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Characteristics of Optimal Wavelength Selection for the Quadrispectral Pyrometer in the Near-Infrared Spectral Range Made for Austenization of Steels

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ABSTRACT: The characteristics of selecting optimal wavelengths for a four-spectrum pyrometer used during the austenitizing of steels will be examined at the end of this article. Thanks to one of the physical properties of hot steels, which has the ability to radiate, its surface temperature can be measured remotely. This temperature is proportional to the emitted infrared radiation. The system is equipped with optical filters to filter the four spectra and converge them towards the respective detectors.

Steel is among the metals with nonlinear emissivity. To overcome this nonlinearity, the model called TNL.Tabc, or Temperature by Nonlinear Model, with T, a, b, and c being the parameters to be estimated, will be used to select the optimal wavelengths. It will focus on minimizing a cost function using the least squares method. With this model, we will sequentially choose the optimal wavelengths one after the other using an inverse method, which consists of fixing the temperature and finding the wavelength corresponding to that temperature. The first wavelength obtained will be used to calculate the second. This principle will be applied to find the second, third, and fourth wavelengths. Each wavelength must be tested against various criteria to minimize measurement errors in the temperature.

KEYWORDS: Multi Spectral Pyrometer, Wavelength, Infrared Radiation, Temperature, Steel, Austenization

I. INTRODUCTION

Temperature is a very essential physical quantity in manufacturing. Most of the time, thermometers are used to measure it, placing the object in direct contact with the temperature being measured. However, this technique is completely unsuitable for moving objects, objects located in hazardous areas, objects with poor thermal conductivity, objects with deformable surfaces, and especially for very high temperatures. Steels are known for their significant nonlinear selective emissivity. The metallurgical industries are particularly affected by these problems, for example, in the heat treatment of metals. The Quadri spectral pyrometer is among the best solutions for overcoming these issues. This is why the multispectral method is adopted for wavelength selection in the design of such a pyrometer.

II. LAW OF ELECTROMAGNETIC RADIATION

2.1 LAW OF PLANCK

Given a black body at temperature, we can calculate the energy density of its radiation. The calculations rely on the assumption that the electromagnetic field within the black body's limited cavity is equivalent to a set of independent harmonic oscillators in thermodynamic equilibrium at temperature T and obeying Boltzmann statistics. It can be shown that the black body's radiance is equal to the energy density of the radiation multiplied by λ, where radiance is the ratio of the luminous intensity, or energy density, of the radiation to the emitting surface area.

Consider a black body at temperature T, we can calculate the energy density of the radiation from this body. The calculations rely on the assumption that the electromagnetic field in the limited cavity of the black body is equivalent to a set of independent harmonic oscillators in thermodynamic equilibrium at temperature T and obeying Boltzmann statistics. It can be shown that the radiance $L_\lambda^0(T)$ of the black body is equal to the energy density of the radiation

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multiplied by $\frac{4\pi}{c}$, where the radiance is the ratio of the luminous intensity or energy density of the radiation to the emitting surface.

$$L_\lambda^0(T) = \frac{2hc^2\lambda^{-5}}{exp\left(\frac{hc}{k\lambda T}\right) - 1}$$

where h = 6 ,6255x10^{-34}Js is constant of Planck, k = 1,38x10^{-23} JK^{-1} constante of Boltzmann, c = 2,996x10^{8} ms^{-1} is the speed of electromagnetic waves in a vacuum.

This formula is also used with the so-called Planck constants C_1 and C_2 :

$$L_\lambda^0(T) = \frac{C_1\lambda_i^{-5}}{\exp\left(\frac{C_2}{\lambda_i T}\right) - 1} \quad \text{whith } C_1 = 2hc^2 \text{ and } C_2 = \frac{hc}{k}$$

2.2. DIFFERENT REGIONS OF THE INFRARED SPECTRUM

The infrared range is relatively broad, covering wavelengths from 0.8 µm to 1000 µm. Within this wavelength range, three regions are generally distinguished: near-infrared, mid-infrared, and far-infrared. The near-infrared spectrum lies between wavelengths of 0.8 µm and 2.5 µm.

2.3. DEFINITION OF SPECTRAL EMISSIVITY

The ratio between the monochromatic luminance of the real source $L_\lambda(T)$ and that of the black body $L_\lambda^0(T)$, for the same values of wavelength λ and temperature T, defines the monochromatic emissivity or spectral emissivity ε_λ of the source.

$$\varepsilon_\lambda = \frac{L_\lambda(T)}{L_\lambda^0(T)}$$

In general, spectral emissivity depends on the source, wavelength λ, temperature T, and direction of emission. The total emissivity, on the other hand, is defined by the following relationship:

$$\varepsilon_t = \int_0^\infty \varepsilon_\lambda d\lambda$$

The luminance of a black body does not depend on the direction of emission, and if the same is true for the real source (radiating source according to Lambert's law), the spectral emissivity also does not depend on the direction of emission.

2.4. SPECTRAL EMISSIVITY OF METALS

The wavelength dependence of emissivity can be expressed in several forms, but we will consider those that can fit experimental measurements or simplify the analysis. Most surfaces have emissivity that varies with wavelength and temperature. The emissivity of metallic surfaces in the visible and near-infrared wavelengths often exhibits a polynomial wavelength dependence.

$$\varepsilon_\lambda = c_0 + c_1\lambda + c_2\lambda^2 + ... + c_n\lambda^n$$

In our case, we use the second-order polynomial model: $\varepsilon_\lambda = a + b\lambda + c\lambda^2$

But in theory, emissivity depends on the material, the nature of its surface, the temperature, the wavelength, and possibly the measurement setup used. In the fig.1, since metals often reflect radiation, they are generally characterized by a low,

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nonlinear degree of emission, highly dependent on the surface structure and tending towards longer wavelengths. This dependence can lead to different and unreliable measurement results.

When selecting appropriate thermal measuring instruments, care should be taken to ensure that the infrared radiation is measured at a specific wavelength and within a temperature range where the metals exhibit a relatively high degree of emission.

