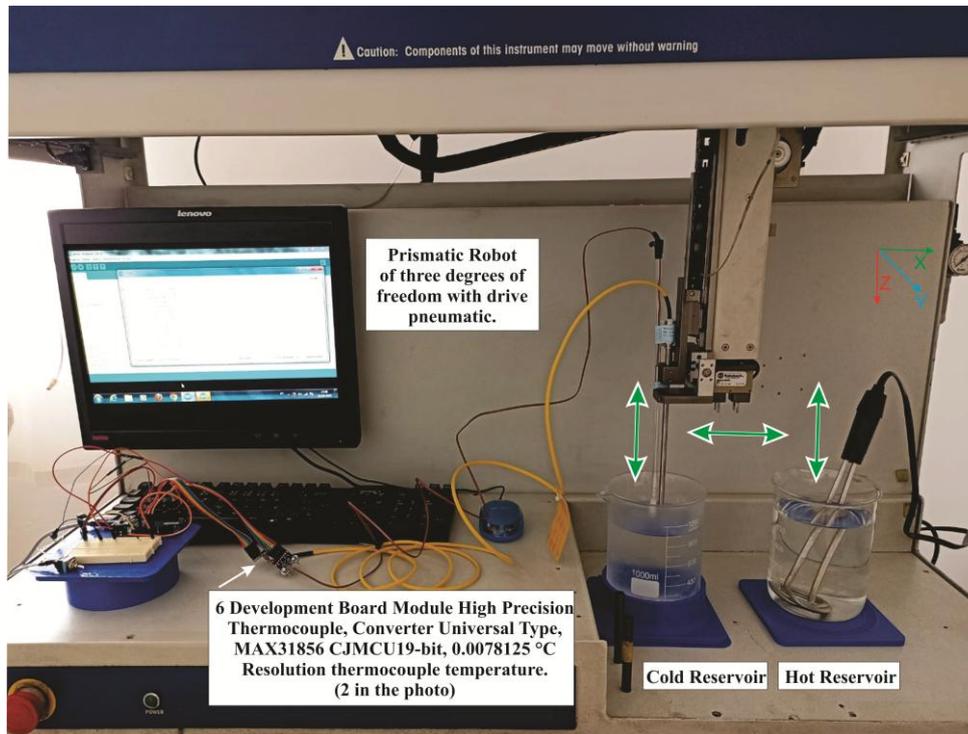


Figure 1. Experimental setup showing the two thermocouples immersed in cold water, the beaker with heated water and the data acquisition system.

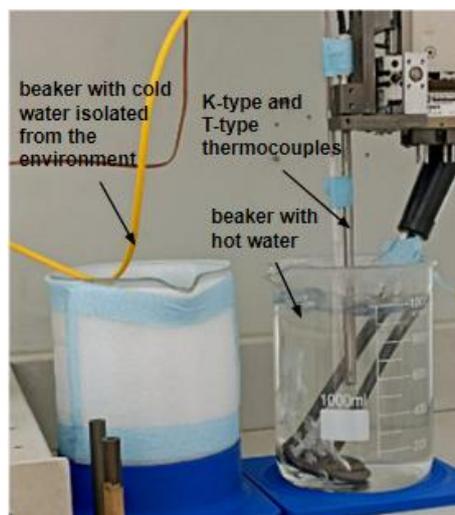


Figure 2. Two thermocouples immersed in hot water and beaker with cold water with insulation.

## 2.2 Calibration of thermocouples

Calibration of thermocouples is essential for measurement reliability. Subsequent measurements were made of the indications of the standard thermometer and of the sensors being calibrated.

The reference value was determined based on the Standard Thermometer Calibration Certificate. The calibration routine used follows the guidelines contained in DOQ-CGCRE-009 Revision 07 – April/2020 and NIT-DICLA-021 – August/2007. The confidence interval used was 95.45% and the rounding of the last significant figure follows the rules defined by the Brazilian Association of Technical Standards ABNT NBR 5891. Tables 1, 2, 3 and 4 show the calibration results for type t thermocouples with sheath thicknesses of 0.5mm and 1.5mm and type k thermocouples with sheath thicknesses of 6mm and 8mm, respectively.

Table 1. T-type 0.5mm thermocouple calibration for four temperature points.

