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Thermal Analysis for Home Vacuum Packing

Uberlândia

2021

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Undergraduate Thesis presented to the Graduate Program in Mechanical Engineering of the University of Uberlândia as a partial requirement to obtain the graduate-level in Mechanical Engineering

University of Uberlândia

Graduate Program in Mechanical Engineering

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Uberlândia

2021

Statement of Authorship

I hereby declare that the thesis submitted is my own work. All direct or indirect sources used are acknowledged as references. I further declare that I have not submitted this thesis at any other institution in order to obtain a degree.

To my friends and family. I am nothing without them.

Acknowledgements

I would like to express my special thanks to my supervisor PhD João Rodrigo Andrade for his invaluable support and encouragement regarding conceptual doubts about the project, the research, and the general acquisition of knowledge.

To my friends and family, my deepest gratitude for your incentive throughout my studies.

Finally, thanks to all companies that provide scientific content online and others that develop engineering software that allow us to develop this type of project at home.

"Heat transfer is a branch of engineering science which seeks to determine the rate of energy transfer between bodies as a result of temperature differences. The concept of rate is the basic difference between heat transfer and thermodynamics. Thermodynamics deals with systems in equilibrium and is concerned with the amount of heat required to change a system from one state to another. Thermodynamics does not answer the question of "how fast" a change is accomplished. It is the science of heat transfer that deals with this question."

John Vlachopoulos
David Strutt

Resumo

As técnicas de conservação dos alimentos estão entre os principais possibilitadores do surgimento das primeiras civilizações. Diariamente, vidas são salvas como resultado de nossa crescente compreensão dos processos de deterioração dos alimentos e de como melhor preservá-los. O presente estudo é motivado pela possibilidade de desenvolver um selador a vácuo caseiro o mais barato e eficiente possível. Para atingir os objetivos, desenvolvemos um sistema térmico e calculamos numericamente os resultados com um código fornecido nos anexos. A maioria dos princípios físicos relacionados à análise térmica são, aqui, considerados e explicados. Várias análises foram efetuadas e os resultados são explicados, o que, em conjunto com o código, permite ao leitor realizar testes por conta própria e compreender seus resultados. Além disso, uma análise de sensibilidade foi realizada para todas as considerações iniciais de parâmetros, definindo quais são relevantes e quais não são. Por exemplo, sobre a influência das dimensões geométricas, verificou-se que apenas o diâmetro do filamento é relevante, pois um fio maior ajuda a derreter mais rapidamente, mesmo que a custo do aumento do consumo da bateria. Também notamos que por ser um procedimento bastante rápido e a área superficial dos componentes ser pequena, as perdas de calor por convecção e radiação não são significativas, menos de $0,3\%$. O que acontece é que a energia que não aquece ou derrete o saco plástico está aumentando as temperaturas do filamento e da placa, outra propriedade relevante, e a mais importante, é a tensão elétrica, quanto mais alta, mais rápido o material derrete. Em relação às propriedades do ambiente, observamos que as alterações nos valores pouco influenciam os resultados, o que significa que o aparelho funciona em qualquer lugar, em qualquer clima ou em qualquer estação do ano. Encontramos um sistema ideal que pode derreter um saco comum de polietileno de baixa densidade em 2 *segundos* com a temperatura máxima do sistema subindo para apenas $120,3°C$ usando uma pilha alcalina AAA simples de $1,5\ V$. Mesmo com os resultados alcançados, mais estudos devem ser feitos em relação ao sistema de vácuo, a carcaça e o sistema elétrico.

Keywords: Transferência, Calor, Termodinâmica, Empacotamento, Vácuo, Dispositivo, Engenharia, Mecânica, Transferência de Calor, Engenharia Mecânica, Seladora a Vácuo.

Abstract

Food preservation techniques are among the main enablers of civilization. Every day, lives are saved as a result of our growing understanding of the processes of food deterioration. The present study is motivated by the theoretical study of the development of a homemade vacuum sealer as cheap and efficient as possible. In order to reach the goals of the present work, we developed a thermal system and numerically calculated the results with a script provided in the annexes. Most of the physical principles relating to thermal analysis are herein considered and explained. Several analyzes were made, and the results are explained, which, along with the script, gives the reader the possibility to take tests on their own and have an understanding of their results. Furthermore, a sensitivity analysis is performed for all parameters considerations, defining which ones are relevant, and which are not. E.g., the influence of the geometrical dimensions, it was found that only the wire diameter is relevant since a larger wire help melting more quickly but enhances the battery consumption. We noticed that since this is a fairly rapid procedure, and the surface's area of the components are small, the heat loss through convection and radiation are not significant, less than 0.3%. Mainly, the energy that is not heating nor melting the bag is rising the temperatures of the wire and the plate. Another relevant input, and the most important one, is the electrical voltage, the higher it is, the faster the material melts. Regarding the environmental properties, we observed that alterations barely change the results, meaning that the device work everywhere, at any weather or in any season. We found an optimal system that can melt a common low density polyethylene bag in 2 *seconds* with a maximum system temperature rising up to just $120.3°C$ by using a simple 1.5 V AAA alkaline battery. Even with the achieved results, more studies must be done in relation to the vacuum system, the casting, and the electrical system.

Keywords: Heat, Transfer, Thermodynamics, Vacuum, Packing, Device, Mechanical, Engineering, Heat Transfer, Mechanical Engineering, Vacuum Sealer.

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1 Introduction

The race against food spoilage dates back to ancient times. Before, with more natural procedures, but with the same objective: to extend as much as possible the time the product maintains its basic characteristics, avoiding undesirable alterations.

As stated by Amit et al. [2017], food is an organic substance consumed because of the nutrients it can provide. The majority is of vegetable or animal origin and contain carbohydrates, proteins, lipids, minerals, and other organic substances, in addition to being hydrated, that is, contains water.

A spoiled food is one that has lost its edibility and nutritional values. That can happen through physical, microbiological or chemical mechanisms. Signs of this degradation can be seen or felt in the change in colors, odor, and texture of the food. Such changes can cause health risks, causing food poisoning, which can even lead to the individual's death. Fig. 1 shows an apple in the natural process of food deterioration along the time.

Figure 1 – Food deterioration along the time, Medallion Labs [2017].

1.1 Food Deterioration

The time it takes for food to deteriorate depends on several factors, those were reported by Amit et al. [2017]:

- Water activity: microorganisms need water to survive and multiply, so the greater the incidence of water in food, the more likely it is to deteriorate.
- Hydrogen potential (pH): the neutral level ($6.5 \leq pH \leq 7.5$) is often the most prone to food spoilage. Bacteria do not tolerate very well any variations in this level, while yeasts and other fungi are acidophilus, surviving in a more acidic pH.

- Oxidation potential (E_h): it is the main factor that contribute to the gain of electrons and represents the ease that an element gains or loses electrons and oxygen. Aerobic microorganisms need positive values to multiply ($E_h > 0$), while anaerobic need negative values ($E_h < 0$).

- Nutrient content: each microorganism has its ideal environment, but their requirements to ensure multiplication vary, they do it by using food nutrients for sources of carbon, nitrogen, vitamin, and mineral salts.

- Antimicrobial: some food of animal and vegetable origin already have antimicrobial components naturally, being resistant to their multiplication.

- Temperature: directly influences the speed at which chemical reactions occur, being determinant for the speed at which a microorganism develops and multiplies.

- Oxygen: is essential for some types of microorganisms to survive and reproduce, however, some are intolerant to it.

- Infestation by insects, parasites, and rodents: they usually use food exposed for their own consumption and to lay eggs which, when hatching, feed and develop. The infestation of these animals generates the proliferation of diseases and increases the degree of food contamination, which consequently deteriorates the food more quickly.

According to the characteristics of each kind of food, it is possible to distinguish them into three main groups: non-perishable (which do not change easily), semi-perishable (which, if preserved correctly, remain unchanged), and perishable (which deteriorate easily).

1.1.1 Physical Deterioration Mechanisms

As claimed by Amit et al. [2017], physical deterioration usually occurs, but not exclusively, through the loss, gain, or migration of water or by the physical separation of components and ingredients.

The main characteristic of physical deterioration is water, but another relevant characteristic is the temperature, whether it is too low or too high. However, cooling is an effective preservation technique for a variety food, such as meat.

1.1.2 Microbiological Deterioration Mechanisms

Among the most common forms of deterioration, the action of microorganisms is the main cause of food poisoning.

As reported by Mathew et al. [2016], the growth of most of these microorganisms can be stopped by lowering the storage temperature, chemically lowering the pH, or using food preservatives, in addition to choosing the correct packing. The main microorganisms involved in food spoilage can be categorized into fungi (mainly yeast) and bacteria.

1.1.3 Chemical Deterioration Mechanisms

One of the most important chemical spoilage mechanisms is oxidation. Amino acids present in food react with oxygen to form ammonia and an organic acid. Frozen beef and fish, in general, deteriorate by this mechanism.

$$Amino\ Acid + O_2 \rightarrow NH_3 + Organic\ Acid \tag{1.1}$$

Unsaturated fats or lipids also react with oxygen causing food to became rancid, a process that generates toxic substances such as carbonyl compounds and can be catalyzed by the presence of metal oxides and exposure to light. This reaction changes color and flavor of the food.

As explained by Amit et al. [2017], oxidation occurs when the surface of the food interacts with the oxygen present in the air, even inside the package, if it is not vacuum sealed. When frozen, it will dehydrate and, if exposed to oxygen in the air, will burn in the cold.

1.2 Food Waste

According to BBC [2017], almost 1 billion tonnes of food is thrown away every year, approximately 17% of the total food available to consumers. From that quantity, 60% are wasted in the home. This is a global problem, and along with social awareness campaigns, access to food preservation techniques and devices could help reduce the amount of food that is lost.

1.3 Food Preservation

As reported by Amit et al. [2017], evidence of food preservation techniques can be found as far back as ancient civilization, when large animals were hunted and their meat could not be fully consumed before it deteriorated. With limited resources and knowledge, the main forms of preservation were sun-drying, smoking, salting, using oils, snow, or preserving in honey. This knowledge is among the main enablers of the creation and stabilization of the first civilizations. Food preservation processes and techniques are those that delay deterioration mechanisms, increasing their durability, that is, maintaining their nutritional values, colors, texture, odor, and flavor for longer.

Among the modern techniques, as stated by Amit et al. [2017] are dehydration or drying, fermentation, cooling or freezing, curing, canning, antibiotics, ultraviolet radiation, pasteurization, vacuum, and addition of chemical preservative substances. For this project we are interested in vacuum sealing and freezing or cooling.

1.4 Cooling, Freezing and Vacuum Packing

1.4.1 Cooling

According to Amit et al. [2017], refrigerating food is the most common technique used in homes, it is mainly effective for meat and dairy products. In the case of fruits and vegetables, cooling is not a good preservation technique as cold burning can occur. This food are sensitive and can suffer damage below $15°C$. Although cooling techniques are widely used, there are psychotropic microorganisms, bacteria that grow faster at lower temperatures, which can be up to four times faster at $10°C$. Other types can develop and produce toxins at refrigeration temperatures, but the vast majority do not grow below $4°C$.

For greater conservation effectiveness, refrigeration is mixed with other methods such as vacuum packing, salting, curing, smoking, heat treatment, and addition of chemical agents, in order to reduce the number of microorganisms in the refrigerated food. Cooling can be performed as a form of cold shock or rapid cooling. The first option alters the permeability of the microbial cell membrane, reducing the temperature without freezing its substrate. Rapid cooling, on the other hand, must be done in small portions of food, quickly, avoiding exposure to the temperature of growth of microorganisms.

1.4.2 Freezing

Also widely used in homes, the freezing method causes the death of several microorganisms, considerably reducing their number compared to refrigeration. Reduces the water activity of food, as it is frozen, causes oxygen loss, pH change, temperature shock in some microorganisms, and metabolic damage to some bacteria, in addition to affecting the concentration of electrolytes. It also can be mixed with other forms of conservation such as vacuum, salting, heat treatment, and addition of chemical agents. For a better use, food should be frozen right after preparation, being more durable when cooked for a minimum time and seasoned. They must be kept in a waterproof package and when thawed, they must not be frozen again.

The freezing process must be carried out correctly, so there is no loss of nutrients and preservation of physical characteristics. For this, there are two options, ultra-fast cooling at $-40°C$ and slow cooling at $-18°C$. It is important to remember that it needs to be frozen at $-18°C$ or lower, which is possible in freezers, but not in refrigerator freezers, making it less effective for those who do not have an upright or horizontal freezer at home.

1.4.3 Vacuum Packing

Vacuum packing fresh food, such as meat, before storing, can stop the oxidation process and delay browning. Using this process before freezing prevents meat from dehydrating, as well as keeping oxygen out, which, according to The VacMaster Team [2017], will keep the meat from burning in the cold for up to five times longer than if it weren't. Storing food under vacuum does not eliminate all risks, however, increases the chances of preventing the proliferation of pathogenic aerobic bacteria. It is estimated that 48 million people suffer from at least one food poisoning in a 12-month period in the United States alone, as reported by foodsafety.gov [2020].

Some bacteria such as Listeria Monocytogenes and Clostridium Botulinum are anaerobic and able to survive and multiply in low oxygen environments. Therefore, this storage procedure is not recommended for all food. Examples are garlic, onion, mushroom, and soft cheese.

Another reason for not vacuum packing is the gases released by plants in the Brassicaceae family, such as cabbage, broccoli, cauliflower, turnip, radish, and others. These gases, if trapped, can cause this food to decay more quickly. To vacuum pack them, they must first be steamed and dried, then sealed and quickly frozen.

Figure 2 – Vacuum packing machine on the market, Amazon.com.br [2021].

Nowadays, there are several small vacuum packing machines available on the market, one of them shown in Fig. 2, making this conservation process more affordable in homes and small businesses. It does not require many techniques and even without in-depth knowledge of the correct ways to preserve food, it still promotes greater durability than not vacuum packing.

1.4.4 Vacuum Packing at Home

Currently, most homes have access to a refrigerator. As a result, they are able to keep food isolated from light, pathogens such as those transmitted by flies, and at low temperatures. These features extend the shelf life of extremely common everyday food, like raw meat or cooked beans. In addition, some homes already have machines to vacuum packing, prolonging their edibility even further. Electric vacuum sealers can be found and purchased in physical stores or on the internet, starting at approximate $R\$ \ 100,00$. It is a relatively low amount, yet, for the vast majority of people, it is a significant one. This fact motivates us to further reduce the costs of this equipment, allowing it to be built at home, with common parts found in any supermarket or hardware store. This alone can increase the quality of life of these mentioned people and even reducing its mortality rate.

1.4.5 Building a Vacuum Packing Device

To achieve this goal, we must study the mechanisms and parts, as well as the physical laws behind electrical vacuum sealer devices. Once the analysis is done, we must make calculations to maximize efficiency and then search the market for components with those specifications and low-cost. In the present work, we study specifically the thermal system behind the sealing part of the process of vacuum sealing.

We analyzed the theory that allows building the device with cheap and recycled parts and how they work, calculating several parameters, for instance, the maximum temperature of the device, and how long it would take to seal the plastic bag.

2 Literature Review

2.1 First Law of Thermodynamics

According to Vlachopoulos and Strutt [2002], the first law of thermodynamics refer to the principle of energy conservation. Energy can not be created nor destroyed, it just changes its nature, as illustrated in Fig. 3.