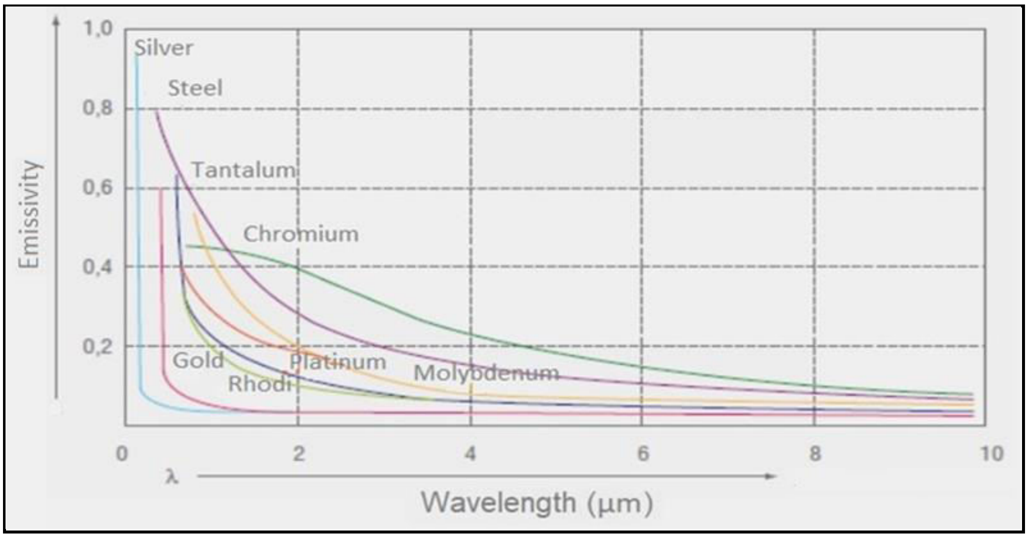

Fig.1 Spectral emission degree of metals

2.5. AUSTENITIZATION OF STEELS

The purpose of austenitization is to dissolve carbon and, possibly, precipitated alloying elements in the form of carbides. To achieve this, it is necessary to create conditions where carbon is soluble in iron, that is, to induce, through heating, the transformation of iron into iron. In the Fig. 2, the austenization temperature range is between 1000.15K and 1421.15K.

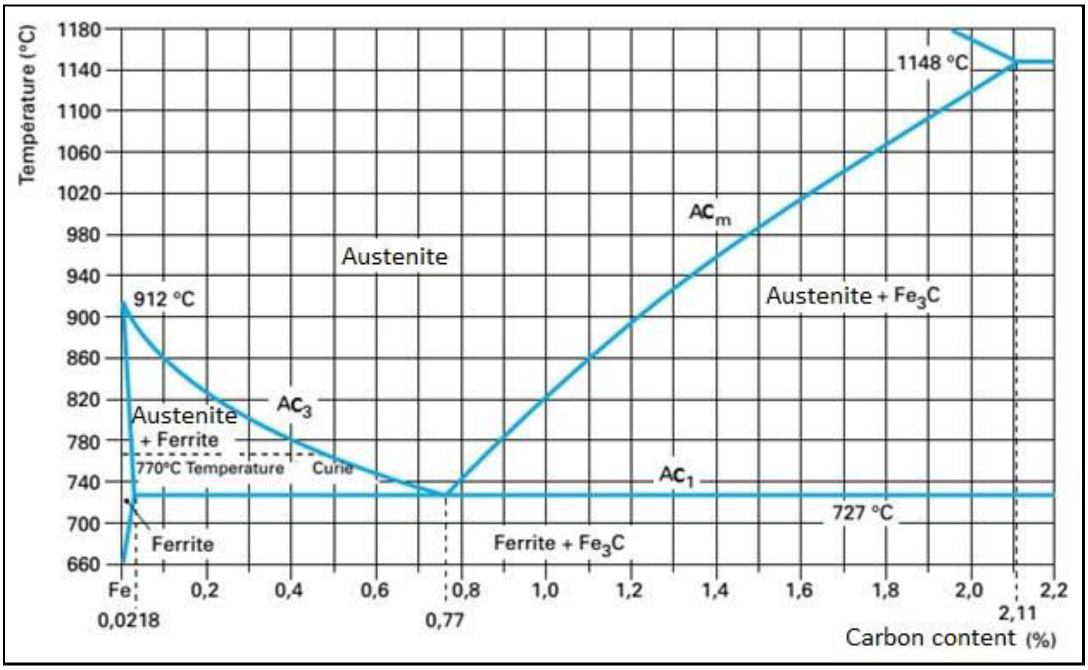

Fig. 2 FeC diagram of the steel domain

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In the context of mass heat treatment, austenitization comprises two steps:
- Heating to the so-called austenitization temperature;
- Holding at this temperature.

III. MULTI-SPECTRAL METHOD BASED ON PLANCK'S LAW

3.1.PRINCIPLE OF QUAD SPECTRAL PYROMETER

In the fig.3 The radiation from the source is filtered by optical systems which allow the four different spectra to pass through and converge them respectively towards the four identical detection systems.