<b>Thermocouples T-type (TJC50-CPIN-020U-S by Omega)</b>	<b>T-type 0.5 mm</b>			
Standard temperature, °C	-10.01	-0.01	100.11	201.94
Thermocouple measurements, °C	-11.52	-0.38	100.44	204.03
Error, °C	-1.51	-0.37	0.33	2.09
Uncertainty, °C	0.83	0.62	0.44	0.58

Table 2. T-type 1.5mm thermocouple calibration for four temperature points.

<b>Thermocouples T-type (22862/PI199022 by Ecil)</b>	<b>T-type 1.5 mm</b>			
Standard temperature, °C	-10.01	-0.01	100.11	201.94
Thermocouple measurements, °C	-12.36	-1.65	99.58	203.62
Error, °C	-2.35	-1.64	-0.53	1.68
Uncertainty, °C	0.25	0.30	0.31	0.45

Table 3. K-type 6 mm thermocouple calibration for four temperature points.

<b>Thermocouples K-type (MS11/K-S-00/310-60-S-200/PL by Ecil)</b>	<b>K-type 6 mm</b>			
Standard temperature, °C	-10.01	-0.01	100.11	201.94
Thermocouple measurements, °C	-9.93	-0.21	98.45	203.08
Error, °C	-0.07	-0.22	-1.66	1.14
Uncertainty, °C	0.54	0.47	0.37	0.57

Table 4. K-type 8 mm thermocouple calibration for four temperature points.

<b>Thermocouples K-type (PT3.8/10 1300C by XNY)</b>	<b>K-type 6 mm</b>			
Standard temperature, °C	-10.01	-0.01	100.11	201.94
Thermocouple measurements, °C	-10.86	-0.25	99.81	203.77
Error, °C	-0.85	-0.23	-0.30	1.83
Uncertainty, °C	0.61	0.54	0.40	0.71

### 2.3 Measurements

The test bench was programmed in G code to perform movements between two beakers, one containing melting ice and the other water at boiling point. The thermocouples, moved by the prismatic robot, were alternately dipped into the beakers and at a constant depth. The depth of immersion of the thermocouples was such that no heat exchange was observed between the sheath and the environment.

The stainless-steel sheath of T-type (TJC50-CPIN-020U-S) and K-type (MS11/K-S-00/310-60-S-200/PL) thermocouples has Specific Heat Capacity of 500 J/gK, Thermal Conductivity of 16.2 W/m-K and Density equal to 8000 kg/m<sup>3</sup>. The thermal conductivity of stainless steel 304, the material the sheath is made of, is 16.2 W/mK, according to MatWeb (MatWeb, 2023).

The properties of the water, used as a test environment, were obtained using the EES® software and are shown in Table 5.

With the aid of the EES® software, the Prandtl number of the water was determined at the two temperatures of interest. From this information, it was possible to calculate the other dimensionless properties shown in Table 6.

Table 5. Water properties at the reference temperatures.

Water	100°C	0°C
Specific Heat Capacity, J/gK	4216	4219
Thermal Conductivity, W/m-K	0.6829	0.5557
Prandtl	1.736	13.6
Absolute Viscosity, Pa·s	0.0002812	0.00179
Density, kg/m <sup>3</sup>	958.2	1000

The Grashof number, which quantifies the forces opposing the buoyancy movement due to fluid viscosity, was calculated according to Eq. (1) and considers the geometry of the thermocouple. The Rayleigh number, defined as the product between the Grashof number and the Prandtl number, is associated with the flow moved by the buoyancy due to the natural convection of the fluid and was calculated considering the Prandtl and Grashof values found for the reference temperatures (Incropera and Bergman, 2008) (Çengel, 2009).

$$Gr_D = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2}, \quad (1)$$

Where,  $g$  is the gravitational acceleration,  $\beta$  is the volume expansion coefficient,  $T_s$  is the surface temperature,  $T_\infty$  is the ambient temperature,  $D$  is the thermocouple diameter and  $\nu$  is the kinematic viscosity of the fluid.

Finally, the mean Nusselt number was obtained, based on Eq. (2), to quantify the ratio between fluid heat transfer by convection and conduction. The correlation used to determine the mean Nusselt was Churchill and Chu, which covers a wide range of Rayleigh numbers (Churchill and Chu, 1975).

$$\overline{Nu} = \left\{ 0.60 + \frac{0.387 Ra_D^{1/6}}{\left[ 1 + \left( \frac{0.559}{Pr} \right)^{9/16} \right]^{8/27}} \right\}^2, \quad (2)$$

The dimensionless quantities used in Eq. (2) are shown in Table 6.