"The increase of internal energy (ΔE) of a given system is equal to heat (Q) absorbed from surroundings plus the mechanical work (W) added."

$$Q + W = \Delta E \quad [J]. \tag{2.1}$$

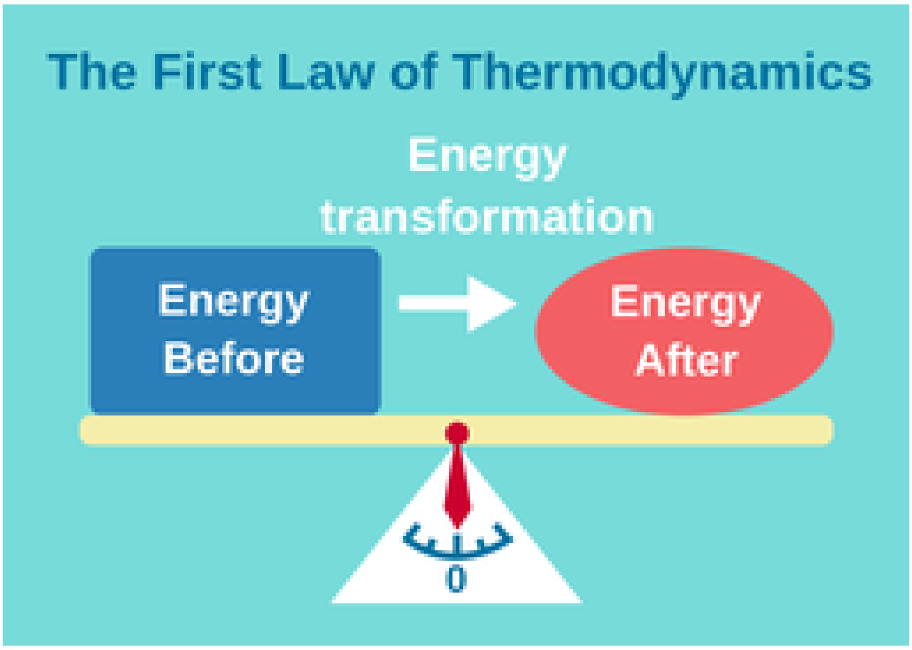

Figure 3 – Energy can not be created nor destroyed, it just changes its nature, Labster Theory [2021]

An adiabatic system is one where there is no heat exchange with the surroundings, is defined as follows:

$$W = \Delta E \quad [J]. \tag{2.2}$$

If, on the other hand, there is no work done by the surroundings, then:

$$Q = \Delta E \quad [J]. \tag{2.3}$$

2.2 Thermal Efficiency

The second law of thermodynamics refer to the direction in which the energy transfers to, or, the conversion of its nature. When one of those two things happens, there is an increase of entropy. The entropy represents a loss in the availability of energy for external purposes.

A heat engine is a device that produces net positive work as a result of heat transfer from a material that has higher temperature to another material that is in a state of relatively lower temperature. In practice, it is impossible that a device operates with 100% of thermal efficiency (η). The thermal efficiency is calculated by the ratio of output over input, or energy sought over energy transferred from the higher temperature source.

$$\text{Thermal Efficiency} = \frac{\text{Energy Sought}}{\text{Energy Provided}}. \tag{2.4}$$

2.3 Heat Transfer

Thermal energy can be transferred in three different modes: conduction, convection, and radiation. Heat is the term used to describe the transfer of thermal energy. Each heat mode is detailed in the next sections.

2.3.1 Conduction

As shown by the second law of thermodynamics and stated by Çengel [1998], heat will be transferred from a region in higher temperature to another with a lower temperature. The heat transferred within a solid or between solids is mainly by conduction.

To calculate the amount of heat transferred by conduction through a solid we need the temperatures (T), the contact area (A) that is normal to the direction the heat flows, and the length (L) of the object that the heat is being transferred through.

For the same situation of area, temperatures, and length, different materials will have different capacities of transferring heat, because every material have a characteristic thermal conductivity (k). The thermal energy transported through solid materials by conduction can be calculated using the following equation, known as Fourier's law:

$$\dot{Q}_{COND} = \frac{-k \cdot A \cdot \Delta T}{L} \quad [W]. \tag{2.5}$$

The negative sign appears because as the heat is transferred from the higher temperature to the lower, the temperature difference ($T_{low} - T_{high}$) will be negative. A didactic way of analyzing heat, is that the Fourier's law (Eq. 2.7) is analogue to the Ohm's law (Eq. 2.6), they being defined by:

$$\text{potential difference} = \text{electrical resistance} \cdot \text{current conducted}, \tag{2.6}$$

$$\text{temperature difference} = \text{thermal resistance} \cdot \text{heat conducted}. \tag{2.7}$$

In which, for thermal conduction, the thermal resistance is:

$$R_{COND} = \frac{L}{k \cdot A} \quad \left[\frac{K}{W}\right]. \tag{2.8}$$

If the heat is conducted through multiple materials, in the same way it would work in the Ohm's law to sum up the electrical resistances when they are arranged in chain (which is called a series circuit), we can sum up the thermal resistances.

$$\dot{Q}_{COND} = \frac{-\Delta T}{\left[\frac{L_1}{k_1 \cdot A_1} + ... + \frac{L_n}{k_n \cdot A_n}\right]} \quad [W], \tag{2.9}$$

and for parallel circuits:

$$\dot{Q}_{COND} = \frac{-\Delta T}{\left[\frac{1}{\left(\frac{L_1}{k_1 \cdot A_1}\right)} + ... + \frac{1}{\left(\frac{L_n}{k_n \cdot A_n}\right)}\right]} \quad [W]. \tag{2.10}$$

2.3.2 Convection

As explained by Incropera and DeWitt [1996], when two fluids are in contact or a solid is in contact with a fluid, the heat also flows from the higher temperature material to the other in lower temperature, but instead of conduction, the main mode of heat transfer here is convection. Here, the mass transport also plays an important role in the thermal dynamics.

The same way every solid material have a characteristic thermal conductivity, for the matter of convection, fluids have a characteristic heat transfer coefficient (h). According to Newton's cooling law, the heat transferred as convection can be calculated by:

$$\dot{Q}_{CONV} = -h \cdot A \cdot \Delta T \quad [W]. \tag{2.11}$$

Where A is the area where the solid and the liquid are in contact. And, again, there is a minus for the same reason as there was for conduction.

For convection, it is also possible to work with a thermal resistance:

$$R_{CONV} = \frac{1}{h \cdot A} \qquad \left[\frac{K}{W}\right]. \tag{2.12}$$

Therefore, for series circuits:

$$\dot{Q}_{CONV} = \frac{-\Delta T}{\left[\frac{1}{h_1 \cdot A_1} + ... + \frac{1}{h_n \cdot A_n}\right]} \qquad [W], \tag{2.13}$$

and parallel circuits:

$$\dot{Q}_{CONV} = \frac{-\Delta T}{\left[\frac{1}{\left(\frac{1}{h_1 \cdot A_1}\right)} + ... + \frac{1}{\left(\frac{1}{h_n \cdot A_n}\right)}\right]} \qquad [W]. \tag{2.14}$$

If in the system happens both conduction and convection, we can sum up the thermal resistances in the same way, for series circuits:

$$\dot{Q}_{TOTAL} = \dot{Q}_{COND} + \dot{Q}_{CONV} = \frac{-\Delta T_{total}}{\sum_{i=1}^{m} \frac{L_m}{k_m \cdot A_m} + \sum_{j=1}^{n} \frac{1}{h_n \cdot A_n}} \qquad [W]. \tag{2.15}$$

It is important to remember that in all cases of thermal resistances summed, the temperature difference is considered between the first and last temperature state. Let us consider heat is being transferred from T_1 to T_2 ($\Delta T_{1,2}$) and from T_2 to T_3 ($\Delta T_{2,3}$):

$$\Delta T_{total} = \Delta T_{1,2} + \Delta T_{2,3} = (\cancel{T_2} - T_1) + (T_3 - \cancel{T_2}) = T_3 - T_1 = \Delta T_{1,3}. \tag{2.16}$$

2.3.3 Radiation

The other form of heat transfer is radiation, this one is very important whenever high temperatures are involved. Referring to Çengel [1998], all materials at temperature above absolute zero will emit this energy by means of electromagnetic waves from its surface.

The same way conduction have the thermal conductivity (k) and convection have the heat transfer coefficient (h), each surface transferring heat through radiation will have a different emissivity (ϵ). Along with the emissivity, in radiation we will have a constant of proportionality called the Stefan-Boltzmann constant (σ). Furthermore, to calculate the heat transferred through radiation we need the surface area (A) and the temperatures (T) of the surface and environment:

$$\dot{Q}_{RAD} = \epsilon \cdot \sigma \cdot A \cdot (T^4 - T_\infty^4) \quad [W], \tag{2.17}$$

where $\sigma = 5.670374419 \cdot 10^{-8}$ $[W/(m^2 \cdot K^4)]$.

Differently from conduction and convection, in the case of radiation, the thermal resistance will be as function of temperature.

$$\dot{Q}_{RAD} = \underbrace{\epsilon \cdot \sigma \cdot A \cdot (T^2 + T_\infty^2)(T + T_\infty)}_{h_{RAD} \cdot A} \underbrace{(T - T_\infty)}_{\Delta T} \quad [W], \tag{2.18}$$

$$h_{RAD} = \epsilon \cdot \sigma \cdot (T^2 + T_\infty^2)(T + T_\infty) \quad \left[\frac{W}{K \cdot m^2}\right], \tag{2.19}$$

$$R_{RAD} = \frac{1}{h_{RAD} \cdot A} \quad \left[\frac{K}{W}\right], \tag{2.20}$$

and so,

$$\dot{Q}_{RAD} = \frac{-\Delta T}{\left(\frac{1}{h_{RAD} \cdot A}\right)} \quad [W]. \tag{2.21}$$

2.4 Dimensionless Numbers

These variables are very useful for understanding the behavior of a system. As explained by Çengel [1998], they are ratios that can show states of momentum, energy, and diffusivity, relatively giving the strengths of the different phenomena that are important for heat transfer and fluid mechanics. The mentioned phenomena being inertia, heat transfer, mass transfer, and viscosity.

2.4.1 Prandtl

The Prandtl number is defined as the ratio of momentum diffusivity over thermal diffusivity. For most gases, the Prandtl number (Pr) have an approximately constant value, and it can be used to determine the thermal conductivity of a gas at high temperatures.

In practice, a low Prandtl number means that the thermal diffusivity is dominant, and a high value, that the momentum diffusivity is the dominant behavior. Meaning that for low Prandtl numbers, heat will diffuse more quickly than the molecules or atoms velocity, which happens frequently for metallic materials.

$$Pr = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}}, \tag{2.22}$$

$$Pr = \frac{\mu \cdot C_p}{k} = \frac{\nu}{\alpha}, \tag{2.23}$$

where μ $[Pa \cdot s]$ is the dynamic viscosity, C_p $[J/(kg \cdot K)]$ is the specific heat, k $[W/(m \cdot K)]$ is the thermal conductivity, ν $[m^2/s]$ is the kinematic viscosity, and α $[m^2/s]$ is the thermal diffusivity. All properties of the fluid.

2.4.2 Grashoff

The Grashoff number is defined as the ratio of the buoyant force over the viscous force acting on a fluid in the velocity boundary layer. Natural convection happens when the motion and mixing of the fluid is caused mostly by density variations caused by the temperature variation. A fluid in higher temperature becomes less dense and moves upwards, that happens because of the buoyant force, and this movement is opposed by the viscous force.

The Grashoff number (Gr) quantify these opposing forces, and for cylindrical bodies, or our filament, according to Çengel [1998], can be calculated by:

$$Gr = \frac{\text{buoyancy force}}{\text{viscous force}}, \tag{2.24}$$

$$Gr = \frac{g \cdot \beta \cdot (T - \overline{T}_{air}) \cdot D^3}{\nu^2}, \tag{2.25}$$

where g $[m/s^2]$ is the acceleration due to Earth's gravity, β $[1/K]$ is the coefficient of thermal expansion of the fluid, T $[K]$ is the surface temperature, $\overline{T}_{air}$ $[K]$ is the average fluid temperature, D $[m]$ is the filament diameter, and ν $[m^2/s]$ is the kinematic viscosity of the fluid.

For a flat plate facing upwards, like our aluminum one and our plastic bag, according to Engineers Edge [2021], the equation is:

$$Gr = \frac{g \cdot \beta \cdot (T - \overline{T}_{air}) \cdot \left(\frac{A}{2 \cdot W + 2 \cdot L} \right)^3}{\nu^2}, \tag{2.26}$$

where T $[K]$, L $[m]$, W $[m]$, and A $[m^2]$ are the properties of the plate, respectively, surface temperature, length, width, and area exposed to the environment.

2.4.3 Rayleigh

The Rayleigh number is the ratio of the timescale for thermal transport via diffusion over the timescale for thermal transport via convection at a specific speed. It is very useful to describe the heat transfer through natural convection. A value in a certain lower range denotes laminar flow and a value in a higher range, turbulent flow.

$$Ra = \frac{\text{timescale for thermal transport via diffusion}}{\text{timescale for thermal transport via convection at a specific speed}}. \tag{2.27}$$

A simple way to define the Rayleigh number (Ra) is:

$$Ra = Pr \cdot Gr \tag{2.28}$$

2.4.4 Nusselt

The Nusselt number is the ratio of convective heat transfer over conductive heat transfer at a boundary layer in a fluid.

$$Nu = \frac{\text{Convection}}{\text{Conduction}}. \tag{2.29}$$

Lower Nusselt numbers represents heat transfer mainly by conduction and a laminar flow. A larger Nusselt number indicates a more active convection and turbulent flow. When it is unitary, it means pure conduction.

A natural convection heat transfer correlation for long horizontal cylinders, like our wire, according to Eisakhani et al. [2011] and developed by Churchill and Chu, allow us to calculate the Nusselt number (Nu):

For a Rayleigh number (Ra) between the values of:

$$10^{-5} < Ra < 10^{12}, \tag{2.30}$$

$$Nu = \left\{ 0.6 + \frac{0.387 \cdot Ra^{1/6}}{\left[ ]1 + \left(\frac{0.599}{Pr} \right)^{9/16} \right]^{8/27}} \right\}^2. \tag{2.31}$$

The Nusselt number can be used to calculate the average heat transfer coefficient (h) of the fluid:

$$h_{air} = \frac{k_{air}}{D} \cdot Nu \qquad \left[\frac{W}{K \cdot m^2} \right]. \tag{2.32}$$

According to Engineers Edge [2021], the Nusselt number for a plate facing upwards can be calculated by:

For a Rayleigh number (Ra) between the values of:

$$2 \cdot 10^4 < Ra < 10^6, \tag{2.33}$$

$$Nu = 0.54 \cdot (Ra)^{0.25}. \tag{2.34}$$

And for a Rayleigh number (Ra) between the values of:

$$10^6 < Ra < 10^{11}, \tag{2.35}$$

$$Nu = 0.15 \cdot (Ra)^{0.3}. \tag{2.36}$$

The average heat transfer coefficient (h) of the fluid for the plate facing upwards is:

$$h_{air} = \frac{k_{air}}{\left(\frac{A}{2 \cdot W + 2 \cdot L}\right)} \cdot Nu \quad \left[\frac{W}{K \cdot m^2}\right]. \tag{2.37}$$

2.5 Electrical Power

Our system will be powered by electricity and to calculate the necessary power ($P_e(T)$) we will have to choose a potential difference, or voltage (V). The equation to calculate power as a function of voltage and temperature is:

$$P_e(T) = \frac{V^2}{R(T)} = R(T) \cdot i^2 \quad [W], \tag{2.38}$$

where $R(T)$ $[\Omega]$ is the filament electrical resistance as function of temperature.

For the temperature to rise, the system cannot be in equilibrium, therefore the balance between power minus heat transferred has to be positive.

$$\dot{Q}_{balance} = P_{e_{in}} + \dot{Q}_{in} - \dot{Q}_{out} \quad [W]. \tag{2.39}$$

The balance equation for heat transfer with temperature as a function of time is known from the first law (Eq. 2.1). Then, the rate of change of temperature along the time is given by:

$$m \cdot C_p \cdot \frac{dT}{dt} = \dot{Q}_{balance} \quad [W], \tag{2.40}$$

where the mass (m) and specific heat of the solid material (C_p) are both positive.

We can reach the time ($t_{sensible}$) it will take to heat the bag by integrating Eq. 2.40 along the time, as presented below:

$$T_{melt} = \int_{t_0}^{t_{sensible}} \frac{\dot{Q}_{balance}}{m \cdot C_p} \cdot dt \quad [K], \tag{2.41}$$

where T_{melt} is the melt temperature of the plastic.

Numerical integration may be applied in order to get this information. We use the first order Euler integration technique in this study, which yields the following relationship:

$$\underbrace{T}_{n+1} = \underbrace{T + \Delta t \cdot \frac{\dot{Q}_{balance}}{m \cdot C_p}}_{n} \quad [K]. \tag{2.42}$$

We have the time step represented by Δt, and n denotes the iteration in time.

2.6 Joule Effect

The Joule effect expression gathers several physical effects, and the Joule-Lenz law in Eq. 2.44 is one of them. According to Halliday et al. [2011], this law states that an electrical conductor that has current flowing generates heat proportionally to its resistance and the square of the current.

$$Q_e(T) = R \cdot i^2 \cdot t \quad [J], \tag{2.43}$$

where t represents time, and substituting from Eq. 2.38,

$$Q_e(T) = P_e(T) \cdot t \quad [J]. \tag{2.44}$$

2.7 Total Time

The time required to achieve the right temperature from the Eq. 2.42 is not the total time. The amount of heat to rise the temperature of a material to the melting point is called sensible heat. After the plastic bag achieves the melting point, further heat will not change the temperature, but melt it. This additional energy is called latent heat. The total time required will be the sum of the time the device will provide sensible heat and the time to melt the bag with the latent heat.