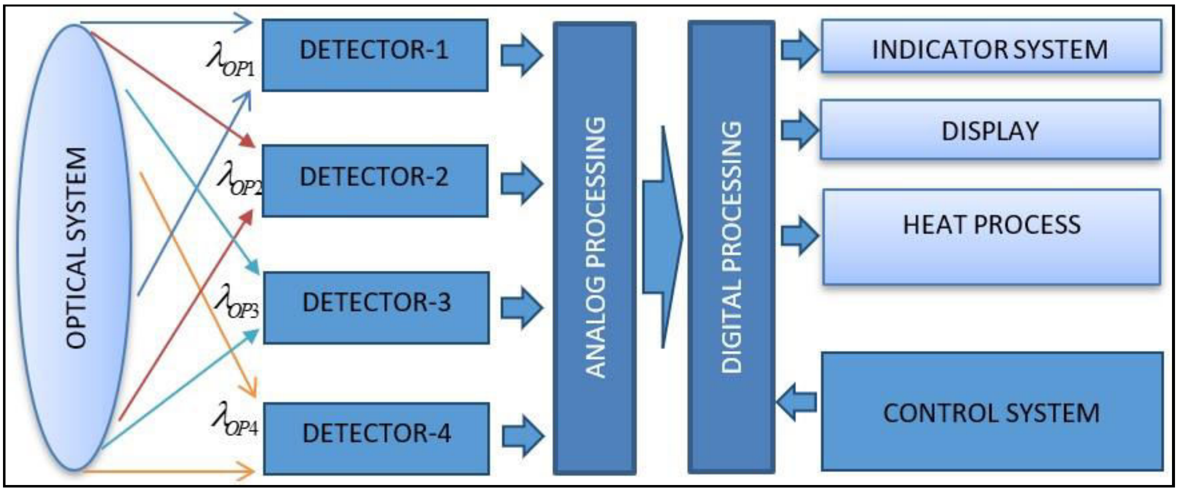

Fig. 3 General principle of quadrispectral pyrometers

3.2.PRESENTATION OF THE TNL.TABC MODEL

The goal is to determine the temperature of the steel during heat treatment along with its emissivity. The model "TNL.Tabc" stands for Temperature by Nonlinear Model, where T, a, b, and c are the parameters to be estimated. This model is unbiased and based on estimating fluxes expressed using Planck's law. It will also incorporate polynomial modeling of the emissivity up to the second order of the overall spectral transfer function of the measurement chain using coefficients (a, b, c). The flux as a function of wavelength and temperature is given by $L_{\lambda}\left(T,a,b,c\right)$

$$L_{\lambda_i}\left(T,a,b,c\right)=\left(a+b\lambda_i+c\lambda_i^2\right)\frac{C_1\lambda_i^{-5}}{\exp\left(\frac{C_2}{\lambda_i T}\right)-1}$$

Whith $\varepsilon_{\lambda_i}=a+b\lambda_i+c\lambda_i^2$ the spectral emissivity.

The estimation of the parameters $\{T,a,b,c\}$ will then be carried out by minimizing the function $J\left(T,a,b,c\right)$, in which $L_{\lambda_i}^{exp}$ designates the experimental spectral flux measured at the wavelength λ_i, and $L_{\lambda_i}\left(T,a,b,c\right)$ is the theoretical spectral flux at the wavelength λ_i.

$$J\left(T,a,b,c\right)=\sum_{i=1}^{4}\left(L_{\lambda_i}^{exp}-L_{\lambda_i}\left(T,a,b,c\right)\right)^2$$

$$J\left(T,a,b,c\right)=\left(L_{\lambda_1}^{exp}-L_{\lambda_1}\left(T,a,b,c\right)\right)^2+\ldots+\left(L_{\lambda_4}^{exp}-L_{\lambda_4}\left(T,a,b,c\right)\right)^2$$

Note : The subscript 4 designates the four (04) wavelengths for estimating the four parameters $\{T,a,b,c\}$. So we have four (04) equations for the theoretical flows $L_{\lambda_1}\left(T,a,b,c\right)$, $L_{\lambda_2}\left(T,a,b,c\right)$, $L_{\lambda_3}\left(T,a,b,c\right)$ et $L_{\lambda_4}\left(T,a,b,c\right)$.

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3.3.MODEL FOR THE SEQUENTIAL WAVELENGTH SELECTION METHOD

The method used for temperature estimation is based on minimizing a cost function using a least-squares method. With this method, we will define the optimal wavelengths using the inverse method. This method involves fixing the temperature and finding the wavelength corresponding to that temperature. These wavelengths minimize the standard deviation of the estimated temperature. The determination of the various optimal wavelengths will be performed using the cost function $J(T,a,b,c)$ associated with the "TNL.Tabc" model.

The statistical properties of the parameter estimator associated with the TNL.Tabc model and the parameters provided by the least squares method are given by the variance-covariance matrix. Using this matrix, we can determine the standard deviations σ_β of the different parameters, and in particular, that of temperature σ_T . The TNL.Tabc model is a nonlinear model ; therefore, we will use the approximate expression of the ordinary least squares variance-covariance matrix, which is given for a parameter vector $\beta=(T,a,b,c)$, under the assumption of additive, independent, identically distributed noise (constant variance σ^2_{noise} and zero mean), by:

$$\mathrm{cov}(\beta)=\begin{bmatrix} \sigma_T^2 & \mathrm{cov}(T,a) & \mathrm{cov}(T,b) & \mathrm{cov}(T,c) \\ \mathrm{cov}(T,a) & \sigma_a^2 & \mathrm{cov}(a,b) & \mathrm{cov}(a,c) \\ \mathrm{cov}(T,b) & \mathrm{cov}(a,b) & \sigma_b^2 & \mathrm{cov}(b,c) \\ \mathrm{cov}(T,c) & \mathrm{cov}(a,c) & \mathrm{cov}(b,c) & \sigma_c^2 \end{bmatrix}=\left(X^t X\right)^{-1}\sigma^2_{noise}$$

And the standard deviation on the temperature σ_T is given as a function of the standard deviation of the noise σ_{noise}, by:

$$\sigma_T=\sqrt{\left(X^t X\right)^{-1}}\sigma_{noise}$$

With X the sensitivity matrix associated with the variance-covariance matrix, defined by :

$$X=\begin{bmatrix} \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial c} \end{bmatrix}$$

The standard deviation of the noise will be taken to be the value obtained experimentally with the infrared camera, and having a value of $\sigma_{noise}\approx 8,97.10^4\,Wm^{-2}$, that is 7,43.10^{-3} % of the maximum of Planck's law.

3.4. PSEUDO-OPTIMAL METHOD FOR WAVELENGTH SELECTION

The pseudo-optimal method consists of sequentially selecting wavelengths while respecting all the different criteria. These wavelengths are those that minimize the standard deviation of the temperature at a fixed temperature, thus finding the temperature range for the heat treatment of steels. In our case, we will use a fixed design temperature (T_F) of 1073.15K, 1173.15K, 1223.15K, 1273.15K, and 1373.15K.