Table 6. Dimensionless properties of water at reference temperatures.

Water	100°C	0°C
Grashof number, (dimensionless)	1.069E+06	27500
Rayleigh, (dimensionless)	373974	1.856E+06
Nusselt, (dimensionless)	19.21	13.98

## 2.4 Mathematical modeling

The behavior of the sheath in the temperature reading by the thermocouple junction is analogous to that of the electrical circuit. The heat that the sheath retains is thermal capacitance and can be compared to electrical capacitance, as well as thermal conductivity can be associated with electrical resistance.

Through the behavior of the mechanical properties, which influence the stored thermal energy, as well as the properties that have the characteristics of resistance to heat flow, it was possible to develop an empirical model capable of simulating the temperatures presented over time in thermocouples exposed to variations of temperature.

In view of the above, the delay in reading the thermocouple for cooling processes can be associated with Eq. (3).

$$T(t) = \Delta T e^{-\frac{t}{\tau}}, \quad (3)$$

For the heating process the reading delay is described by Eq. (4).

$$T(t) = \Delta T \left[ 1 - e^{-\frac{t}{\tau}} \right], \quad (4)$$

Where,  $T(t)$  is the temperature as a function of time,  $\Delta T$  is the temperature variation, and  $\tau$  is defined considering the type of thermocouple tested, its radius, the properties of the sheath material and the convection of the surrounding medium.  $\tau$  is shown in Eq. (5) for type K thermocouples with 6mm and 8mm sheath diameter. Eq. (7) presents the  $\tau$  for T-type thermocouples with 0.5mm and 1.5mm sheaths.

$$\tau = \underbrace{\frac{\rho_{sT|C} C_{p_{sT|C}} \Delta T}{L}}_{1^\circ} \underbrace{\left( \frac{k_{sT|C} \Delta T}{r_{sT|C}} \frac{1}{(h_w \Delta T)^2} \right)}_{2^\circ} \underbrace{r_{sT|C}^2 \left( \frac{C_{p_w}}{C_{p_{sT|C}}} \right)^{f(r_{sT|C})}}_{3^\circ}, \quad (5)$$

Where,  $k_{sT|C}$  is the thermal conductivity of the stainless steel that coats the thermocouple,  $C_{p_{sT|C}}$  is the specific heat of the stainless steel,  $h_w$  the coefficient of convection of the medium in which the thermocouple is immersed and are, respectively,  $r_{sT|C}$  the radius of the thermocouple sheath and  $\rho_{sT|C}$  its specific mass.

The deduction of the equation for the time constant was obtained out by relating the thermodynamic effects with the effects of an RC electrical circuit, since  $\tau=RC$  in these circuits (Halliday et al., 2011). This way, the capacitive and resistive behavior in heat transfer phenomena was sought. The amount of heat obtained through the thermal capacity  $mc_p \Delta T$ , is similar to the capacitive behavior, as they retain energy. The thermal conductivity of the steel, present in the thermocouple sheath, and the convection of the fluid in which the thermocouple is immersed, are related as the inverse of the electrical resistances by creating resistance to the flow of heat.

Following the concepts of electrical circuits generated in the analogy with heat transfer, better correlations were observed when adopting the ratio between the convection of the medium, squared, by the thermal conduction of the sheath. This reason took the analogy with the inverse of resistance. Multiplying by  $mc_p \Delta T$  gives  $RC$ . With this product, multiply by the ratio between the heat capacity of the steel by the heat capacity of the medium, which in this case was water, and raise this ratio to an experimentally adjusted function of the radius. The radius function found was a polynomial called lambda, which proved to be a better correlation for obtaining the time constant. The existence of the lambda polynomial is due to the need to adjust the thermal capacity of the sheath, which is not entirely composed of stainless steel, having the presence of ceramic insulators and the presence of the thermocouple metals.

The Eq. (5) defines the time constant, where the first part of the equation represents the thermal energy accumulated in the sheath material. The analysis will not be carried out considering the volume, but the area of the thermocouples, with the need to divide the product of the first portion by a unit length with a dimension of meter [m], which is related to the capacitance of the system. The second installment of Eq. (5) establishes a relationship between the conductivity in the thermocouple sheath material and the square of the convection occurring in the medium. The conductivity has a linear behavior because it is found in a homogeneous medium, analyzing the cross-section of the thermocouple radially, the natural convection on an almost horizontal thermocouple immersed in water obeys Eq. (2), where the thickness of the x-axis thermal layer in the fluid has the same thickness in the positive and negative directions. The y-axis has different thermal layer thicknesses in the positive and negative direction.