According to Vlachopoulos and Strutt [2002], the total heat required to melt the material, after reaching the melting temperature, can be calculated with the heat of fusion (ΔH_f), the density of the polymer (ρ), and the material volume (V) that will melt.

$$Q_{Latent} = \Delta H_f \cdot \rho \cdot V \quad [J]. \tag{2.45}$$

The energy to melt the bag will come from the wire, subtracting the heat the system is losing, we have this from the Eq. 2.41, and as a consequence the time needed:

$$Q_{Latent} = \int_0^{t_{latent}} \dot{Q}_{balance} \cdot dt \quad [J]. \tag{2.46}$$

Summing the time taken to heat the system until the bag reaches the melting point (sensible heat) plus the time it takes to melt (latent heat), we have the total time:

$$t_{total} = t_{sensible} + t_{latent} \quad [s]. \tag{2.47}$$

3 Methodology

3.1 Design

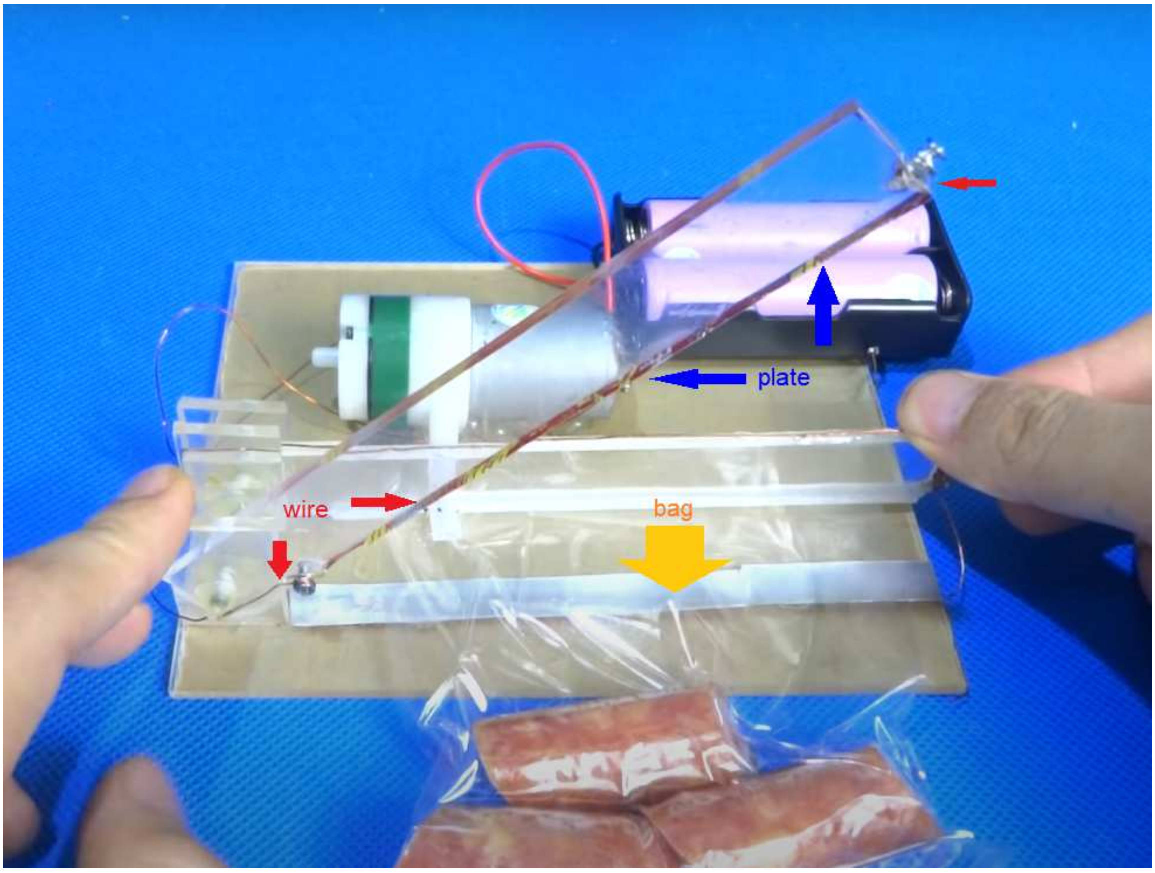

Figure 4 – Real vaccuum sealer project example, X-Creation YouTube Channel [2017].

A homemade vacuum sealer, built by X-Creation YouTube Channel [2017], can be seen in Fig. 4. A section of the thermal system of the device is shown in Fig. 5. The electrical power source feeds the tungsten wire, in red, that works as an electrical resistance, the wire elevates its temperature and transfer heat to the solder, drawn in gray. We will assume that the solder transfers all the heat to the aluminum plate, in blue. The plate will spread the heat to the sealing area of the plastic bag (yellow) and melt it.

3.2 Thermal System

In order to simplify the mathematical model, we assume that only the wire and the plate lose heat to the environment by radiation. One more consideration is that, since the entire system has small dimensions, we are neglecting the conduction inside the plate throughout itself.

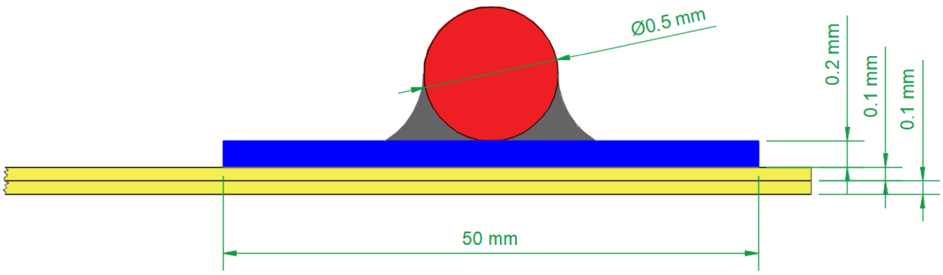

Figure 5 – Dimensions of the thermal system.

The plastic bag will lose heat to its cooler parts, but we can not consider the end of the bag to define the length because the heat won't reach that far. So we will branch the bag near the melting volume in 1000 small parts, in which the last one will be at room temperature along with the rest of the bag. A scheme of the thermal resistances is drawn on the Fig. 6.

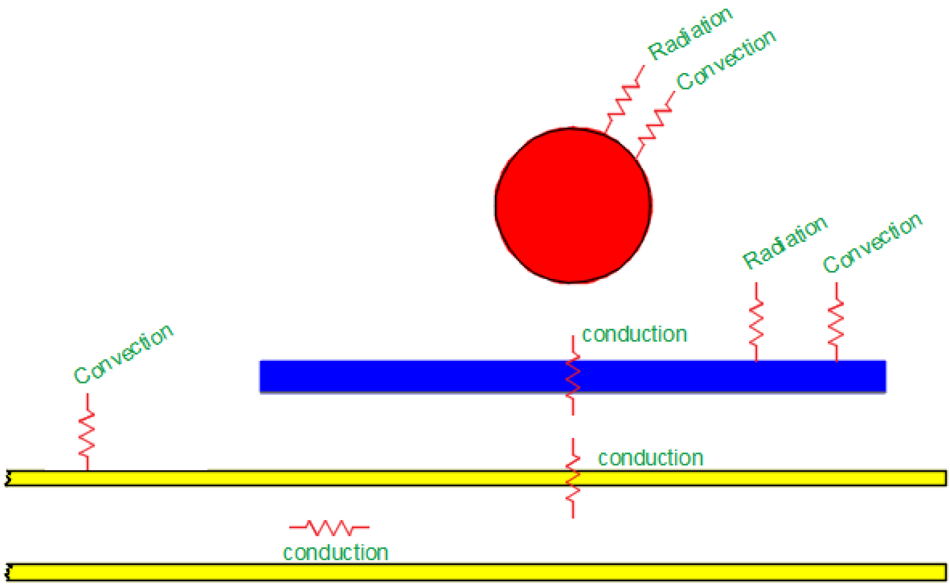

Figure 6 – Heat transfer modes.

One reason for that division in parts is that if we considered the total length of the bag it would be too far for the heat to reach, i.e., we would have wrong results, and it is not easy to choose the right point. Another reason is that when we consider conduction for a point to another we are working with a linear temperature variation and in this way the curve will be more precise. We expect that from some point further the temperature will barely change, so we are forcing the system to choose the right point automatically for us.

There are a few points of interest that we will have to know the temperature, those are the circles in pink in the Fig. 7. We assume no conduction inside the wire. T_w, T_p, and T_b are respectively the temperatures of the wire, plate, and bag. T_{b1} to T_{b1000} are the temperatures of the each intersection we are branching the bag.

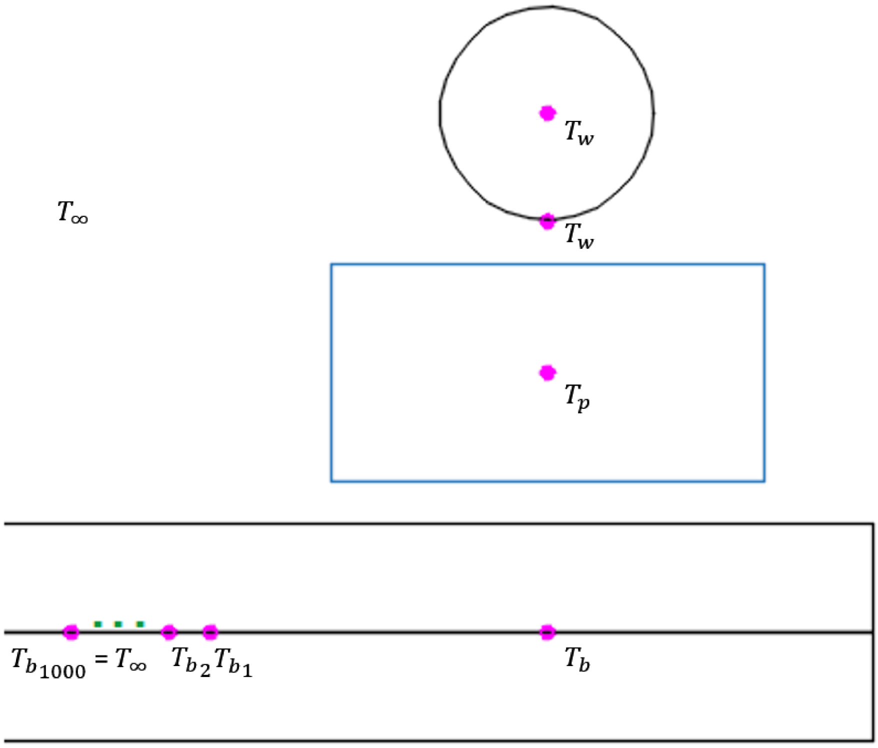

Figure 7 – Temperature points of interest.

The thermal resistance length for conduction between T_p and T_b will be half of the plate plus half of the bag, so we can work with the average temperature of the melting volume. We can neglect an additional point at the surface of contact between the plate and the bag because we are not considering radiation nor conduction from the bag. Even if we would consider, since the area of the plate is fully in contact with the bag, in that point, there would be only conduction.

Using the analogy between the Fourier's law and the Ohm's law we can have an easier understanding of how the heat will flow, the diagram is represented on the Fig. 8.

3.2.1 Wire Temperature Point

Considering the balance of thermal energy at this point, the energy entering is the electrical power (P_e), and leaving there is the conduction through half of the plate ($\dot{Q}_{cond1}$), and the radiation ($\dot{Q}_{rad,w}$) and convection ($\dot{Q}_{conv,w}$) from the wire. Thus, the energy balance in this point, from the Eq. 2.41 is given by:

$$m_w \cdot C_{p_w} \cdot \left.\frac{dT}{dt}\right|_w = P_e - \dot{Q}_{cond1} - \dot{Q}_{rad,w} - \dot{Q}_{conv,w}. \tag{3.1}$$

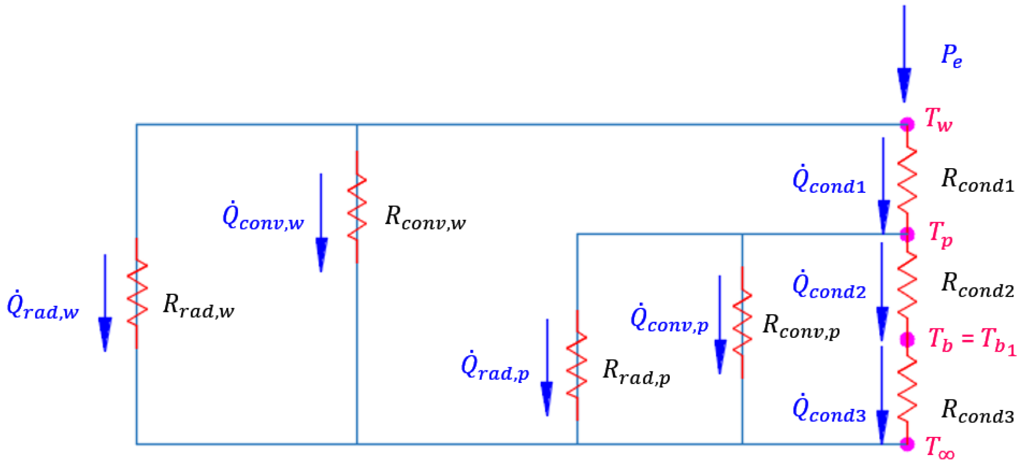

Figure 8 – Heat flow diagram.

Therefore, by considering the numerical time integration (Eq. 2.42), we have:

$$\underbrace{T_w}_{n+1} = \underbrace{T_w + \Delta t \cdot \left[\frac{P_e - \frac{T_w - T_p}{R_{cond1}} - \frac{T_w - T_\infty}{R_{rad,w}} - \frac{T_w - T_\infty}{R_{conv,w}}}{m_w \cdot C_{p_w}} \right]}_{n} \quad [K], \tag{3.2}$$

where,

$$R_{cond1} = \frac{\left(\frac{H_p}{2}\right)}{k_p \cdot A_w} \quad \left[\frac{K}{W}\right], \tag{3.3}$$

$$R_{rad,w} = \frac{1}{h_{RADw} \cdot A_w} \quad \left[\frac{K}{W}\right], \tag{3.4}$$

$$R_{conv,w} = \frac{1}{h_{air} \cdot A_{wp}} \quad \left[\frac{K}{W}\right], \tag{3.5}$$

where H_p is the plate thickness, A_w is the top half of the surface area of the wire and A_{wp} is the bottom half,

$$A_w = A_{wp} = \frac{1}{2} \cdot \pi \cdot D_w \cdot L_w \quad [m^2], \tag{3.6}$$

where D_w and L_w are the wire diameter and length, respectively.

3.2.2 Plate Temperature Point

The energy entering is the conduction heat from the wire ($\dot{Q}_{cond1}$), and leaving there is the radiation ($\dot{Q}_{rad,p}$) and convection ($\dot{Q}_{conv,p}$) from the plate plus the conduction through the other half of the plate and half of the bag ($\dot{Q}_{cond2}$), therefore, the energy balance in this point, from the Eq. 2.41 is given by:

$$m_p \cdot C_{p_p} \cdot \left.\frac{dT}{dt}\right|_p = \dot{Q}_{cond1} - \dot{Q}_{rad,p} - \dot{Q}_{conv,p} - \dot{Q}_{cond2}. \tag{3.7}$$

Consequently:

$$\underbrace{T_p}_{n+1} = \underbrace{T_p + \Delta t \cdot \left[\frac{\dfrac{T_w - T_p}{R_{cond1}} - \dfrac{T_p - T_\infty}{R_{rad,p}} - \dfrac{T_p - T_\infty}{R_{conv,p}} - \dfrac{T_p - T_b}{R_{cond2}}}{m_p \cdot C_{p_p}} \right]}_{n} \quad [K], \tag{3.8}$$

where,

$$R_{rad,p} = \frac{1}{h_{RADp} \cdot A_p} \qquad \left[\frac{K}{W}\right], \tag{3.9}$$

$$R_{conv,p} = \frac{1}{h_{air} \cdot A_p} \qquad \left[\frac{K}{W}\right], \tag{3.10}$$

$$R_{cond2} = \frac{\left(\dfrac{H_p}{2}\right)}{k_p \cdot A_{wp}} + \frac{\left(\dfrac{H_b}{2}\right)}{k_b \cdot A_{pb}} \qquad \left[\frac{K}{W}\right], \tag{3.11}$$

where H_b is the melting volume height, A_p is the top surface area of the plate and A_{pb} is the bottom,

$$A_p = A_{pb} = L_p \cdot W_p \qquad [m^2], \tag{3.12}$$

where L_p and W_p are the plate length and width, respectively.