Selection of the first optimal wavelengths

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The method of sequential selection of "pseudo-optimal" wavelengths consists of choosing for the first wavelength filter λ_{OP1}, the one which minimizes the standard deviation σ_T on the temperature, assuming that the measurement is mono spectral. The cost function $J(\beta)$ consists of only one parameter : the temperature T.

$$J(T)=\left(L_{\lambda_1}^{exp}-L_{\lambda_1}(T,a,b,c)\right)^2$$

The temperature T is then the only parameter to estimate. The sensitivity matrix X is composed only of the first column and first row.

$$X=\left[\frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T}\right]$$

The minimization of the cost function $J(T)$, involves the sensitivity matrix X of the flux at the various parameters to be estimated. The first optimal wavelength λ_{OP1} will minimize this standard deviation.

Selection of the second optimal wavelengths
The selection of the second filter is performed by setting a = 1, b = 1, and $\lambda_1=\lambda_{OP1}$. And looking for second wavelength, the shortest that minimizes the local standard deviation of temperature in the *TNL.Ta* model. The function cost $J(T,a)$ and the sensitivity matrix X are respectively composed as follows:

$$J(T,a)=\sum_{i=1}^{2}\left(L_{\lambda_i}^{exp}-L_{\lambda_i}(T,a,b,c)\right)^2=\left(L_{\lambda_1}^{exp}-L_{\lambda_1}(T,a,b,c)\right)^2+\left(L_{\lambda_2}^{exp}-L_{\lambda_2}(T,a,b,c)\right)^2$$

$$X=\begin{bmatrix}\frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a}\\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a}\end{bmatrix}$$

Selection of the third optimal wavelengths
For the third wavelength, it is obtained by minimizing the cost function $J(T,a,b)$ with the sensitivity matrix X associated with the model TNL.Tab by fixing $\lambda_1=\lambda_{OP1}$ and $\lambda_2=\lambda_{OP2}$.

$$J(T,a,b)=\sum_{i=1}^{3}\left(L_{\lambda_i}^{exp}-L_{\lambda_i}(T,a,b,c)\right)^2=\left(L_{\lambda_1}^{exp}-L_{\lambda_1}(T,a,b,c)\right)^2+\ldots+\left(L_{\lambda_3}^{exp}-L_{\lambda_3}(T,a,b,c)\right)^2$$

$$X=\begin{bmatrix}\frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial b}\\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial b}\\ \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial b}\end{bmatrix}$$

Selection of the fourth and last optimal wavelengths
The fourth optimal wavelength will be obtained on the same principle as how to obtain the second and the third optimal wavelength by fixing a = 1, b = 1, c=1, $\lambda_1=\lambda_{OP1}$, $\lambda_2=\lambda_{OP2}$ and $\lambda_3=\lambda_{OP3}$. The cost function $J(T,a,b,c)$ and the sensitivity matrix X associated with the model TNL.Tabc are respectively represented as follows:

$$J(T,a,b,c)=\sum_{i=1}^{4}\left(L_{\lambda_i}^{exp}-L_{\lambda_i}(T,a,b,c)\right)^2=\left(L_{\lambda_1}^{exp}-L_{\lambda_1}(T,a,b,c)\right)^2+\ldots+\left(L_{\lambda_4}^{exp}-L_{\lambda_4}(T,a,b,c)\right)^2$$

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$$X = \begin{bmatrix} \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_1}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_2}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_3}(T,a,b,c)}{\partial c} \\ \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial T} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial a} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial b} & \frac{\partial L_{\lambda_4}(T,a,b,c)}{\partial c} \end{bmatrix}$$

IV. CRITERIA FOR SELECTING THE OPTIMAL WAVELENGTHS

Our pyrometer must be very sensitive to the temperature between 975.15 °K and 1473.15 °K. This range borders the temperature range of the heat treatment of steels which is between 1000.15 °K and 1421.15 °K [8]. So that we can have better optimal wavelengths, we will try to find optimal wavelengths from the temperature set (TS) at 1073.15 °K, 1173.15 °K, 1223.15 °K, 1273.15 °K and 1373.15 °K.

.1. PYROMETER SPECTRAL RANGE CRITERION

Our first criterion for selecting optimal wavelengths is the spectral range of our pyrometer, which operates in the band between 0.8µm and 2.5µm. Measuring the temperature of a metal requires the use of short wavelengths to avoid the relative error due to emissivity.

Table.1 Optimal wavelengths pre-selected according to the pyrometer's spectral range

	Channel 1		Channel 2		Channel 3		Channel 4	
Tc[K]	λ_{OP1} [µm]	σ_T [K]	λ_{OP2} [µm]	σ_T [K]	λ_{OP3} [µm]	σ_T [K]	λ_{OP4} [µm]	σ_T [K]
1073.15	2.246	0.000959	1.535	0.005373	1.186	0.043606	0.967	0.461628
							1.392	0.471311
							2.000	0.132117
					1.945	0.038898	1.099	0.128315
							1.719	0.484844
							2.122	0.659303
1173.15	2.054	0.000671	1.403	0.003772	1.085	0.030674	0.884	0.323962
							1.273	0.333100
							1.896	0.090029
					1.778	0.027332	1.005	0.090259
							1.572	0.340205
							1.939	0.465602
1223.15	1.970	0.000568	1.346	0.003185	1.041	0.025831	0.848	0.272897
							1.222	0.279541
							1.821	0.075742
					1.707	0.023056	0.965	0.075973
							1.509	0.287155
							1.857	0.392977
1273.15	1.893	0.000684	1.294	0.002712	1	0.022004	0.815	0.232649
							1.174	0.238138
							1.749	0.064520
					1.640	0.019644	0.900	0.065571
							1.449	0.244430
							1.788	0.334194
1373.15	1.755	0.000357	1.199	0.002005	0.927	0.016302	0.756	0.172321
							1.088	0.176781
							1.622	0.047746
					1.520	0.014494	0.855	0.047922
							1.343	0.180200
							1.658	0.245986

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Multispectral measurement minimizes error, therefore choosing a short wavelength gives better accuracy on temperature. We observe that each time a wavelength is added, the standard deviation deteriorates by about a factor of 10. So with this method, the more the number of spectra increases, the measurement error also increases, whereas our goal is to minimize it as much as possible.