Figure 3 shows a sketch of the variation of the thermal layer in the x and y axes, applied in Eq. (5).

In this way, the convection portion must be analyzed as an area and the adjustments are left for the third portion. The third installment of Eq. (5) represents the relationship between thermal conductivities and radius, and was multiplied by an experimental adjustment constant. Simplifying Eq. (5) we obtained Eq. (6):

$$\tau = \frac{\rho_{sT|C} C_{p_{sT|C}}}{L} \left( \frac{k_{sT|C}}{h_w^2} r_{sT|C} \right) \left( \frac{C_{p_w}}{C_{p_{sT|C}}} \right)^\lambda, \quad (6)$$

The dimensional magnitude of  $\tau$  is second and its exponent is dimensionless, like every exponent, when the radius is raised to constants  $C_1$  and  $C_2$  it must have the dimensions shown in Table 7. The exponent  $\lambda$  represents a polynomial of degree two. Its value is shown in Eq. (7). However, its constants are defined according to the measured process, which can be a decrease or increase in the temperature of the medium. The constant values are shown in Table 7.

$$\lambda = C_1 r_{sT|C}^2 + C_2 r_{sT|C} + C_3, \quad (7)$$

Table 7. Coefficients of Eq. (7)

Applicable to thermocouples in the range of 0.5mm to 8mm in diameter	$C_1[m^{-2}]$	$C_2[m^{-1}]$	$C_3$
Medium with decreasing temperature	119462	225.987	1.48867
Medium with rising temperature	221587	643.587	1.96363

(1) measured at 0°C to 100°C

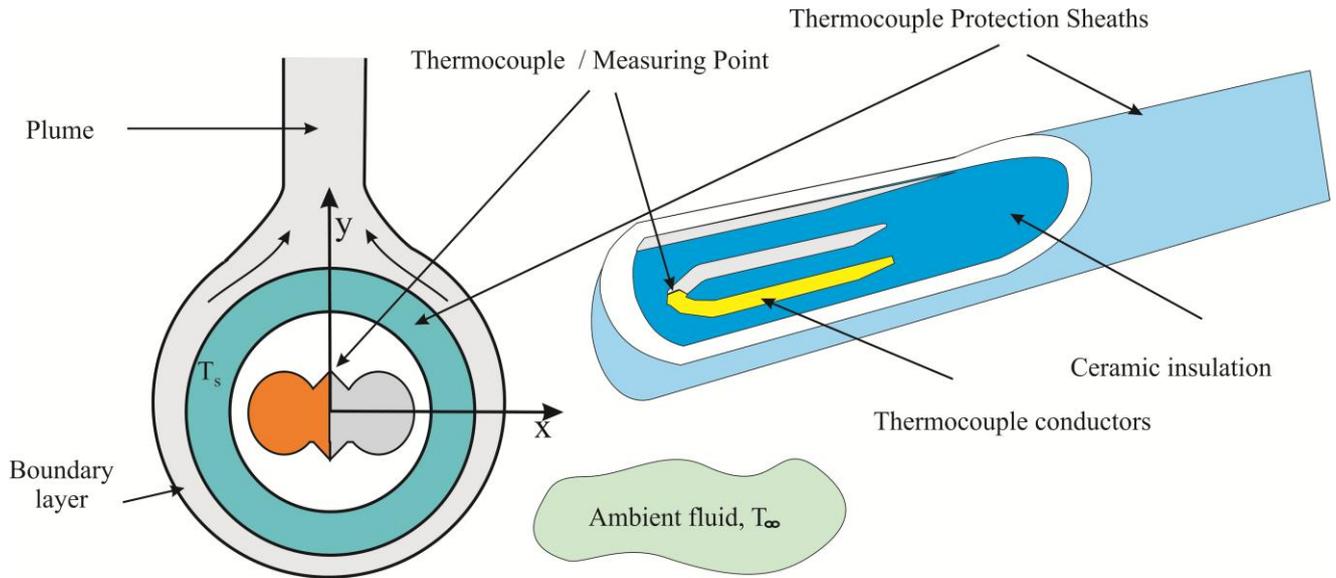


Figure 3. Boundary layer development for a cylinder immersed in liquid.