3.2.3 Temperature of the Melting Point

In the middle height of the melting volume, the energy entering is the conduction heat from the plate ($\dot{Q}_{cond2}$), and leaving there is the conduction bidirectionally to the rest of the plastic bag ($\dot{Q}_{cond3}$), hence, the energy balance in this point, from the Eq. 2.41 is given by:

$$m_b \cdot C_{p_b} \cdot \left.\frac{dT}{dt}\right|_b = \dot{Q}_{cond2} - \dot{Q}_{cond3}. \tag{3.13}$$

The $\dot{Q}_{cond3}$ will actually be divided in small parts in which we will temporally store the temperature values of the intersections, additionally, those sections also lose heat by convection, thus:

$$\underbrace{T_b}_{n+1} = \underbrace{T_b + \Delta t \cdot \left[\frac{\dfrac{T_p - T_b}{R_{cond2}} - \dfrac{T_b - T_{T_{b_2}}}{R_{cond3}}}{m_b \cdot C_{p_b}} \right]}_{n} \quad [K], \tag{3.14}$$

$$... \tag{3.15}$$

$$\underbrace{T_{b_{999}}}_{n+1} = \underbrace{T_{b_{999}} + \Delta t \cdot \left[\frac{T_{b_{998}} - T_{b_{999}}}{R_{cond3}} - \frac{T_{b_{999}} - T_{\infty}}{R_{conv,b}} - \frac{T_{b_{999}} - T_{\infty}}{R_{cond3}} \right]}_{n} \quad [K], \tag{3.16}$$

where R_{cond3} is the thermal resistance for the sections of the bag, $R_{conv,b}$ the convection of those parts, each with a small dL length that we will define:

$$R_{cond3} = \frac{dL}{k_b \cdot A_b} \quad \left[\frac{K}{W}\right], \tag{3.17}$$

$$R_{conv,p} = \frac{1}{h_{air} \cdot A_{b,sec}} \quad \left[\frac{K}{W}\right], \tag{3.18}$$

where A_b is the cross-section area of the plastic bag and considered for both directions,

$$A_b = 2 * H_b \cdot L_b \quad [m^2], \tag{3.19}$$

and $A_{b,sec}$ is the exposed area of the plastic bag sections,

$$A_{b,sec} = dL_b \cdot L_b \quad [m^2]. \tag{3.20}$$

4 Properties

4.1 Properties of the Environment

The process will take place probably in the kitchen, so we can consider that the fluid will be air, and that air is an ideal gas.

4.1.1 Air Temperature and Relative Humidity

The data shown on Tab. 1 collected from Petrucci [2018] from the last 40 years and adjusted with Gumbel's probability density function.

Data	Average	Amplitude
Temperature	$22.6°C$	$1.4°C$
Relative Humidity	68%	5%

Table 1 – Temperature and humidity in Uberlândia-MG, Brazil, Petrucci [2018].

We will consider the initial temperature as the average temperature (T_{air}):

$$T_{air} = 22.6 + 273.15 \quad [K], \tag{4.1}$$

$$T_{air} = 295.75 \quad [K], \tag{4.2}$$

and average the relative humidity $\phi_{air} = 68\%$.

4.1.2 Air Thermal Conductivity

The thermal conductivity for most gases is very low. Theoretically, the conduction in gases is provided by the kinetic gas theory. The collision between the atoms or molecules are the source of the contact that allows heat to be conducted through the small area of contact of those atoms or molecules.

According to Çengel [1998], the thermal conductivity of air as a function of temperature, can be calculated by:

$$k_{air} = 1.5207 \cdot 10^{-11} \cdot \overline{T}_{air}^{3} - 4.8574 \cdot 10^{-8} \cdot \overline{T}_{air}^{2} + 1.0184 \cdot 10^{-4} \cdot \overline{T}_{air} - 3.9333 \cdot 10^{-4}, \tag{4.3}$$

with k_{air} in $[W/m \cdot K]$.

4.1.3 Air Specific Heat

Also, as stated by Çengel [1998], the specific heat of air as a function of temperature:

$$C_{p_{air}} = \frac{-1.9660 \cdot 10^{-9} \cdot \overline{T}_{air}^{3} + 0.4802 \cdot 10^{-5} \cdot \overline{T}_{air}^{2} + 0.1967 \cdot 10^{-2} \cdot \overline{T}_{air} + 28.11}{M_{dry\ air}} \quad , \tag{4.4}$$

where $C_{p_{air}}$ is in $[kJ/kg \cdot K]$ and $M_{dry\ air}$ is the molar mass for dry air and equal to 28.9647 $[kg/kmol]$.

T_{air} will vary in the neighboring of the wire and plate so, for simplification, we can consider the average value $T_{air} = \overline{T}_{air}$,

$$\overline{T}_{air} = \frac{1}{2} \cdot T_M + \frac{1}{2} \cdot T_\infty \quad [K], \tag{4.5}$$

where T_M is the mean between T_w and T_p.

4.1.4 Air Thermal Expansion Coefficient

Also known as the coefficient of expansion, this property demonstrates the change in volume when temperature is varied. The thermal expansion coefficient (β_{air}) of an ideal gas can be calculated by:

$$\beta_{air} = \frac{1}{\overline{T}_{air}} \quad \left[\frac{1}{K}\right]. \tag{4.6}$$

4.1.5 Air Density

4.1.5.1 Gravity

We will consider the city of Uberlândia, so we have the known data:

Average altitude in Uberlândia:

$$H_{UDIA} = 854 \quad [m]. \tag{4.7}$$

Average radius of Earth:

$$r_{Earth} = 6.3781 \cdot 10^{6} \quad [m]. \tag{4.8}$$

Mass of Earth:

$$m_{Earth} = 5.9722 \cdot 10^{24} \quad [kg]. \tag{4.9}$$

Gravitational constant:

$$G = 6.67430 \cdot 10^{-11} \qquad \left[\frac{m^3}{kg \cdot s^2}\right]. \tag{4.10}$$

Therefore, we can calculate the average gravity in the city using the Newton's law of universal gravitation, referring to Halliday et al. [2011]:

$$g_{UDIA} = \left[\frac{G \cdot m_{Earth}}{(r_{Earth} + H_{UDIA})^2}\right] \qquad \left[\frac{m}{s^2}\right]. \tag{4.11}$$

$$g_{UDIA} = 9.79582744 \qquad \left[\frac{m}{s^2}\right]. \tag{4.12}$$

As shown by Çengel [1998], the density of air can be calculated as function of temperature and pressure of dry air and steam:

$$\rho_{air}(\overline{T}_{air}) = \rho_{\text{dry air}}(\overline{T}_{air}) + \rho_{steam}(\overline{T}_{air}) \qquad \left[\frac{kg}{m^3}\right]. \tag{4.13}$$

The saturation pressure of steam can be calculated by:

$$p_{sat,steam}(\overline{T}_{air}) = \frac{e^{77.3450+0.0057 \cdot \overline{T}_{air} - \frac{7235}{\overline{T}_{air}}}}{\overline{T}_{air}^{8.2}} \qquad [Pa], \tag{4.14}$$

and the relative pressure of the steam:

$$p_{steam}(\overline{T}_{air}) = \phi_{air} \cdot p_{sat,steam}(\overline{T}_{air}) \qquad [Pa]. \tag{4.15}$$

For the pressure of the dry air, considering the sea level pressure and temperature,

$$p_{sea} = 101325 \qquad [Pa], \tag{4.16}$$

$$T_{sea} = 288.15 \qquad [K], \tag{4.17}$$

and the mass-specific gas constant for dry air and steam,

$$R_{\text{dry air}} = 287.058 \qquad \left[\frac{J}{kg \cdot K}\right]. \tag{4.18}$$

$$R_{steam} = 461.495 \qquad \left[\frac{J}{kg \cdot K}\right]. \tag{4.19}$$

the absolute pressure will be:

$$p_{abs} = p_{sea} \cdot e^{\left(\frac{H_{UDIA} \cdot g_{UDIA}}{T_{sea} \cdot R_{\text{dry air}}}\right)} \qquad [Pa]. \tag{4.20}$$

The density of dry air:

$$\rho_{\text{dry air}} = \frac{p_{\text{dry air}}}{R_{\text{dry air}} \cdot \overline{T}_{air}} \qquad \left[\frac{kg}{m^3}\right], \tag{4.21}$$

and steam:

$$\rho_{steam} = \frac{p_{steam}}{R_{steam} \cdot \overline{T}_{air}} \qquad \left[\frac{kg}{m^3}\right], \tag{4.22}$$

therefore,

$$\rho_{\text{dry air}} = \rho_{abs} - \rho_{steam} \qquad \left[\frac{kg}{m^3}\right]. \tag{4.23}$$

4.1.6 Air Viscosity

The viscosity of a fluid is a measurement of its fluidity. For instance, we know that honey takes much more time to flow than water, it happens because honey is more viscous than water. Dynamic viscosity, also called shear viscosity or absolute viscosity, represents the resistance to the movement of one layer of a fluid over another, and kinematic viscosity is the ratio of dynamic viscosity over density. That is, simplistically, dynamic viscosity shows information on the force needed to make the fluid flow at a certain rate, and the kinematic viscosity shows information of how fast the fluid will move when applied a certain force. Dynamic viscosity can be calculated with the Sutherland's law, reported by Halliday et al. [2011]:

$$\mu_{air}(\overline{T}_{air}) = \mu_0 \cdot \left(\frac{\overline{T}_{air}}{T_0}\right)^{\frac{3}{2}} \cdot \frac{T_0 + S_\mu}{\overline{T}_{air} + S_\mu} \qquad \left[\frac{kg}{m \cdot s}\right], \tag{4.24}$$

where the parameters for air to the Sutherland's law are:

$$\mu_0 = 1.719 \cdot 10^{-5} \qquad \left[\frac{N \cdot s}{m}\right] \tag{4.25}$$

$$T_0 = 273 \qquad [K], \tag{4.26}$$

and the Sutherland constant:

$$S_\mu = 111 \quad [K]. \tag{4.27}$$

4.1.7 Air Thermal Diffusivity

The thermal diffusivity is a specific property in which the heat conduction is characterized, defining the rate of transfer of heat of a material from the hot end to the cold end.

$$\alpha_{air} = \frac{k_{air}}{\rho_{air} \cdot C_{p_{air}}} \quad \left[\frac{m^2}{s}\right]. \tag{4.28}$$

4.2 Properties of the Tungsten Wire

4.2.1 Tungsten Wire Resistivity

The electrical resistance of any material will depend on cross-section area, length, and a particular characteristic property known as resistivity, but also called specific electrical resistance. In practice, two wires made with the same cross-section area and length but with different materials will provide different electrical resistances. That happens because each material will have its own resistivity.

In order to deal with the objectives of the present work, we will need a wire to work as a resistance, providing heat to the plastic bag. Tungsten has the properties we are looking for, mainly low-cost and high resistivity, consequently, high electrical resistance.

According to the table reported in "Electrical Resistivity of Selected Elements" published by Desai et al. [1984], the resistivity (P_w) of tungsten varies with its temperature (T_w) in an approximately linear way, where:

$$P_w(T_w) = 1.928910 \cdot 10^{-14} \cdot T_w^2 + 2.571315 \cdot 10^{-10} \cdot T_w - 2.516510 \cdot 10^{-8}, \tag{4.29}$$

with $P_w(T_w)$ in $[\Omega \cdot m]$.

4.2.2 Tungsten Wire Electrical Resistance

Electrical resistance is a measurement of how much a material will oppose the flow of electrical current throughout itself when submitted to a potential difference. With the resistivity as a function o temperature, and neglecting any length (L_w) or cross-section ($A_{w,sec}$) area variation, we can calculate the electrical resistance (R_w) as a function of temperature (T_w). For that, we will also assume an ideal material, with a uniform composition across the entire wire. According to Halliday et al. [2011] the Pouillet's law can be used to calculate the resistance:

$$R_w(T) = \frac{L_{w,total}}{A_{w,sec}} \cdot P_w(T) \quad [\Omega]. \tag{4.30}$$

Considering a commercial tungsten filament with a diameter of 0.5 mm and with a total length of 24 cm, being 4 cm for the setup of the device.

$$L_w = 2 \cdot 10^{-1} \quad [m], \tag{4.31}$$

$$L_{w,x} = 4 \cdot 10^{-2} \quad [m], \tag{4.32}$$

$$L_{w,total} = L_w + L_{w,x} = 2.4 \cdot 10^{-1} \quad [m], \tag{4.33}$$

$$D_w = 5 \cdot 10^{-4} \quad [m], \tag{4.34}$$

with the diameter, we have the circular cross-section area:

$$A_{w,sec} = \pi \cdot \frac{D_w^2}{4} \quad [m^2], \tag{4.35}$$

$$A_{w,sec} = 1.963495 \cdot 10^{-7} \quad [m^2]. \tag{4.36}$$

Substituting the area, length, and resistivity in the Pouillet's Law (Eq. 4.30):

$$R_w(T_w) = 1.222310 \cdot 10^{6} \cdot P_w(T_w) \quad [\Omega]. \tag{4.37}$$

$$R_w(T_w) = 2.357726 \cdot 10^{-8} \cdot T_w^2 + 3.142944 \cdot 10^{-4} \cdot T_w - 3.075955 \cdot 10^{-2} \quad [\Omega]. \tag{4.38}$$

4.2.3 Tungsten Wire Emissivity

Emissivity is the property that measure a material's ability to emit infrared frequency energy by electromagnetic radiation from its surface. All materials at temperature above absolute zero will emit this energy. This property is relative, that is, the emissivity of a material is a value from 0% to 100% comparing it with a mirrored surface ($\epsilon_{mirror} = 0$) and with a black body ($\epsilon_{black} = 1$)

According to the "Table of Emissivity of Various Surfaces" reported by Jones and Langmuir and published by Weast [1978], the emissivity of tungsten (ϵ_w) varies with its temperature, as shown on Fig. 9.

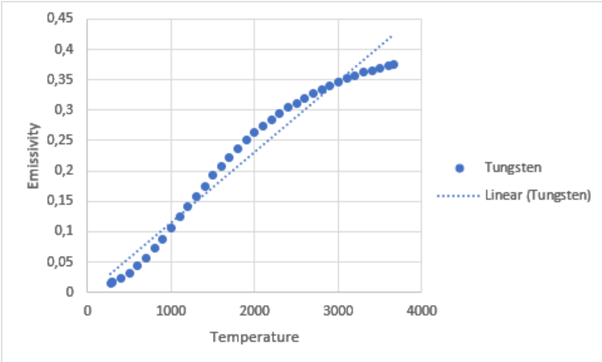

Figure 9 – Tungsten: emissivity vs temperature.

Between 273 K and 1000 K we can consider a second-order polynomial model with the data shown in Table 2 and Fig. 10.

Temperature $[K]$	Emissivity $[nondimensional]$
273	0.0154
293	0.0166
300	0.0170
400	0.0238
500	0.0320
600	0.0435
700	0.0570
800	0.0720
900	0.0880
1000	0.1050

Table 2 – Tungsten: emissivity vs temperature by Jones and Langmuir, Weast [1978].

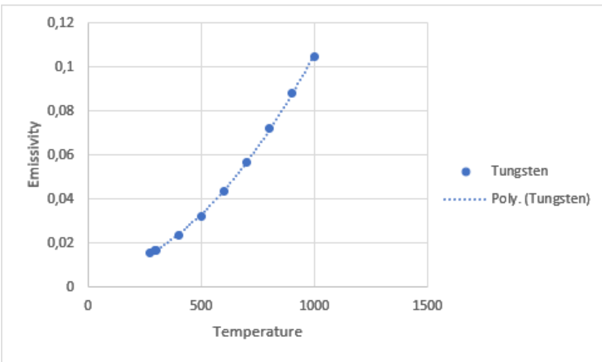

Figure 10 – Tungsten: emissivity vs temperature - polynomial regression.