4.2. CRITERIA FOR THE MINIMUM DIFFERENCE BETWEEN TWO SUCCESSIVE WAVELENGTHS

To avoid amplifying the measurement error, while remaining as close as possible to minimize the measurement error due to the spectral variation of the emissivity, the minimum difference between the two successive wavelengths must be respected.

$$\Delta_{M\,\mathrm{in}}\lambda_{ji} = \left|\lambda_j - \lambda_i\right| \succ \left.\frac{T\lambda_j^2}{C_2}\right|_{\lambda_j \succ \lambda_i}$$

The minimum difference between the first and second wavelengths will therefore be:

$$\lambda_{OP1} - \lambda_{OP2} \geq \Delta_{M\,\mathrm{in}}\lambda_{1-2}$$

The second maximum wavelength will be selected according to this relationship:

$$\lambda_{OP2Max} \leq \lambda_{OP1} - \Delta_{M\,\mathrm{in}}\lambda_{1-2}$$

The difference between the second and third wavelengths will therefore be:

$$\lambda_{OP2} - \lambda_{OP3} \geq \Delta_{M\,\mathrm{in}}\lambda_{2-3}$$

The maximum value of the third wavelength is then:

$$\lambda_{OP3Max} \leq \lambda_{OP2} - \Delta_{M\,\mathrm{in}}\lambda_{2-3}.$$

The same principle applies to the last and fourth optimal wavelength:

$$\lambda_{OP3} - \lambda_{OP4} \geq \Delta_{M\,\mathrm{in}}\lambda_{3-4},\ \lambda_{OP4Max} \leq \lambda_{OP3} - \Delta_{M\,\mathrm{in}}\lambda_{3-4}$$

The four optimal wavelengths selected respecting the criterion of minimum standard deviation on temperature and minimum difference between two successive wavelengths, for a temperature of 1073.15K, 1173.15K, 1223.15K, 1273.15K and 1373.15K will be represented in table.2.

In the infrared measurement, the standard deviation cannot exceed 5%. The largest values were obtained for the shortest wavelength and for wavelengths affected by atmospheric absorption. In the other infrared spectral ranges, the standard deviation between the first and last spectra was less than 2%.

Table.2 Optimal wavelength obtained from 1073.15K, 1173.15K, 1223.15K, 1273.15K and 1373.15K according to the criterion of $\Delta_{\min}\lambda$

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T_C[K]	λ_{OP} [µm]	σ_T [K]	σ_T [%]	$\Delta\lambda$ [µm]	$\Delta_{min}\lambda$ [µm]
1073.15	$\lambda_{OP1} = 2.246$	0.000959	0.000089	$\lambda_{OP1} - \lambda_{OP2} = 0.711$	$\lambda_{OP1} - \lambda_{OP2} = 0.411$
	$\lambda_{OP2} = 1.535$	0.005373	0.000501	$\lambda_{OP2} - \lambda_{OP3} = 0.349$	$\lambda_{OP2} - \lambda_{OP3} = 0.192$
	$\lambda_{OP3} = 1.186$	0.043606	0.004063	$\lambda_{OP3} - \lambda_{OP4} = 0.219$	$\lambda_{OP3} - \lambda_{OP4} = 0.114$
	$\lambda_{OP4} = 0.967$	0.461628	0.043016		
1173.15	$\lambda_{OP1} = 2.054$	0.000671	0.000057	$\lambda_{OP1} - \lambda_{OP2} = 0.651$	$\lambda_{OP1} - \lambda_{OP2} = 0.344$
	$\lambda_{OP2} = 1.403$	0.003772	0.000321	$\lambda_{OP2} - \lambda_{OP3} = 0.318$	$\lambda_{OP2} - \lambda_{OP3} = 0.160$
	$\lambda_{OP3} = 1.085$	0.030674	0.002614	$\lambda_{OP3} - \lambda_{OP4} = 0.201$	$\lambda_{OP3} - \lambda_{OP4} = 0.095$
	$\lambda_{OP4} = 0.884$	0.323962	0.027614		
1223.15	$\lambda_{OP1} = 1.970$	0.000568	0.000046	$\lambda_{OP1} - \lambda_{OP2} = 0.624$	$\lambda_{OP1} - \lambda_{OP2} = 0.329$
	$\lambda_{OP2} = 1.346$	0.003185	0.000260	$\lambda_{OP2} - \lambda_{OP3} = 0.305$	$\lambda_{OP2} - \lambda_{OP3} = 0.154$
	$\lambda_{OP3} = 1.041$	0.025831	0.002112	$\lambda_{OP3} - \lambda_{OP4} = 0.193$	$\lambda_{OP3} - \lambda_{OP4} = 0.092$
	$\lambda_{OP4} = 0.848$	0.272897	0.022311		
1273.15	$\lambda_{OP1} = 1.893$	0.000684	0.000054	$\lambda_{OP1} - \lambda_{OP2} = 0.599$	$\lambda_{OP1} - \lambda_{OP2} = 0.317$
	$\lambda_{OP2} = 1.294$	0.002712	0.000213	$\lambda_{OP2} - \lambda_{OP3} = 0.294$	$\lambda_{OP2} - \lambda_{OP3} = 0.148$
	$\lambda_{OP3} = 1.000$	0.022004	0.001728	$\lambda_{OP3} - \lambda_{OP4} = 0.185$	$\lambda_{OP3} - \lambda_{OP4} = 0.088$
	$\lambda_{OP4} = 0.815$	0.232649	0.018273		
1373.15	$\lambda_{OP1} = 1.755$	0.000357	0.000026	$\lambda_{OP1} - \lambda_{OP2} = 0.556$	$\lambda_{OP1} - \lambda_{OP2} = 0.293$
	$\lambda_{OP2} = 1.199$	0.002005	0.000146	$\lambda_{OP2} - \lambda_{OP3} = 0.272$	$\lambda_{OP2} - \lambda_{OP3} = 0.119$
	$\lambda_{OP3} = 0.927$	0.016302	0.001187	$\lambda_{OP3} - \lambda_{OP4} = 0.171$	$\lambda_{OP3} - \lambda_{OP4} = 0.082$
	$\lambda_{OP4} = 0.756$	0.172321	0.012549		

We observe that only one group of optimal wavelengths, obtained from each calculation temperature, meets the criterion of minimum distance between two successive optimal wavelengths.