The time constant  $\tau$ , which characterizes the response time for the thermocouple, can be obtained through Eq. (3). The actual measured temperature is reached after  $5\tau$  with an accuracy of 99.3%.

### 3. RESULTS

#### 3.1 Experimental results

Figure 4 to 7 shows the thermocouple measurements along with the values simulated by Eq. (6) for cooling and heating, respectively.

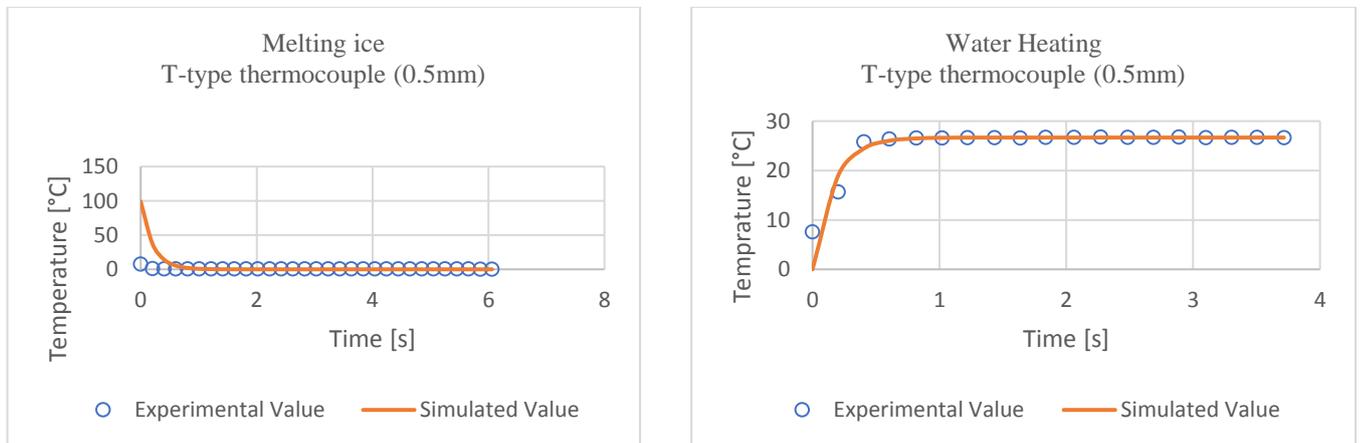


Figure 4. Experimental Result versus Simulated Result for 0.5mm T-type thermocouple

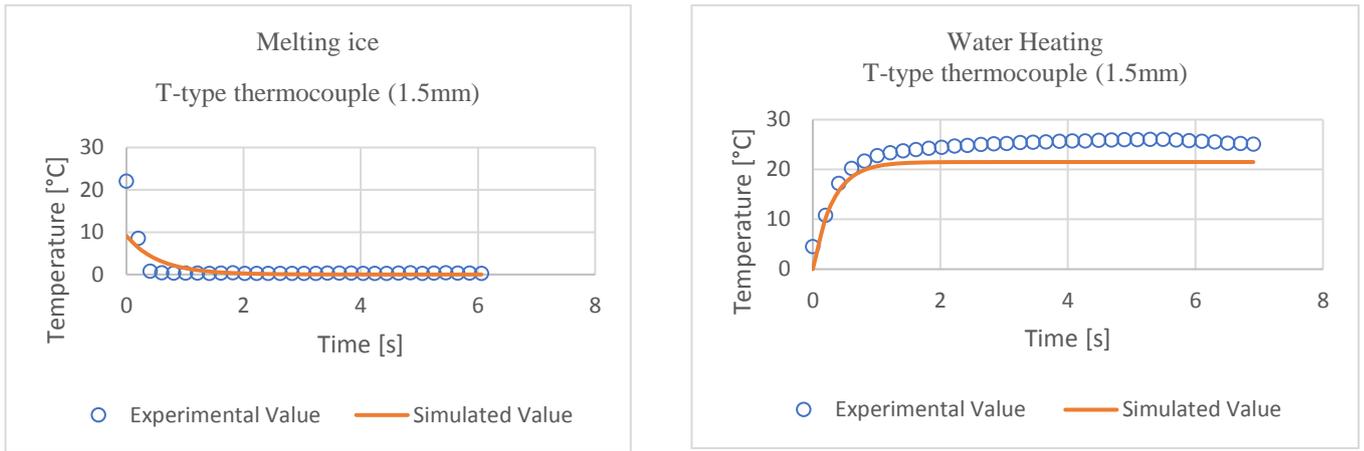


Figure 5. Experimental Result versus Simulated Result for 1.5mm T-type thermocouple