Calculated on the Ke!san Online Calculator [2021], our results are shown in table 3.

$$Y = A + B \cdot X + C \cdot X^2 \tag{4.39}$$

Constant	Value
A	$6.3351076 \cdot 10^{-3}$
B	$7.2946410 \cdot 10^{-6}$
C	$9.2134646 \cdot 10^{-8}$
$\|r\|$	0.9998366652

Table 3 – Tungsten: quadratic regression of emissivity as function of temperature.

The correlation coefficient |r| above 0.7 indicates a strong correlation, meaning that our equation represents very well the experimental data from the table.

$$\epsilon_w = 9.2134646 \cdot 10^{-8} \cdot T_w^2 + 7.2946410 \cdot 10^{-6} \cdot T_w + 6.3351076 \cdot 10^{-3}, \tag{4.40}$$

where ϵ_w is nondimensional.

4.2.4 Tungsten Wire Thermal Efficiency

The wire will lose thermal efficiency (η_w) if part of the energy is directed to pulling out electrons in the form of photons, that is, if it glows. Our goal is for the filament to heat up briefly, not reaching that point, so, no glowing, all the energy provided only heats it. Therefore, the thermal efficiency is as shown by the Eq. 2.4:

$$\eta_w = 1 \tag{4.41}$$

4.2.5 Tungsten Wire Specific Heat

Neglecting the small variations for the specific heat of the wire (C_{p_w}) we can consider it constant and, according to Callister [1997], equal to:

$$C_{p_w} = 138 \quad \left[\frac{J}{kg \cdot K}\right], \tag{4.42}$$

4.2.6 Tungsten Wire Initial Temperature

We consider the system in thermal equilibrium with the environment as initial temperature, i.e., $T_{w,i} = T_\infty$,

4.2.7 Tungsten Wire Density

Since we are considering the material of the wire uniformly distributed, the density will be the specific mass of tungsten:

$$\rho_w = 1.925 \cdot 10^4 \qquad \left[\frac{kg}{m^3}\right]. \tag{4.43}$$

4.2.8 Tungsten Wire Exposed Area

The wire will be with half of its superficial area in contact with the solder, therefore, the radiation and convection area will be:

$$A_w = \frac{1}{2} \cdot \pi \cdot D_w \cdot L_w \qquad [m^2], \tag{4.44}$$

$$A_w = \frac{1}{2} \cdot \pi \cdot 5 \cdot 10^{-4} \cdot 2 \cdot 10^{-1} \qquad [m^2], \tag{4.45}$$

$$A_w = 1.570796 \cdot 10^{-4} \qquad [m^2]. \tag{4.46}$$

4.2.9 Tungsten Wire Volume

The volume of the wire will be calculated considering the total length and the cross-section area:

$$V_w = A_{w,sec} \cdot L_{w,total} \qquad [m^3]. \tag{4.47}$$

Substituting the values from Equations 4.33 and 4.36:

$$V_w = 1.9634955 \cdot 10^{-7} \cdot 2.4 \cdot 10^{-1} \qquad [m^3], \tag{4.48}$$

$$V_w = 4.712389 \cdot 10^{-8} \qquad [m^3]. \tag{4.49}$$

4.2.10 Tungsten Wire Mass

With the density from Eq. 4.43 and volume from Eq. 4.49 we can calculate the total mass of the wire:

$$m_w = V_w \cdot \rho_w = 4.712389 \cdot 10^{-8} \cdot 1.925 \cdot 10^4 \qquad [kg], \tag{4.50}$$

$$m_w = 9.071349 \cdot 10^{-4} \quad [kg]. \tag{4.51}$$

4.3 Properties of the Aluminum Plate

4.3.1 Aluminum Plate Thermal Conductivity

Thermal conductivity is the property responsible to quantify how well a material will conduct heat throughout itself. This characteristic varies strongly with temperature and, for aluminum, can be calculated with an equation from Abu-Eishah [2000]:

For temperatures between:

$$100 < T_p < 933.2 \quad [K], \tag{4.52}$$

$$k_p = 1.724468 \cdot T_p^{0.815012} \cdot e^{(-9.95310^{-4} \cdot T_p)} \cdot e^{\left(\frac{164.93990}{T_p}\right)} \quad \left[\frac{W}{m \cdot K}\right]. \tag{4.53}$$

4.3.2 Aluminum Plate Contact Area

The area of the wire that will be conducting heat through a solder that we will assume to transfer all the energy to the plate will be considered the bottom half of the wire's superficial area:

$$A_{wp} = \frac{1}{2} \cdot \pi \cdot D_w \cdot L_w \quad [m^2]. \tag{4.54}$$

Substituting the diameter and length of the wire from Equations 4.31 and 4.34:

$$A_{wp} = \frac{1}{2} \cdot \pi \cdot 5 \cdot 10^{-4} \cdot 2 \cdot 10^{-1} \quad [m^2], \tag{4.55}$$

$$A_{wp} = 1.570796 \cdot 10^{-4} \quad [m^2], \tag{4.56}$$

and the area of the plate that will transfer heat to the plastic bag will be its bottom surface area, the plate have the following dimensions:

Thickness:

We can use a piece of a beverage can, neglecting the paintwork. According to the manufacturer alu [2021]:

$$H_p = 5 \cdot 10^{-5} \quad [m]. \tag{4.57}$$

Length:

The length will coincide with the useful length of the wire, so from Eq. 4.31.

$$L_p = L_w \quad [m], \tag{4.58}$$

$$L_p = 2 \cdot 10^{-1} \quad [m]. \tag{4.59}$$

Width:

We will assume 5 $[mm]$ for the width.

$$W_p = 5 \cdot 10^{-3} \quad [m]. \tag{4.60}$$

Therefore, the contact area between the plate and the bag can be calculated:

$$A_{pb} = L_p \cdot W_p = 2 \cdot 10^{-1} \cdot 5 \cdot 10^{-3} [m^2], \tag{4.61}$$

$$A_{pb} = 1 \cdot 10^{-3} \quad [m^2]. \tag{4.62}$$

4.3.3 Aluminum Plate Exposed Area

The bottom side of the plate will be in contact with the plastic bag, and the top side will be exposed, except the part that is in contact with the solder, therefore, the radiation and convection area will be:

$$A_p = L_p \cdot W_p - A_{wp} \quad [m^2], \tag{4.63}$$

as the plate is very thin we can neglect the side area. Substituting the dimensions:

$$A_p = 2 \cdot 10^{-1} \cdot 5 \cdot 10^{-3} + 2 \cdot (5 \cdot 10^{-3} \cdot 5 \cdot 10^{-5}) + 2 \cdot (2 \cdot 10^{-1} \cdot 5 \cdot 10^{-5}) - 1.570796 \cdot 10^{-4} \quad [m^2], \tag{4.64}$$

$$A_p = 8.634204 \cdot 10^{-4} \quad [m^2]. \tag{4.65}$$

4.3.4 Aluminum Plate Initial Temperature

In the beginning, the plate will be in contact with the wire and the environment, so the initial temperature of the plate will be the same of both, from Eq. 4.2: $T_{p,i} = T_\infty$.

4.3.5 Aluminum Plate Emissivity

The emissivity of the aluminum, if not oxidized, is very low, it is a very shiny metal, we will assume the value to be constant and equal to:

$$\epsilon_p = 0.09. \tag{4.66}$$

4.3.6 Aluminum Plate Specific Heat

In the same way for the wire, for the specific heat of the plate (C_{p_p}) we will consider it constant and, according to Callister [1997], equal to:

$$C_{p_w} = 900 \quad \left[\frac{J}{kg \cdot K}\right]. \tag{4.67}$$

4.4 Properties of the Plastic Bag

4.4.1 Plastic Bag Melting Temperature

The plastic bags are usually made of low density polyethylene (LDPE). This material can withstand a temperature of 80 $°C$ for a long period of time, and 90 $°C$ for a short period. The melting temperature is between 106 $°C$ and 112 $°C$.

For the project to work for all qualities of LDPE plastic bags, we will assume the higher melting temperature (T_{melt}), which, according to Vlachopoulos and Strutt [2002], is given by:

$$T_{melt} = 112 \quad [°C], \tag{4.68}$$

or,

$$T_{melt} = 385.15 \quad [K]. \tag{4.69}$$

4.4.2 Plastic Bag Initial Temperature

Along with the plate and the wire, the plastic bag will be in the same temperature of the environment, from Eq. 4.2, i.e., $T_{b,i} = T_\infty$ $[K]$.

4.4.3 Plastic Bag Thermal Conductivity

The thermal conductivity of the LDPE is very low, so we will consider it a constant and equal to:

$$k_b = 0.33 \quad \left[\frac{W}{m \cdot K}\right]. \tag{4.70}$$

4.4.4 Plastic Bag Density

According to Vlachopoulos and Strutt [2002], the LDPE density (ρ_b) vary from 915 $[kg/m^3]$ to 935 $[kg/m^3]$. For the same reason of the melting temperature, we will consider the maximum density.

$$\rho_b = 935 \quad \left[\frac{kg}{m^3}\right]. \tag{4.71}$$

4.4.5 Plastic Bag Dimensions

Thickness

The thickness of a common plastic bag for everyday items such as food or clothes, according to Multi-pak USA | inc. [2021] is between 1 mil and 2 mil, where *mil* is the unity used for such purposes and equal a thousandth of an inch. Considering 2 mils:

$$e_b = 5.08 \cdot 10^{-5} \quad [m]. \tag{4.72}$$

The bag will have two sheets of the polymer, so the melting volume will have a height of:

$$H_b = 2 \cdot e_{bag} \quad [m], \tag{4.73}$$

$$H_b = 1.016 \cdot 10^{-4} \quad [m]. \tag{4.74}$$

Melting Volume

Considering that the melting volume (V_b) will be in touch with the device at the aluminum plate the surface area will be the same of the plate, and from the Equations 4.62 and 4.74:

$$V_b = A_{pb} \cdot H_b = 1 \cdot 10^{-3} \cdot 1.016 \cdot 10^{-4} \tag{4.75}$$

$$V_b = 1.016 \cdot 10^{-7} \quad [m^3]. \tag{4.76}$$

Plastic Bag Cross-Section Area

The melting volume will lose temperature to the rest of the bag through the cross-section area from both directions. The height of the area is calculated in the Eq. 4.74 and the length is the same of the plate and the wire, from Eq. 4.31:

$$A_b = 2 \cdot H_b \cdot L_w = 2 \cdot 1.016 \cdot 10^{-4} \cdot 2 \cdot 10^{-1} \quad [m^3] \tag{4.77}$$

$$A_b = 4.064 \cdot 10^{-5} \quad [m^3] \tag{4.78}$$

4.5 Latent Heat

For melting a solid, heat must be added, so the energy can break the crystal structure. Meaning that to melt a polymer that is not amorphous, it is necessary a certain amount of heat after the material reaches the melting temperature (T_{melt}). According to Vlachopoulos and Strutt [2002], this amount of heat is known as heat of fusion (ΔH_f). An average value for the LDPE:

$$\Delta H_{f_{bag}} = 2 \cdot 10^5 \quad \left[\frac{J}{kg}\right]. \tag{4.79}$$

5 Results

As initial considerations, the following parameters are applied: voltage $V = 12\ V$, room temperature is $T_\infty = 22.6\ °C$, air humidity $\phi_{air} = 68\%$, wire length $L_w = 20\ cm$, wire diameter $D_w = 0.5\ mm$, and plate width $W_p = 5\ mm$.

The calculations were made in mathematical software and the script can be found in Annex A. Executing the script, the result for the total time required: $t_{total} = 0.10\ seconds$. The time to reach the melting temperature was $t_{sensible} = 0.06\ seconds$, representing $\approx 60\%$ of the total time. The remaining $\approx 40\%$, necessary for melting, is $t_{latent} = 0.04\ seconds$.

Fig. 11 illustrates the temperature throughout the simulation time, temperature for the wire, the plate, and the melting point are given. We notice that the wire temperature line (in red) overlaps the plate temperature line (in blue), their values are very close to each other. Since aluminum is a great heat conductor, thermal energy transfers almost instantaneously. The green line represents the melting point temperature. We observe that it rises to the melting temperature and stabilizes until the material is completely melted. The temperature of the wire and the plate have an average difference of $\approx 0.2°C$, as shown in Fig. 12, where a zoom is applied in order to provide a more complete analysis.

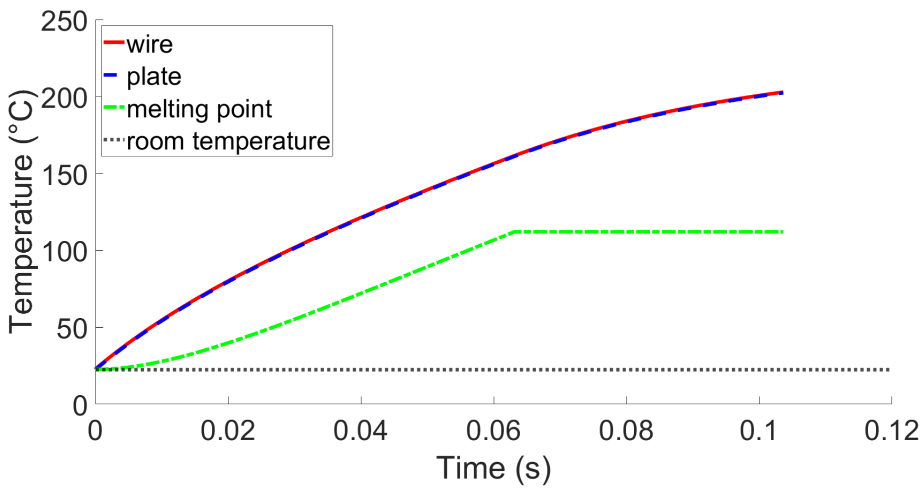

Figure 11 – Temperature vs time for the wire, plate, and melting point.

The temperature growth of the plastic bag in the neighbourhood of the melting volume is represented in Fig. 13. We can see the temperatures of the melting point, 5 points of the small sections at 10%, 20%, 30%, 40%, 50%, and the total length considered, 100%, of $2\ mm$. The temperature after $\approx 0.94\ mm$ barely changes, the difference being less than $0.01\ °C$ and as expected, there is not much heat flowing through this point and after. Since the LDPE have a low thermal conductivity, it is not a good conductor and

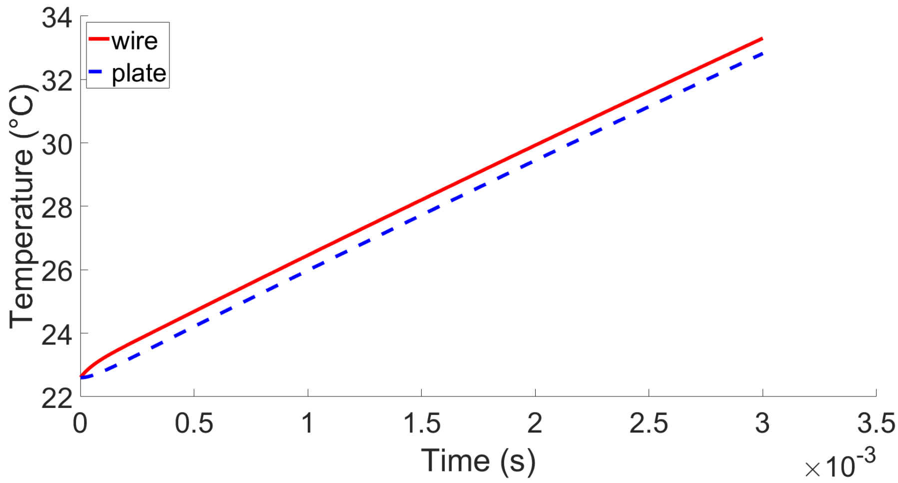

Figure 12 – Wire and plate temperatures zoomed in.

the heat is lost mainly by convection to the environment. Fig. 14 shows the variation of temperature along the plastic bag.