Furthermore, the minimum required distance between two wavelengths is proportional to the longer of the two successive wavelengths.

We also note that all groups of optimal wavelengths with the lowest standard deviations fail to meet the criterion of minimum distance between two successive wavelengths.

From the temperature 1373.15K, the optimal wavelengths begin to enter to the visible region (λ_{OP4} = 0.756 µm), so the measurable temperature in the near-infrared spectral band does not exceed this value.

4.3.STANDARD DEVIATION ON THE TEMPERATURE FROM THE TEMPERATURE RANGE OF THE FLUXES OBTAINED FROM THE OPTIMAL WAVELENGTHS

In tha table-3, verification of the standard deviation of optimal wavelengths is almost necessary to know the errors on the temperature in the entire temperature range from 975.15K to 1473.15K of the austenization of steels.

Table.3 Standard deviation on temperature σ_T [K] from the pyrometer spectral range of optimal wavelengths obtained

T_C[K]	λ_{OP} [µm]	**Gamme de température du pyromètre**						
		975.15K	**1073.15K**	**1173.15K**	**1223.15K**	**1273.15K**	**1373.15K**	**1473.15K**
1073.15	$\lambda_{OP1} = 2.246$	0.001459	0.000959	0.000686	0.000595	0.000524	0.000420	0.000349
	$\lambda_{OP2} = 1.535$	0.003146	0.001559	0.000884	0.000693	0.000555	0.000378	0.000273
	$\lambda_{OP3} = 1.186$	0.011394	0.004336	0.001977	0.001408	0.001033	0.000600	0.000379
	$\lambda_{OP4} = 0.967$	0.056348	0.016485	0.006042	0.003911	0.002627	0.001305	0.000719
1173.15	$\lambda_{OP1} = 2.054$	0.001582	0.000982	0.000671	0.000571	0.000493	0.000382	0.000310
	$\lambda_{OP2} = 1.403$	0.004541	0.002068	0.001094	0.000832	0.000648	0.000419	0.000290
	$\lambda_{OP3} = 1.085$	0.021317	0.007281	0.003035	0.002078	0.001471	0.000801	0.000478
	$\lambda_{OP4} = 0.884$	0.138194	0.035367	0.011602	0.007152	0.004595	0.002106	0.001084
1223.15	$\lambda_{OP1} = 1.970$	0.001674	0.001011	0.000675	0.000568	0.000486	0.000371	0.000296
	$\lambda_{OP2} = 1.346$	0.005532	0.002417	0.001235	0.000925	0.000711	0.000448	0.000304
	$\lambda_{OP3} = 1.041$	0.029580	0.009576	0.003817	0.002564	0.001782	0.000940	0.000546
	$\lambda_{OP4} = 0.848$	0.219035	0.052467	0.016292	0.009805	0.006161	0.002715	0.001351

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1273.15	$\lambda_{OP1} = 1.893$	0.001789	0.001050	0.000685	0.000571	0.000484	0.000343	0.000286
	$\lambda_{OP2} = 1.294$	0.006791	0.002847	0.001406	0.001038	0.000786	0.000484	0.000321
	$\lambda_{OP3} = 1.000$	0.041610	0.012759	0.004862	0.003202	0.002185	0.001116	0.000631
	$\lambda_{OP4} = 0.815$	0.349686	0.078430	0.023061	0.013551	0.008329	0.003529	0.001697
1373.15	$\lambda_{OP1} = 1.755$	0.002101	0.001164	0.000725	0.000592	0.000492	0.000357	0.000274
	$\lambda_{OP2} = 1.199$	0.010626	0.004095	0.001886	0.001350	0.000995	0.000582	0.000370
	$\lambda_{OP3} = 0.927$	0.084590	0.023272	0.008105	0.005130	0.003377	0.001616	0.000863
	$\lambda_{OP4} = 0.756$	0.917752	0.180401	0.047544	0.026628	0.015659	0.006132	0.002754

We have four (4) optimal wavelengths that respect the minimum difference between two (2) successive wavelengths for a given temperature. As the calculation temperature increases up to 1373.15 K, the optimal wavelengths decrease to at least 0.140 µm.

We also observe that the standard deviation of the temperature improves as the measurement temperature increases. Therefore, temperature errors decrease for measurements at high temperatures.

As the wavelength decreases, the standard deviation deteriorates, i.e., it increases (T_C=1223.15K: λ_{OP1} = 1.970µm, λ_{OP2}=1.346 µm, λ_{OP3} = 1.041 µm, λ_{OP4} = 0.848 µm. If we apply these wavelengths to T=1073.15K, we have respectively a standard deviation of 0.001011K, 0.002417K, 0.001023K, 0.052467K).

The standard deviation deteriorates rapidly if the wavelength exceeds the lower limit of the near-infrared range (λ_{OP4} = 0.756 µm calculated from the temperature at T_C = 1373.15K; the standard deviations at this wavelength for the temperature range of our pyrometer are at T = 975.15K -> σ_T = 0.917752K and at T = 1473.15K -> σ_T = 0.002754K).
The temperature range of our pyrometer is from 975.15K to 1473.15K. We observe that the optimal wavelengths obtained at T_C = 1073.15 K have a lower standard deviation compared to those obtained at TC = 1373.15 K. The worst standard deviation is 0.056348K at T=975.15K for T_C=1073.15K, while it is 0.917752K at T=975.15K for T_C=1373.15K. Therefore, the standard deviation increases, meaning the measurement error increases, as the wavelength decreases and the temperature being measured becomes significant.

4.3. SENSITIVITY OF THE FLUX TO TEMPERATURE AND WAVELENGTH

The model called TNL.Tabc involves taking temperature measurements without fully controlling all influencing factors. However, certain precautions must be taken to minimize measurement error in temperature. Our working range lies on the increasing portion of the Planck curve because the reduced sensitivities of the flux to temperature χ_T and wavelength χ_λ are enhanced at shorter wavelengths.

$$\chi_T = \frac{1}{L_\lambda(T)}\frac{dL_\lambda(T)}{dT}, \quad \chi_\lambda = \frac{1}{L_\lambda(T)}\frac{dL_\lambda(T)}{d\lambda}$$

The wavelengths obtained should provide greater sensitivity to both temperature and wavelength.
In table-4, we show the sensitivity of the flux obtained from the optimal wavelengths at temperature and in table-5, flux sensitivity to wavelength in the pyrometer temperature range will be presented.