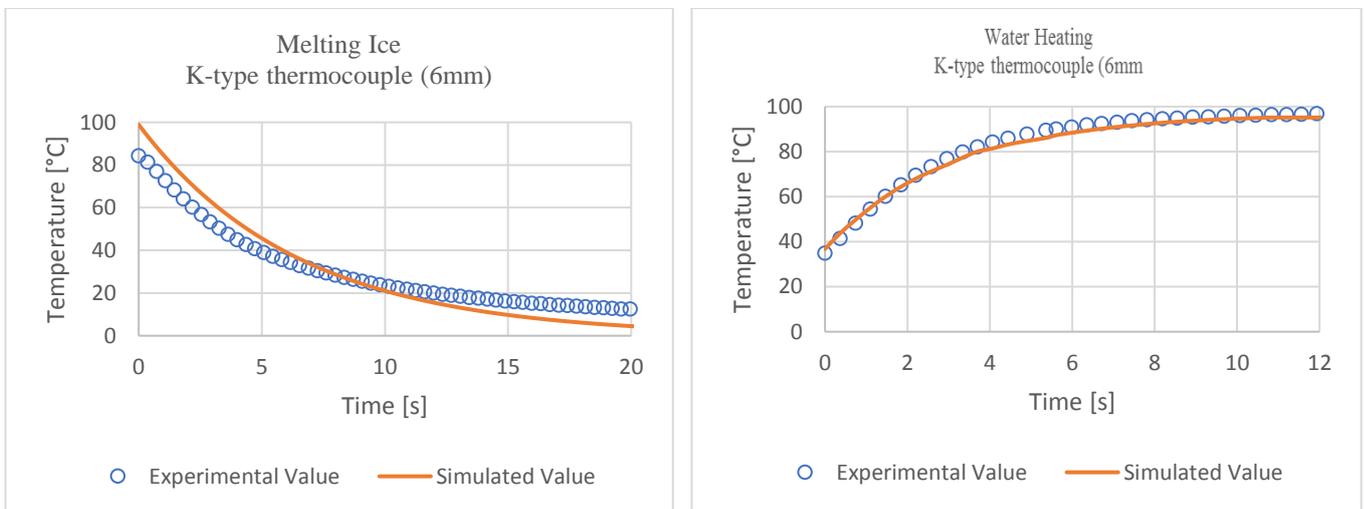


Figure 6. Experimental Result versus Simulated Result for 6mm K-type thermocouple

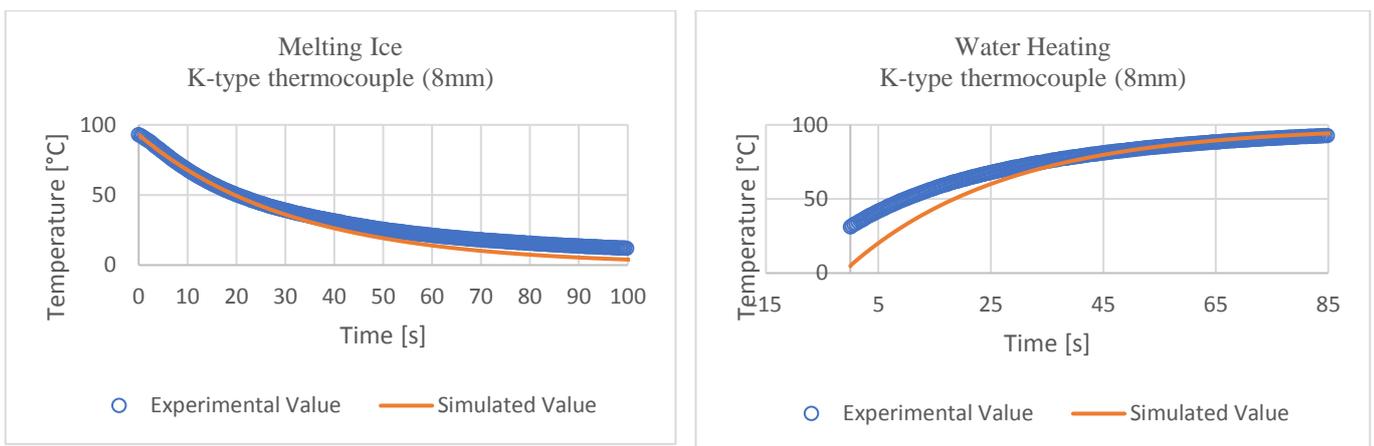


Figure 7. Experimental Result versus Simulated Result for 8mm K-type thermocouple