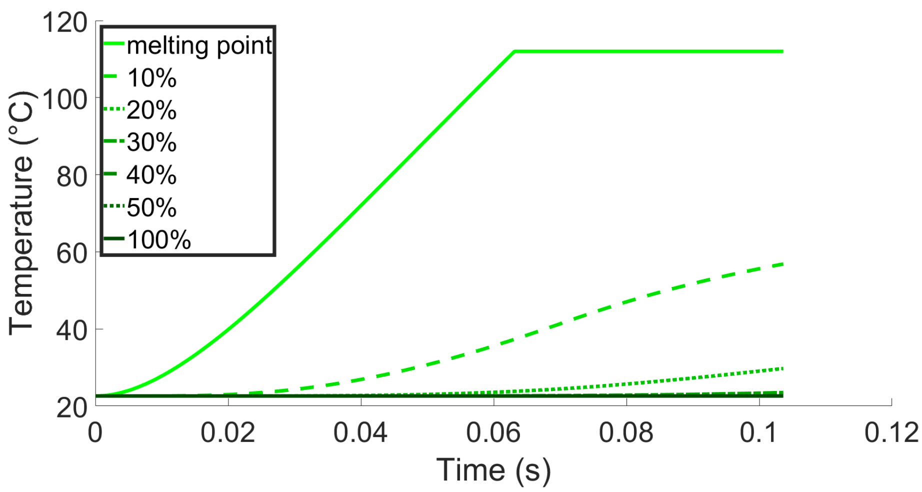

Figure 13 – Bag temperature rising in the neighbourhood of the melting point.

The total thermal energy generated, lost by the system, and transferred inside it is shown in Tab. 4. Follows an overall analysis of the physical principles behind the device: first, we close the electrical circuit providing a potential difference to the tungsten wire, provoking the electrons to move and, therefore, generating an electrical current. When the current flows throughout the wire, it generates power. Considering the total time the device is working in this setup, it generates $\approx 93\ J$, this is the total energy entering the system and this energy must be entirely transferred, lost, or used. Of that energy, $\approx 0.3\%$ is lost (through convection and radiation to the environment, and through conduction from the melting volume to the cooler parts of the plastic bag). Other $\approx 24.3\%$ stays in the wire and this energy agitates the atoms and molecules, this agitation rises the temperature $\approx 180.2°C$. Another $\approx 37.0\%$ stays in the plate, rising its temperature $\approx 179.8°C$. The

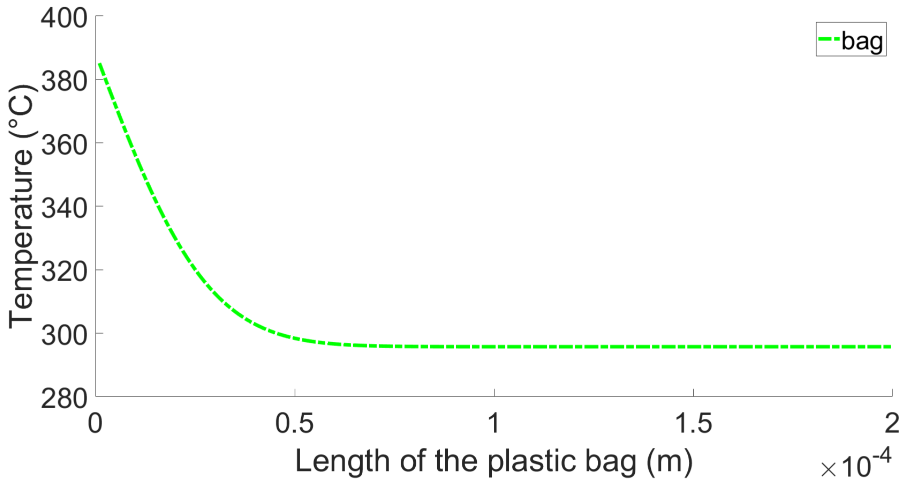

Figure 14 – Temperatures at the neighbourhood of the plastic bag after sealing.

remaining energy is used on the melting volume, ≈ 17.9% rises the temperature ≈ 89.4°C to the melting temperature, and ≈ 20.5% melts the volume.

It would be interesting to avoid losing heat as much as possible, therefore we could use thermal insulation over the wire, plate, and neighbourhood of the bag, like glass fiber needle mat. Using polyurethane foam would be cheaper, but temperatures over 180°C will degrade the material, even for short-term duration, according to Gallagher [2021], and the glass fiber can resist up to 1200°C.

5.1 Sensitivity Analysis

Sensitivity analysis is a study of how changing the set of parameters can affect the dependant variables and the result, it is very useful for financial modeling. Changing, individually, all initial considerations allow us to estimate what would be the optimal configuration for the system to be built. Each table below presents, in the first column, which property was changed, the second column shows the new value to that variable, and the third column the total time required to melt the plastic bag.

5.1.1 Environment Properties

The results are shown in Tab. 5 and Fig. 15. Changing any of those properties did not affect significantly the result, therefore the device is usable at any place, under any weather, and in any season.

5.1.2 Wire and Plate Dimensions

The results are shown in Tab. 6 and Fig. 16. Only the wire diameter shown significantly different results. Different wire length and plate width will not change much

Point of Reference		Heat Mode	Energy Value [J]
T_w *point*			
	$\hookrightarrow$	Total power generated	$+92.791$
	$\hookleftarrow$	Total conduction from wire to plate	-70.150
	$\hookleftarrow$	Total convection from the wire	-0.077
	$\hookleftarrow$	Total radiation from the wire	-0.001
		Balance	$+22.563$
		Sensible heat	22.563
		Latent heat	0
		Temperature risen	$+180.23°C$
T_p *point*			
	$\hookrightarrow$	Total conduction from wire to plate	$+70.150$
	$\hookleftarrow$	Total conduction from plate to bag	-35.694
	$\hookleftarrow$	Total convection from the plate	-0.140
	$\hookleftarrow$	Total radiation from the plate	-0.009
		Balance	$+34.306$
		Sensible heat	34.306
		Latent heat	0
		Temperature risen	$+179.75°C$
T_b *point*			
	$\hookrightarrow$	Total conduction from plate to bag	$+35.694$
	$\hookleftarrow$	Total conduction in the bag neighbourhood	-0.040
	$\hookleftarrow$	Total convection from the bag neighbourhood	-0.009
		Balance	$+35.645$
		Sensible heat	16.646
		Latent heat	19.000
		Temperature risen	$+89.40°C$

Table 4 – Total heat generated, transferred, and lost by the system.

the results, it is important to remember that altering the wire length also changes the plate and the bag length. Another relevant consideration is that there is a limit for how thin the wire is, using 0.01 mm for example, would not allow it to generate enough energy using just 12 V, entering in thermodynamic equilibrium and would never achieve the melting temperature. A larger plate, would just lose more heat through convection instead of helping the conduction, we do not need a large sealing area, so this property can only be reduced.

Property	New Value	Total Time $[s]$
Room temperature	$-27.4°C$	0.126
Room temperature	$-17.4°C$	0.122
Room temperature	$-7.4°C$	0.117
Room temperature	$2.6°C$	0.113
Room temperature	$12.6°C$	0.108
Room temperature	$22.6°C$	0.104
Room temperature	$32.6°C$	0.099
Room temperature	$42.6°C$	0.094
Air humidity	0%	0.103637
Air humidity	48%	0.103627
Air humidity	68%	0.103622
Air humidity	88%	0.103618
Air humidity	100%	0.103615
City's average altitude	$0\ m$	0.103630
City's average altitude	$500\ m$	0.103625
City's average altitude	$1000\ m$	0.103621
City's average altitude	$1500\ m$	0.103616
City's average altitude	$2000\ m$	0.103615

Table 5 – Sensitivity analysis of environmental properties.

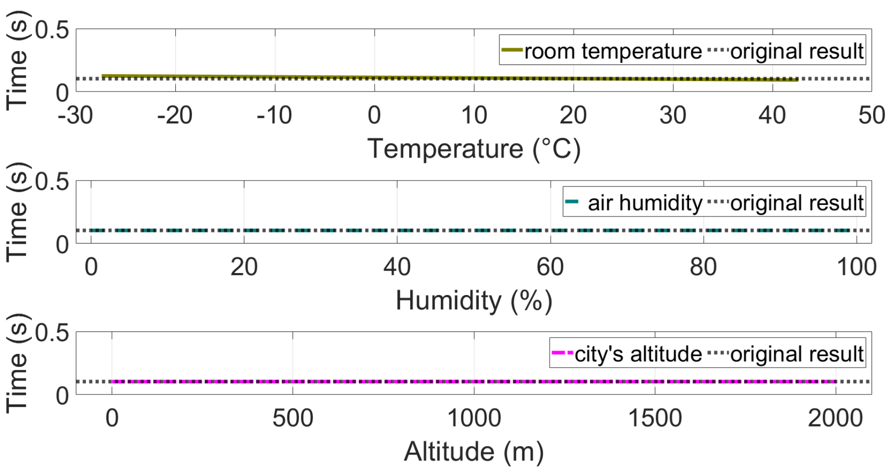

Figure 15 – Graphical sensitivity analysis of environmental properties.

Even though augmenting the diameter would directly increase the heat loss through convection and radiation, it also reduces the wire resistance and, therefore, elevates electrical power. The process occurs fast and the surface areas of the components are very small, then, the heat loss is very little in comparison with electrical power, lesser than 0.3%, thus, a larger wire melts the bag more quickly.

Property	New Value	Total Time [s]
Wire Diameter	0.04 mm	10.21
Wire Diameter	0.05 mm	5.271
Wire Diameter	0.06 mm	3.354
Wire Diameter	0.07 mm	2.361
Wire Diameter	0.08 mm	1.769
Wire Diameter	0.09 mm	1.384
Wire Diameter	0.10 mm	1.118
Wire Diameter	0.50 mm	0.104
Wire Diameter	1.00 mm	0.070
Wire Diameter	2.00 mm	0.058
Wire Diameter	3.00 mm	0.054
Wire Diameter	4.00 mm	0.053
Wire Length	05.00 cm	0.027
Wire Length	10.00 cm	0.048
Wire Length	15.00 cm	0.073
Wire Length	20.00 cm	0.104
Wire Length	30.00 cm	0.131
Plate Width	1.0 mm	0.087
Plate Width	2.5 mm	0.092
Plate Width	5.0 mm	0.104
Plate Width	7.5 mm	0.117
Plate Width	10.0 mm	0.131

Table 6 – Sensitivity analysis of dimensional properties.

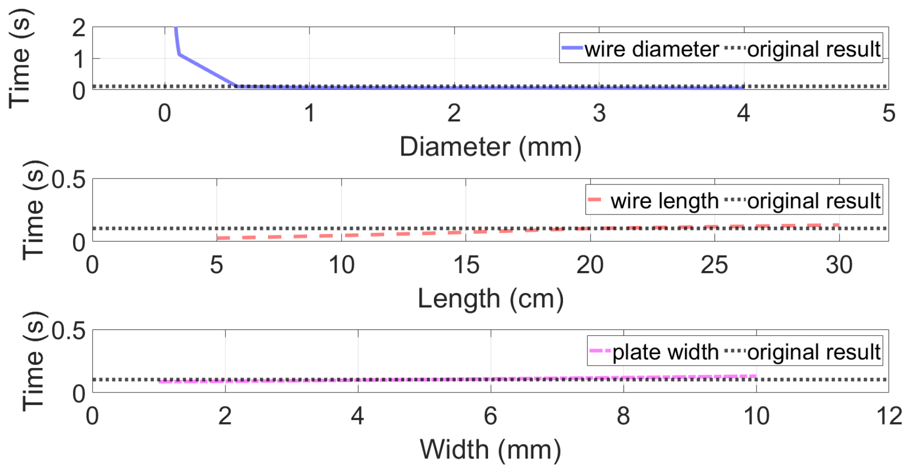

Figure 16 – Graphical sensitivity analysis of dimensional properties.

5.1.3 Electrical Power

The electrical power is the most important property in regard to the result, we can alter its value through the selected voltage, the influence of voltage to the results are shown in Tab. 7 and Fig. 17. We notice that the relation between electrical voltage and time needed is not linear. Due to various types of thermal energy loss, the temporal variation at high voltages is insignificant. This indicates that we are capable of determining the most optimum voltage levels.

Property	New Value	Total Time [s]
Voltage	1.5 V	4.897
Voltage	3.0 V	1.134
Voltage	4.5 V	0.523
Voltage	6.0 V	0.312
Voltage	7.5 V	0.214
Voltage	9.0 V	0.160
Voltage	10.5 V	0.126
Voltage	12.0 V	0.104

Table 7 – Sensitivity analysis of electrical power

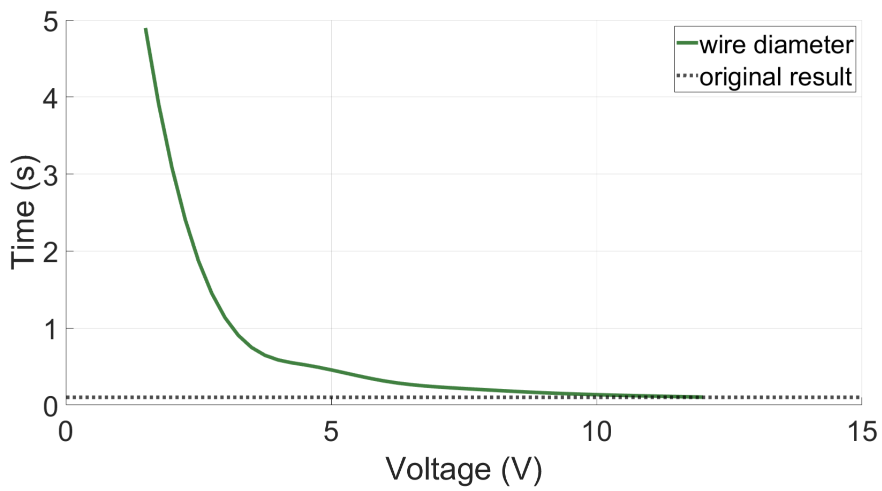

Figure 17 – Graphical sensitivity analysis of electrical power.

5.2 Optimal Setup

The voltage and the wire diameter are the properties that strongly defines the results. Working with there two variables, changing them at the same time, and making a few tests for different wire lengths, provided very interesting results, as shown in Tab. 8.

Voltage [V]	Wire Length [mm]	Wire Diameter [mm]	Total Time [s]
1.5 V	10.00 cm	1.00 mm	0.690933
1.5 V	15.00 cm	1.00 mm	1.264869
1.5 V	20.00 cm	1.00 mm	2.033683

Table 8 – Optional results for voltage and wire diameter.

Figure 18 – AAA rechargeable alkaline battery.

Using a wire with 1 *mm* of diameter make possible the employment of a single common AAA battery (Fig. 18) that is very small and cheap. Of course, with the vacuum pump, the device will need more power, but just for the thermal system the battery suffice. It takes ≈ 2 *seconds* to seal and in this scenario the temperature of the wire and the plate have an average difference of just $\approx 0.007\ K$, the lines are indiscernible in the graph (Fig. 19), and even the melting point temperature is closer all the time, meaning that at the end, the final temperature of the wire is lower, allowing us to use cheaper materials for the casting.

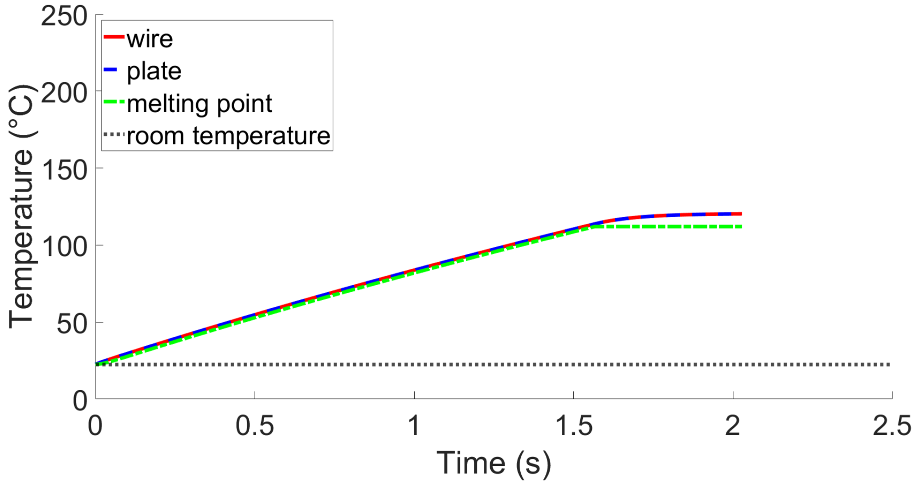

Figure 19 – Optional temperature vs time for the wire, plate, and melting point.

Another important difference is that the wire temperature goes up to just $120.3°C$ which now allow the utilization of polyurethane foam as insulator and, above that, lower temperatures are towards safety of the operator.