Table.4 Sensitivity of the flux obtained from the optimal wavelengths at temperature

T_C[K]	λ_{OP} [µm]	**Gamme de température du pyromètre**						
		975.15K	**1073.15K**	**1173.15K**	**1223.15K**	**1273.15K**	**1373.15K**	**1473.15K**
1073.15	$\lambda_{OP1} = 2.246$	0.006773	0.005576	0.004674	0.004304	0.003978	0.003429	0.002990
	$\lambda_{OP2} = 1.535$	0.009898	0.008140	0.006813	0.006268	0.005786	0.004976	0.004326
	$\lambda_{OP3} = 1.186$	0.012810	0.010534	0.008815	0.008109	0.007485	0.006435	0.005591
	$\lambda_{OP4} = 0.967$	0.015711	0.012919	0.010811	0.009945	0.009179	0.007891	0.006856
1173.15	$\lambda_{OP1} = 2.054$	0.007402	0.006091	0.005102	0.004697	0.004339	0.003737	0.003255
	$\lambda_{OP2} = 1.403$	0.010829	0.008905	0.007452	0.006856	0.006328	0.005442	0.004729
	$\lambda_{OP3} = 1.085$	0.014002	0.115147	0.009635	0.008863	0.008181	0.007033	0.006111
	$\lambda_{OP4} = 0.884$	0.017186	0.014132	0.011826	0.010879	0.010041	0.008632	0.007500

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1223.15	λ_{OP1} = 1.970	0.007716	0.006348	0.005317	0.004894	0.004520	0.003892	0.003389
	λ_{OP2} = 1.346	0.011287	0.009282	0.007767	0.007146	0.006596	0.005671	0.004929
	λ_{OP3} = 1.041	0.014594	0.012001	0.010042	0.009238	0.008527	0.007330	0.006369
	λ_{OP4} = 0.848	0.017916	0.014732	0.012328	0.011341	0.010467	0.008998	0.007818
1273.15	λ_{OP1} = 1.893	0.008029	0.006605	0.005531	0.005090	0.004701	0.004047	0.003522
	λ_{OP2} = 1.294	0.011741	0.009655	0.008079	0.007432	0.006861	0.005898	0.005126
	λ_{OP3} = 1.000	0.015193	0.012493	0.010454	0.009617	0.008876	0.007631	0.006630
	λ_{OP4} = 0.815	0.018641	0.015329	0.012827	0.011800	0.010891	0.009363	0.008135
1373.15	λ_{OP1} = 1.755	0.008658	0.007122	0.005962	0.005486	0.005066	0.004359	0.003792
	λ_{OP2} = 1.199	0.012671	0.010420	0.008719	0.008021	0.007403	0.006365	0.005531
	λ_{OP3} = 0.927	0.016389	0.013477	0.011277	0.010374	0.009575	0.008231	0.007152
	λ_{OP4} = 0.756	0.020096	0.016525	0.013828	0.012721	0.011741	0.010093	0.008769

The sensitivity of the flux to temperature increases as the wavelength decreases. In the spectral band of our pyrometer, the temperature sensitivity of the flux applied at a given wavelength decreases as the temperature increases.
In the spectral band between 0.8 µm and 2.5 µm, the temperature sensitivity of the flux is significantly better at 975.15 K than at 1473.15 K, the upper limit of our measurement temperature. Therefore, the lower the measurement temperature, the better the temperature sensitivity of the flux.

Table.5 Flux sensitivity to wavelength in the pyrometer temperature range

T_C[K]	λ_{OP} [µm]	**Pyrometer temperature range**						
		975.15K	**1073.15K**	**1173.15K**	**1223.15K**	**1273.15K**	**1373.15K**	**1473.15K**
1073.15	λ_{OP1} = 2.246	708783	438419	215437	118132	28815.5	-129307	-264699
	λ_{OP2} = 1.535	3017940	2433730	1949550	1737360	1541990	1194490	894948
	λ_{OP3} = 1.186	6295360	5315970	4503650	4147350	3819100	3234490	2729580
	λ_{OP4} = 0.967	10640700	9167330	7945180	7409060	6915060	6035040	5274610
1173.15	λ_{OP1} = 2.054	1072800	748273	480169	363010	255370	64539.6	-99164.8
	λ_{OP2} = 1.403	3947540	3247910	2667830	2413500	2179270	1762380	1402700
	λ_{OP3} = 1.085	7950900	6780620	5809910	5384100	4991770	4292950	3689210
	λ_{OP4} = 0.884	13263700	11500700	10038200	9396680	8805530	7752420	6842330
1223.15	λ_{OP1} = 1.970	1273700	920437	628392	500698	383333	175134	-3618.14
	λ_{OP2} = 1.346	4446190	3685950	3055540	2779110	2524490	2071220	1680020
	λ_{OP3} = 1.041	8840230	7568920	6514380	6051800	5624470	4866320	4210320
	λ_{OP4} = 0.848	14664100	12748200	11158900	10461700	9819330	8674880	7685850
1273.15	λ_{OP1} = 1.893	1486270	1103270	786471	647884	520461	294298	99976.3
	λ_{OP2} = 1.294	4965930	4143300	3461080	3161900	2886300	2395610	1971990
	λ_{OP3} = 1.000	9784980	8407280	7264470	6763160	6301240	5478390	4767390
	λ_{OP4} = 0.815	16124000	14049800	12329300	11574500	10879000	9639990	8569220
1373.15	λ_{OP1} = 1.755	1952330	1506060	1136600	974840	826027	561657	334207
	λ_{OP2} = 1.199	6114380	5156120	4361330	4012740	3691580	3119630	2625670
	λ_{OP3} = 0.927	11811500	10208300	8878370	8294970	7757400	6799760	5972200
	λ_{OP4} = 0.756	19255100	16844500	14844900	13967800	13159500	11719500	10475000

The sensitivity of flux to wavelength increases as the wavelength decreases. Therefore, measurements using wavelength spectra in the near-infrared region are highly recommended.