### 3.2 Results and discussions

Table 8 presents the values obtained for the time constant of four thermocouples in the process of cooling in melting ice, two type T and two type K, with sheath diameters of 0.5 mm, 1.5 mm, 6 mm and 8 mm, respectively. All simulated results in Table 8 are in uncertainty range of the experimental results and the mean error is 1.48%.

Table 9 presents the time constants obtained for the same set of thermocouples, but in the process of heating in boiling water. The mean error in Table 9 is 5.66%.

Table 8. Comparison of experimental and simulated results for cooling in melting ice.

Thermocouples in the cooling process	EXPERIMENTAL VALUES (s)	SIMULATED VALUES (s)	ERROR (%)
T-type thermocouple, 0.5 mm <sup>(1)</sup>	0.21 ± 0.04	0.21	1.71
T-type thermocouple, 1.5 mm <sup>(1)</sup>	0.54 ± 0.6	0.56	2.37
K-type thermocouple, 6 mm <sup>(1)</sup>	6.55 ± 0.8	6.46	1.27
K-type thermocouple, 8 mm <sup>(1)</sup>	31.48 ± 2.58	31.65	0.58

<sup>(1)</sup>measured at an ambient temperature of 22°C

Table 9. Comparison of experimental and simulated results for heating in boiling water

Thermocouples in the heating process	EXPERIMENTAL VALUES (s)	SIMULATED VALUES (s)	ERROR %
T-type thermocouple, 0.5 mm <sup>(1)</sup>	0.18 ± 0.05	0.16	8.36
T-type thermocouple, 1.5 mm <sup>(1)</sup>	0.32 ± 0.02	0.31	3.63
K-type thermocouple, 6 mm <sup>(1)</sup>	3.28 ± 0.17	3.06	6.70
K-type thermocouple, 8 mm <sup>(1)</sup>	27.21 ± 1.00	28.27	3.95

<sup>(1)</sup>measured at an ambient temperature of 22°C

Table 10 presents the time constant necessary to reach 99.3% of the final temperature, defined in control theory as  $5\tau$ , with a  $\pm 2\%$  error margin (Nise, 2009).

Table 10. Experimental results for achieving 99.3% of the temperature variation based on Eq. (6) and Eq. (7).

Stabilization time considering the time constant $5\tau$	COOLING (s)	HEATING (s)
T-type thermocouple, 0.5 mm <sup>(1)</sup>	1.05	0.90
T-type thermocouple T, 1.5 mm <sup>(1)</sup>	2.7	1.55
K-type thermocouple, 6 mm <sup>(1)</sup>	32.75	15.3
K-type thermocouple 8 mm <sup>(1)</sup>	157.4	141.35

<sup>(1)</sup>measured at an ambient temperature of 22°C

#### 4. CONCLUSIONS

The study of the response time constant for type T and K thermocouples in the temperature range from 0°C to 100°C allows adjustments in the real-time responses for processes where high temperature gradients are observed. Eq. (6) presents a time constant  $\tau$ , which is independent of  $\Delta T$ , whose value was confirmed experimentally, making this equation a tool that can be applied to any temperature variation within experimental limits. It was observed that for the K-type thermocouples tested, due to their greater sheath thickness, Eq. (6) showed better results due to the longer response times involved, which allowed adjustments to the constants as shown in Table 8. The simulation accuracy for the T-type thermocouple showed satisfactory results. However, the thermocouple with a 0.5mm sheath, due to the speed of its variation, was limited by the speed of the data acquisition system, but the simulated final times showed acceptable with mean deviations of 3.57%. The stabilization time of the temperature measured in the thermocouple in relation to the temperature in real time will be obtained in  $4\tau$  for an approximation of 1.8% and in  $5\tau$  for an approximation of 0.7% of the temperature of the observed medium.

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