6 Conclusion

The current study established a simplified numerical approach for determining the thermal characteristics of a homemade sealer. The research aimed to identify if it is possible to build it at home at lower prices. For now, it is difficult to assume the final cost of the device we are projecting, but even considering the purchase of a vacuum pump instead of developing one, the device is already feasible with the cost being less than half of the market price.

It is worth commenting that, although the behaviors and values experienced were expected and coherent, our study does not have analytical nor experimental validation, further usage of different software and techniques must be done to fully validate the data acquired.

The electrical voltage and tungsten wire diameter were determined to be the most important estimated variables. This work has shown the effect of the different setups to the time it takes to the device for sealing the plastic bag. Furthermore, we still can develop the thermal system calculations doing the following enhancements:

- Consider the conduction inside the plate, the wire, and the melting volume;
- Calculate the radiation from the plastic bag;
- Include the properties of the solder;
- Work with a retractile wire enhancing efficiency for different sizes of plastic bags;
- Test different materials for the wire and the plate;
- Branch the wire, solder, plate, and melting volume to have more realistic curves;
- Consider the expansion of the materials as function of temperature;
- Add a thermal insulator.

Further, studies can be done about the vacuum pump, the casting material, and the electrical system, including sensors and a display.

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Annex

ANNEX A – Calculation Script (*.m)

```
%-------------------------------------------------------------------
%% SETUP
%-------------------------------------------------------------------

clear;
close all;
format long;

%-------------------------------------------------------------------
%% GENERAL DECLARATIONS
%-------------------------------------------------------------------

% time variation
dt = 1e-6; % [s]
% potential difference
%                                             VOLTAGE = 1.5; % [V]
                                            VOLTAGE = 12; % [V]
% room temperature
%                                             room_T = 273.15 + ...
    42.6; % [K]
                                            room_T = 273.15 + 22.6; ...
                                               % [K]
% relative humidity
%                                             room_phi = 1 ; % ...
    [nondimensional]
                                            room_phi = 0.68 ; % ...
                                               [nondimensional]
% altitude in Uberlandia
%                                             CITY_H = 2000; % [m]
                                            CITY_H = 854; % [m]

%% WIRE
% wire useful length
%                                             wire_L = 3e-1; % [m]
                                            wire_L = 2e-1; % [m]
% wire extra length
wire_extra_L = 4e-2; % [m]
% wire diameter
%                                             wire_D = 10e-4; % [m]
                                            wire_D = 5e-4; % [m]