The flux sensitivity to wavelength of wavelengths obtained from the upper temperature range is increasingly better than that obtained at the lower limit within the temperature range to be measured.

The existence of negative values explains why the use of these wavelengths obtained at T_C between 1073.15 K and 1223.15 K, i.e., wavelengths greater than 1970 µm, can lead to significant errors if the temperature to be measured is above 1373.15 K. Therefore, these wavelengths do not cover, in terms of flux sensitivity, the temperatures required for the austenitization of steels.

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V. CONCLUSION

The TNL.Tabc model, based on Planck's law, allows for the simultaneous determination of temperature and spectral emissivity. This model enabled us to sequentially select the optimal wavelengths for a multispectral pyrometer designed for the heat treatment of steels.

Among the optimal wavelengths obtained from 1073.15 K, 1173.15 K, 1223.15 K, 1273.15 K, and 1373.15 K, only a group of four wavelengths meets the criterion of minimum distance between two successive wavelengths. Therefore, selecting these wavelengths based on the minimum standard deviation is insufficient.

All the optimal wavelengths exhibit good temperature sensitivity between 975.15 K and 1473.15 K. However, the fluxes at these optimal wavelengths are not at all sensitive if the temperature is between 1373.15K and 1473.15K. In addition, their standard deviation is far from exceeding the 5% error limit.

In conclusion, only the optimal wavelengths obtained from a temperature of 1273.15 K meet all the selection criteria for the four optimal wavelengths for a multispectral pyrometer intended for the heat treatment of steels. Therefore, with the sequential least-squares method for selecting optimal wavelengths in the TNL.Tabc model, it is better to use the temperature towards the upper limit of the temperature range (975.15 K to 1473.15 K) to be measured than the temperature towards the lower limit. And the closer one gets to the upper limit, the more the wavelengths reach the visible spectrum.

For the austenization of steels, the temperature varies approximately between 1073.15K and 1173.15K, the use of wavelengths in the near-infrared region while respecting the permeability of the area is completely recommended because all parameters such as flux sensitivity to wavelength and temperature, standard deviation on the temperature to the temperature range, the minimum difference between the two successive wavelengths are all acceptable.

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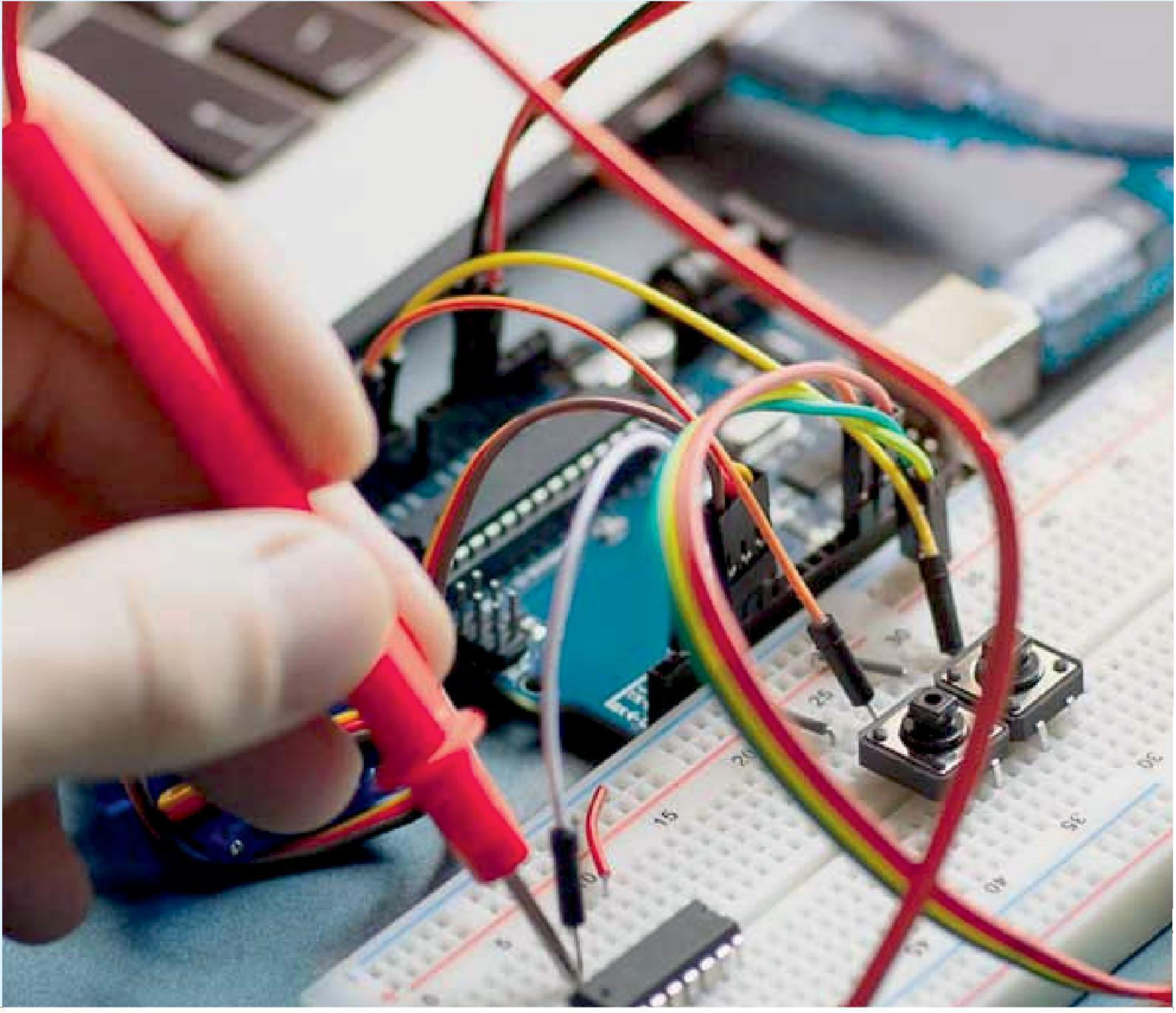

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