```

```
%% PLATE
% plate width
%                                             plate_W = 10e-3; % [m]
                                            plate_W = 5e-3; % [m]

% BAG
% numbe rof small sections
bag_sections = 200;
% small length of the sections of the bag
bag_dL = 1e-5; % [m]

%-------------------------------------------------------------------
%% VARIABLES DECLARATIONS
%-------------------------------------------------------------------

% total sensible time
t_total_sensible = 0; % [s]
% total latent time
t_total_latent = 0; % [s]
% total  time
t_total = 0; % [s]
% total latent heat
q_latent = 0; % [J]
% temperatures of the bag
bag_T = zeros; % [K]
% heat of the bag
Q_cond_3 = zeros; % [W]
Q_conv_b = zeros; % [W]
% counter
COUNTER = 1;
% plot
array_time = zeros;
array_melt_point_Temperature = zeros;
array_wire_Temperature = zeros;
array_plate_Temperature = zeros;
array_bag_Temperature_1 = zeros;
array_bag_Temperature_2 = zeros;
array_bag_Temperature_3 = zeros;
array_bag_Temperature_4 = zeros;
array_bag_Temperature_5 = zeros;
array_bag_Temperature_10 = zeros;
% total heat
total_power_generated = 0;
total_Q1_conduction = 0;
total_Q2_conduction = 0;
total_bag_conduction = 0;
total_wire_convection = 0;
```

```
total_wire_radiation = 0;
total_plate_convection = 0;
total_plate_radiation = 0;
total_bag_convection = 0;

%-------------------------------------------------------------------
%% CONSTANTS
%-------------------------------------------------------------------

% heat transfer
% Stefan-Boltzmann constant
sigma = 5.670374419e-8; % [W/(m^2*K^4)]
% Newton's law of universal gravitation
% universal gravitation constant
universal_G = 6.67430e-11; % [N*m^2/kg^2]

%-------------------------------------------------------------------
%% PROPERTIES OF THE ENVIRONMENT ***NOT*** AS FUNCTION OF TEMPERATURE
%-------------------------------------------------------------------

% initial temperature
air_T = room_T; % [K]
% relative humidity
air_phi = room_phi ; % [nondimensional]

% sea level pressure
sea_p = 101325; % [Pa]
% sea level temperature
sea_T = 15 + 273.15; % [K]
% specific gas constant for dry air
air_R_dry_air = 287.058; % [J/(kg*K)]
% specific gas constant for saturated steam
air_R_steam = 461.495; % [J/(kg*K)]

% gravity
% mass of earth
earth_M = 5.9722e24; % [kg]
% radius of earth
earth_R = 6.3781e6; % [m]
% Newton's Law of Universal Gravitation
CITY_g = (universal_G * earth_M) / (earth_R + CITY_H)^2; % [m/s^2]

%-------------------------------------------------------------------
%% PROPERTIES OF THE TUNGSTEN WIRE ***NOT*** AS FUNCTION OF TEMPERATURE
%-------------------------------------------------------------------

% initial temperature
```

```
wire_T = room_T;

% estimated efficiency
% assuming there is no glow
wire_eta_term = 1; % [nondmentional]
% total length of the wire
wire_total_L = wire_L + wire_extra_L; % [m]
% cross-section area of the wire
wire_cross_section_A = 0.25 * pi * wire_D^2; % [m^2]
% exposed area
wire_A = 0.5 * pi * wire_D * wire_L; % [m^2]
% total length of the wire over cross-section area of the wire for ...
    the Pouillet's law
wire_total_L__over__wire_section_A =  wire_total_L / ...
    wire_cross_section_A ; % [m^2]
% tungsten density
wire_density = 19250; % [kg/m^3]
% total volume of the wire
wire_total_V = wire_cross_section_A * wire_total_L; % [m^3]
% total mass of the wire
wire_total_m = wire_density * wire_total_V; % [kg]
% specific heat
wire_cp = 138; % [J/(kg*K)]

%-------------------------------------------------------------------
%% PROPERTIES OF THE ALUMINUM PLATE ***NOT*** AS FUNCTION OF TEMPERATURE
%-------------------------------------------------------------------

% initial temperature
plate_T = room_T;

% emissivity
plate_epsilon = 0.09; % [nondimensional]
% plate thickness
plate_thickness = 5e-5; % [m]
% plate density
plate_density = 27000; % [kg/m^3]
% plate length
plate_L = wire_L; % [m]
% contact area between solder and wire
plate_wire_contact_A = 0.5 * pi * wire_D * wire_L; % [m^2]
% contact area between plate and bag
plate_bag_contact_A = plate_L * plate_W; % [m^2]
% total volume of the plate
plate_total_V = plate_wire_contact_A * plate_thickness; % [m^3]
% total mass of the plate
plate_total_m = plate_density * plate_total_V; % [kg]
```

```
% exposed area
plate_A = plate_L * plate_W - plate_wire_contact_A; % [m^2]
% specific heat
plate_cp = 900; % [J/(kg*K)]

%------------------------------------------------------------------
%% PROPERTIES OF THE PLASTIC BAG ***NOT*** AS FUNCTION OF TEMPERATURE
%------------------------------------------------------------------

% initial temperature
bag_T_melting_point = room_T;
for bag_counter = 1:bag_sections
    bag_T(bag_counter) = room_T;
end

% melting temperature
bag_melting_T = 273.15 + 112; % [K]
% Thermal Conductivity
bag_k = 0.33 ; % [W/m*K]
% bag density
bag_density = 9.35e2; % [kg/m^3]
% thickness
bag_thickness = 5.08e-5; % [m]
% volume height
bag_H = 2 * bag_thickness; % [m]
% volume
bag_V = plate_bag_contact_A * bag_H; % [m^3]
% length
bag_L = wire_L; % [m]
% small sections exposed area
bag_dA = bag_dL * bag_L; % [m^2]
% small sections volume
bag_dV = bag_dA * bag_H; % [m^3]
% total mass of the plate
bag_dm = bag_density * bag_dV; % [kg]
% total mass of the bag
bag_total_m = bag_density * bag_V; % [kg]
% cross-section area of the bag
bag_cross_section_A = 2 * bag_H * wire_L; % [m^2]
% latent heat for melting
bag_Delta_H = 2e5; % [J/kg]
% latent heat
q_total_latent = bag_Delta_H * bag_density * bag_V; % [J]
% specific heat
bag_cp = 1900; % [J/(kg*K)]

%------------------------------------------------------------------
```

```
%% numerical iterations
%-----------------------------------------------------------------
while q_latent < q_total_latent

    %-----------------------------------------------------------------
    %% PROPERTIES AS FUNCTION OF TEMPERATURE
    %-----------------------------------------------------------------

    %% ENVIRONMENT
    % assuming air is an ideal gas
    % average temperature
    air_T_average_wire = 0.5 * room_T + 0.5 * wire_T; % [K]
    air_T_average_plate = 0.5 * room_T + 0.5 * plate_T; % [K]
    air_T_average_bag = 0.5 * room_T + 0.5 * (0.5*bag_T(2) + ...
       0.5*bag_T(bag_sections)); % [K]

    % thermal conductivity of air
    air_k_wire = 1.5207e-11 * air_T_average_wire^3 -4.8574e-8 * ...
       air_T_average_wire^2 + 1.0184e-4 * air_T_average_wire ...
       -3.9333e-4; % [W/(m*K)]
    air_k_plate = 1.5207e-11 * air_T_average_plate^3 -4.8574e-8 * ...
       air_T_average_plate^2 + 1.0184e-4 * air_T_average_plate ...
       -3.9333e-4; % [W/(m*K)]
    air_k_bag = 1.5207e-11 * air_T_average_bag^3 -4.8574e-8 * ...
       air_T_average_bag^2 + 1.0184e-4 * air_T_average_bag ...
       -3.9333e-4; % [W/(m*K)]

    % specific heat of air values
    air_cp_A = 28.11;
    air_cp_B = 0.1967e-2;
    air_cp_C = 0.4802e-5;
    air_cp_D = -1.966e-9;
    % molar mass of dry air
    air_MM = 28.9647; % [kg/kmol]
    % converting kJ to J and dividing air_MM
    air_cp_A = air_cp_A * 1e3 / air_MM;
    air_cp_B = air_cp_B * 1e3 / air_MM;
    air_cp_C = air_cp_C * 1e3 / air_MM;
    air_cp_D = air_cp_D * 1e3 / air_MM;
    % specific heat of air
    air_cp_wire = air_cp_A + air_cp_B * air_T_average_wire + ...
       air_cp_C * air_T_average_wire^2 + air_cp_D * ...
       air_T_average_wire^3; % [J/(kg*K)]
    air_cp_plate = air_cp_A + air_cp_B * air_T_average_plate + ...
       air_cp_C * air_T_average_plate^2 + air_cp_D * ...
       air_T_average_plate^3; % [J/(kg*K)]
```

```
air_cp_bag = air_cp_A + air_cp_B * air_T_average_bag + air_cp_C ...
    * air_T_average_bag^2 + air_cp_D * air_T_average_bag^3; % ...
    [J/(kg*K)]

% coeficient of thermal expansion
air_beta_wire = air_T_average_wire^-1; % [1/K]
air_beta_plate = air_T_average_plate^-1; % [1/K]
air_beta_bag = air_T_average_bag^-1; % [1/K]

% density values
% saturated steam pressure
air_p_sat_steam_wire  = exp(77.3450 + 0.0057 * ...
    air_T_average_wire - 7235 / air_T_average_wire) / ...
    air_T_average_wire^8.2; % [Pa]
air_p_sat_steam_plate  = exp(77.3450 + 0.0057 * ...
    air_T_average_plate - 7235 / air_T_average_plate) / ...
    air_T_average_plate^8.2; % [Pa]
air_p_sat_steam_bag  = exp(77.3450 + 0.0057 * air_T_average_bag ...
    - 7235 / air_T_average_bag) / air_T_average_bag^8.2; % [Pa]
% steam pressure
air_p_steam_wire = air_phi * air_p_sat_steam_wire ; % [Pa]
air_p_steam_plate = air_phi * air_p_sat_steam_plate; % [Pa]
air_p_steam_bag = air_phi * air_p_sat_steam_bag; % [Pa]
% absolute pressure
air_p_abs_dry_air = sea_p * exp(-CITY_H*CITY_g / (sea_T * ...
    air_R_dry_air)); % [Pa]
% dry air pressure
air_p_dry_air_wire = air_p_abs_dry_air - air_p_steam_wire; % [Pa]
air_p_dry_air_plate = air_p_abs_dry_air - air_p_steam_plate; % [Pa]
air_p_dry_air_bag = air_p_abs_dry_air - air_p_steam_bag; % [Pa]
% dry air density
air_density_dry_air_wire = air_p_dry_air_wire / (air_R_dry_air * ...
    air_T_average_wire); % [kg/m^3]
air_density_dry_air_plate = air_p_dry_air_plate / (air_R_dry_air ...
    * air_T_average_plate); % [kg/m^3]
air_density_dry_air_bag = air_p_dry_air_bag / (air_R_dry_air * ...
    air_T_average_bag); % [kg/m^3]
% steam density
air_density_steam_wire = air_p_steam_wire / (air_R_steam * ...
    air_T_average_wire); % [kg/m^3]
air_density_steam_plate = air_p_steam_plate / (air_R_steam * ...
    air_T_average_plate); % [kg/m^3]
air_density_steam_bag = air_p_steam_bag / (air_R_steam * ...
    air_T_average_bag); % [kg/m^3]
% density
air_density_phi_wire = air_density_dry_air_wire + ...
    air_density_steam_wire; % [kg/m^3]
```

```
    air_density_phi_plate = air_density_dry_air_plate + ...
        air_density_steam_plate; % [kg/m^3]
    air_density_phi_bag = air_density_dry_air_bag + ...
        air_density_steam_bag; % [kg/m^3]

    % dynamic viscosity (Sutherland Equation)
    air_mu_wire = 1.719e-5 * (air_T_average_wire/273)^(3/2) * ...
        (273+111)/(air_T_average_wire + 111); % [kg/(m*s)]
    air_mu_plate = 1.719e-5 * (air_T_average_plate/273)^(3/2) * ...
        (273+111)/(air_T_average_plate + 111); % [kg/(m*s)]
    air_mu_bag = 1.719e-5 * (air_T_average_bag/273)^(3/2) * ...
        (273+111)/(air_T_average_bag + 111); % [kg/(m*s)]

    % kinematic viscosity
    air_nu_wire = air_mu_wire / air_density_phi_wire; % [m^2/s)]
    air_nu_plate = air_mu_plate / air_density_phi_plate; % [m^2/s)]
    air_nu_bag = air_mu_bag / air_density_phi_bag; % [m^2/s)]

    % thermal diffusivity of air
    air_alpha_wire = air_k_wire / (air_density_phi_wire * ...
        air_cp_wire); % [m^2/s]
    air_alpha_plate = air_k_plate / (air_density_phi_plate * ...
        air_cp_plate); % [m^2/s]
    air_alpha_bag = air_k_bag / (air_density_phi_bag * air_cp_bag); ...
        % [m^2/s]

    %% WIRE
    % Resistivity
    wire_RHO_300K = 5.65e-8; % [ohm*m]
    wire_RHO_A = 3.414e-7;
    wire_RHO_B = 4.551e-3;
    wire_RHO_C = -4.454e-1;
    wire_RHO_A = wire_RHO_A * wire_RHO_300K;
    wire_RHO_B = wire_RHO_B * wire_RHO_300K;
    wire_RHO_C = wire_RHO_C * wire_RHO_300K;
    wire_RHO = wire_RHO_A * wire_T^2 + wire_RHO_B * wire_T + ...
        wire_RHO_C; % [ohm*m]

    % Electrical Resistance
    % Pouillet's law
    wire_R_A = wire_RHO_A * wire_total_L__over__wire_section_A;
    wire_R_B = wire_RHO_B * wire_total_L__over__wire_section_A;
    wire_R_C = wire_RHO_C * wire_total_L__over__wire_section_A;
    wire_R = wire_R_A * wire_T^2 + wire_R_B * wire_T - wire_R_C; % [ohm]

    % Emissivity
    % Linear Regression the table reported by Jones and Langmuir
```

```
    wire_epsilon_A = 6.3351076e-3;
    wire_epsilon_B = 7.2946410e-6;
    wire_epsilon_C = 9.2134646e-8;
    wire_epsilon = wire_epsilon_C * wire_T^2 + wire_epsilon_B * ...
        wire_T + wire_epsilon_A; % [nondimensional]

    %% PLATE
    % Thermal Conductivity
    %Correlations for the Thermal Conductivity of Metals as a ...
        Function of Temperature S. I. Abu-Eishah1:
    % 100 < plate_T < 933.2 [K]
    plate_k_a = 1.724468;
    plate_k_b = 0.815012;
    plate_k_c = -9.953e-4;
    plate_k_d = 164.93990;
    plate_k = plate_k_a * plate_T ^ plate_k_b * exp(plate_k_c * ...
        plate_T) * exp(plate_k_d / plate_T); % [W/(m*K)]

    %--------------------------------------------------------------------
    %% DIMENSIONLESS
    %--------------------------------------------------------------------

    % Prandtl
    Pr_wire = air_nu_wire / air_alpha_wire; % [nondimensional]
    Pr_plate = air_nu_plate / air_alpha_plate; % [nondimensional]
    Pr_bag = air_nu_bag / air_alpha_bag; % [nondimensional]

    % OPTIONAL Prandtl
    Pr2_wire = air_mu_wire * air_cp_wire / air_k_wire; % ...
        [nondimensional]
    Pr2_plate = air_mu_plate * air_cp_plate / air_k_plate; % ...
        [nondimensional]
    Pr2_bag = air_mu_bag * air_cp_bag / air_k_bag; % [nondimensional]

    % Grashof for horizontal cylinder
    Gr_wire = CITY_g * air_beta_wire * (wire_T - air_T_average_wire) ...
        * wire_D^3 / air_nu_wire^2; % [nondimensional]

    % OPTIONAL Grashoff for horizontal cylinder
    Gr_wire2 = CITY_g * air_beta_wire * (wire_T - ...
        air_T_average_wire) * wire_D^3 / (air_mu_wire^2 / ...
        air_density_phi_wire^2); % [nondimensional]

    % Grashof for horizontal plate facing upwards
    Gr_plate = CITY_g * air_beta_plate * (plate_T - ...
        air_T_average_plate) * (plate_A/(2*plate_W + 2*plate_L))^3 / ...
        air_nu_plate^2; % [nondimensional]
```

```
Gr_bag = CITY_g * air_beta_bag * ...
    ((0.5*bag_T(2)+0.5*bag_T(bag_sections)) - air_T_average_bag) ...
    * (bag_dA/(2*bag_dL + 2*bag_L))^3 / air_nu_bag^2; % ...
    [nondimensional]

% Rayleigh for horizontal cylinder
Ra_wire = Gr_wire * Pr_wire; % [nondimensional]

% Rayleigh for horizontal plate facing upwards
Ra_plate = Gr_plate * Pr_plate; % [nondimensional]
Ra_bag = Gr_bag * Pr_bag; % [nondimensional]

% Average Nusselt for external flow, horizontal cylinder, ...
    sufficient lenght, 10^-5 < Ra_wire < 10^12
% Churchill and Chu correlation
Nu_wire =(0.6 + ( ( 0.387*Ra_wire^(1/6) ) / ( 1 + ...
    (0.559/Pr_wire)^(9/16))^(8/27) ) )^2;

% air heat transfer Coefficient for external flow, horizontal ...
    cylinder, sufficient lenght, 10^-5 < Ra_wire < 10^12
air_h_wire = (air_k_wire/wire_D) * Nu_wire; % [W /m^2*K]

% Average Nusselt for horizontal plate facing upwards, 10^4 < ...
    Ra_plate < 10^6
Nu_plate1 = 0.54 * (Ra_plate)^0.25;
Nu_bag1 = 0.54 * (Ra_bag)^0.25;

% Average Nusselt for horizontal plate facing upwards, 10^6 < ...
    Ra_plate < 10^11
Nu_plate2 = 0.15 * (Ra_plate)^0.3;
Nu_bag2 = 0.15 * (Ra_bag)^0.3;

% air heat transfer Coefficient for external flow, horizontal ...
    cylinder, sufficient lenght, 10^4 < Ra_plate < 10^11
if Ra_plate < 1e6
    air_h_plate = (air_k_plate/(plate_A/(2*plate_W + ...
        2*plate_L))) * Nu_plate1; % [W /m^2*K]
    air_h_bag = (air_k_bag/(bag_dA/(2*bag_dL + 2*bag_L))) * ...
        Nu_bag1; % [W /m^2*K]
elseif Ra_plate > 1e6
    air_h_plate = (air_k_plate/(plate_A/(2*plate_W + ...
        2*plate_L))) * Nu_plate2; % [W /m^2*K]
    air_h_bag = (air_k_bag/(bag_dA/(2*bag_dL + 2*bag_L))) * ...
        Nu_bag2; % [W /m^2*K]
end

%-------------------------------------------------------------------
```

```
%% POWER SUPPLY
%-------------------------------------------------------------------

P_e = VOLTAGE^2 / wire_R; % [W]

%-------------------------------------------------------------------
%% SENSIBLE HEAT
%-------------------------------------------------------------------

% THERMAL RESISTANCES
R_cond_1 = R_conduction(0.5 * plate_thickness, plate_k , ...
    plate_wire_contact_A); % [K/W]
R_cond_2 = R_conduction(0.5 * plate_thickness, plate_k , ...
    plate_bag_contact_A) + R_conduction(0.5 * bag_H, bag_k , ...
    plate_bag_contact_A); % [K/W]
R_cond_3 = R_conduction(bag_dL, bag_k , bag_cross_section_A); % ...
    [K/W]
relative_R_cond_3 = R_conduction(bag_dL*(bag_sections-1), bag_k ...
    , bag_cross_section_A); % [K/W]

R_conv_w = R_convection(air_h_wire , wire_A); % [K/W]
R_conv_p = R_convection(air_h_plate , plate_A); % [K/W]
R_conv_b = R_convection(air_h_bag , bag_dA); % [K/W]
R_rad_w = R_radiation(wire_epsilon, sigma, wire_A, wire_T, ...
    room_T); % [K/W]
R_rad_p = R_radiation(plate_epsilon, sigma, plate_A, plate_T, ...
    room_T); % [K/W]

% HEAT TRANSFER
Q_cond_1 = (1/R_cond_1) * (wire_T - plate_T); % [W]
Q_cond_2 = (1/R_cond_2) * (plate_T - bag_T_melting_point); % [W]
for bag_counter = 1:(bag_sections - 1)
    Q_cond_3(bag_counter) = (1/R_cond_3) * (bag_T(bag_counter) - ...
        bag_T(bag_counter + 1)); % [W]
end
relative_Q_cond_3 = (1/relative_R_cond_3) * (bag_T_melting_point ...
    - room_T); % [W]

Q_conv_w = (1/R_conv_w) * (wire_T - room_T); % [W]
Q_conv_p = (1/R_conv_p) * (plate_T - room_T); % [W]
for bag_counter = 1:(bag_sections - 1)
    Q_conv_b(bag_counter) = (1/R_conv_b) * (bag_T(bag_counter) - ...
        room_T); % [W]
end
Q_rad_w = (1/R_rad_w) * (wire_T - room_T); % [W]
Q_rad_p = (1/R_rad_p) * (plate_T - room_T); % [W]
```

```

    total_power_generated = total_power_generated + P_e;
    total_Q1_conduction = total_Q1_conduction + Q_cond_1;
    total_Q2_conduction = total_Q2_conduction + Q_cond_2;
    total_wire_convection = total_wire_convection + Q_conv_w;
    total_wire_radiation = total_wire_radiation + Q_rad_w;
    total_plate_convection = total_plate_convection + Q_conv_p;
    total_plate_radiation = total_plate_radiation + Q_rad_p;
    total_bag_conduction = total_bag_conduction + relative_Q_cond_3;
    total_bag_convection = total_bag_convection + sum (Q_conv_b);

    % TEMPERATURES
    wire_T = wire_T + dt * (P_e - Q_cond_1 - Q_conv_w - ...
        Q_rad_w)/(wire_total_m * wire_cp); % [K]
    plate_T = plate_T + dt * (Q_cond_1 - Q_cond_2 - Q_conv_p - ...
        Q_rad_p)/(plate_total_m * plate_cp); % [K]
    bag_T_melting_point = bag_T_melting_point + dt * (Q_cond_2 - ...
        Q_cond_3(1))/(bag_total_m * bag_cp); % [K]
    bag_T(1) = bag_T_melting_point; % [K]
    for bag_counter = 2:(bag_sections - 1)
        bag_T(bag_counter) = bag_T(bag_counter) + dt * ...
            (Q_cond_3(bag_counter-1) - Q_cond_3(bag_counter) - ...
            Q_conv_b(bag_counter-1))/(bag_dm * bag_cp); % [K]
    end

    % TIME
    t_total_sensible = t_total_sensible + dt; % [s]
    t_total = t_total + dt; % [s]

    array_time(COUNTER) = t_total; % [s]
    array_wire_Temperature(COUNTER) = wire_T -273.15; % [oC]
    array_plate_Temperature(COUNTER) = plate_T -273.15; % [oC]
    array_melt_point_Temperature(COUNTER) = bag_T_melting_point ...
        -273.15; % [oC]
    array_bag_Temperature_1(COUNTER) = bag_T(bag_sections/100*10) ...
        -273.15; % [oC]
    array_bag_Temperature_2(COUNTER) = bag_T(bag_sections/100*20) ...
        -273.15; % [oC]
    array_bag_Temperature_3(COUNTER) = bag_T(bag_sections/100*30) ...
        -273.15; % [oC]
    array_bag_Temperature_4(COUNTER) = bag_T(bag_sections/100*40) ...
        -273.15; % [oC]
    array_bag_Temperature_5(COUNTER) = bag_T(bag_sections/100*50) ...
        -273.15; % [oC]
    array_bag_Temperature_10(COUNTER) = bag_T(bag_sections/100*100) ...
        -273.15; % [oC]
    %-------------------------------------------------------------------
```

```
    %% LATENT HEAT
    %--------------------------------------------------------------------

    if bag_T_melting_point > bag_melting_T

        % total latent heat
        q_latent =  q_latent + dt * (Q_cond_2 - Q_cond_3(1)); % [J]
        % total latent time
        t_total_latent = t_total_latent + dt; % [s]

        % stabilizing total sensible time
        t_total_sensible = t_total_sensible - dt; % [s]

        % stabilizing bag temperature
        bag_T_melting_point = bag_melting_T; % [K]
        bag_T(1) = bag_T_melting_point; % [K]
        for bag_counter = 2:(bag_sections - 1)
            if bag_T(bag_counter) > bag_melting_T
                bag_T(bag_counter) = bag_T_melting_point; % [K]
            end
        end
        % stabilizing plot
        array_melt_point_Temperature(COUNTER) = bag_T_melting_point ...
           -273.15; % [oC]
    end

    COUNTER = COUNTER +1;
end

%--------------------------------------------------------------------
%% SHOW TOTAL TIME
%--------------------------------------------------------------------

result = array_time(length(array_time))

%--------------------------------------------------------------------
%% PLOT
%--------------------------------------------------------------------

%% RESULTS 1 n 3
figure; hold on
p1 = plot(array_time,array_wire_Temperature, '-', 'LineWidth', 5, ...
   'Color', [255/255 0/255 0/255]); L1 = "wire";
p2 = plot(array_time,array_plate_Temperature, '--', 'LineWidth', 5, ...
   'Color', [0/255 0/255 255/255]); L2 = "plate";
p3 = plot(array_time,array_melt_point_Temperature, '-.', ...
   'LineWidth', 5, 'Color', [0/255 255/255 0/255]); L3 = "melting ...
```

```
    point";
p4 = yline(room_T-273.15, ':', 'LineWidth', 5, 'Color', [0/255 0/255 ...
    0/255]); L4 = "room temperature";
legend([p1,p2,p3, p4], [L1, L2, L3, L4], 'Location', 'northwest');
ylim([0 250])
set(gca,'FontSize',40)
xlabel('Time (s)')
ylabel('Temperature (oC)')
grid on
hold off

%% RESULTS 2
dL_vector = 1:bag_sections;
dL_vector = dL_vector*1e-6;
figure; hold on
p1 = plot(array_time(1:3000),array_wire_Temperature(1:3000), '-', ...
    'LineWidth', 5, 'Color', [255/255 0/255 0/255]); L1 = "wire";
p2 = plot(array_time(1:3000),array_plate_Temperature(1:3000), '--', ...
    'LineWidth', 5, 'Color', [0/255 0/255 255/255]); L2 = "plate";
legend([p1,p2], [L1,L2], 'Location', 'northwest');
set(gca,'FontSize',40)
xlabel('Time (s)')
ylabel('Temperature (oC)')
grid on
hold off

%% RESULTS 4
figure; hold on
p1 = plot(array_time,array_melt_point_Temperature, '-', 'LineWidth', ...
    5, 'Color', [0/255 255/255 0/255]); L1 = "melting point";
p2 = plot(array_time,array_bag_Temperature_1, '--', 'LineWidth', 5, ...
    'Color', [0/255 225/255 0/255]); L2 = "10%";
p3 = plot(array_time,array_bag_Temperature_2, ':', 'LineWidth', 5, ...
    'Color', [0/255 195/255 0/255]); L3 = "20%";
p4 = plot(array_time,array_bag_Temperature_3, '-.', 'LineWidth', 5, ...
    'Color', [0/255 165/255 0/255]); L4 = "30%";
p5 = plot(array_time,array_bag_Temperature_4, '--', 'LineWidth', 5, ...
    'Color', [0/255 135/255 0/255]); L5 = "40%";
p6 = plot(array_time,array_bag_Temperature_5, ':', 'LineWidth', 5, ...
    'Color', [0/255 105/255 0/255]); L6 = "50%";
p7 = plot(array_time,array_bag_Temperature_10, '-', 'LineWidth', 5, ...
    'Color', [0/255 75/255 0/255]); L7 = "100%";
legend([p1,p2,p3,p4,p5,p6,p7], [L1, L2, L3, L4, L5, L6, L7], ...
    'LineWidth', 5, 'Location', 'northwest');
set(gca,'FontSize',40)
xlabel('Time (s)')
ylabel('Temperature (oC)')
```

```
grid on
hold off


%% RESULTS 5
dL_vector = 1:bag_sections;
dL_vector = dL_vector*1e-6;
figure; hold on
p1 = plot(dL_vector, bag_T, '-.', 'LineWidth', 5, 'Color', [0/255 ...
    255/255 0/255]); L1 = "bag";
legend([p1], [L1], 'Location', 'northeast');
set(gca,'FontSize',40)
xlabel('Length of the plastic bag (m)')
ylabel('Temperature (oC)')
grid on
hold off


Total_Balance_1 = total_power_generated -total_Q1_conduction ...
    -total_wire_convection -total_wire_radiation;
Total_Balance_2 = total_Q1_conduction -total_Q2_conduction ...
    -total_plate_convection -total_plate_radiation;
Total_Balance_3 = total_Q2_conduction -total_bag_conduction ...
    -total_bag_convection;



%% functions
%% conductive thermal resistance
function [R] = R_conduction(L,k,A)
R = L/(k*A);
end
%% convective thermal resistance
function [R] = R_convection(h,A)
R = 1/(h*A);
end
%% radiative thermal resistance
function [R] = R_radiation(epsilon,sigma,A,T,room_T)
R = 1/( epsilon*sigma*A * (T^2+room_T^2) * (T+room_T) );
end

%% Sensitivity Analysis
%% 1
% roomtemperature(1) = -27.4;
% roomtemperaturetime(1) = 0.125875000000105;
% roomtemperature(2) = -17.4;
% roomtemperaturetime(2) = 0.121644000000101;
```

```
% roomtemperature(3) = -7.4;
% roomtemperaturetime(3) = 0.117304000000097;
% roomtemperature(4) = 2.6;
% roomtemperaturetime(4) = 0.112855000000092;
% roomtemperature(5) = 12.6;
% roomtemperaturetime(5) = 0.108295000000088;
% roomtemperature(6) = 22.6;
% roomtemperaturetime(6) = 0.103622000000083;
% roomtemperature(7) = 32.6;
% roomtemperaturetime(7) = 0.098833000000078;
% roomtemperature(8) = 42.6;
% roomtemperaturetime(8) = 0.093925000000073;
%
% airhumidity(1) = 0;
% airhumiditytime(1) = 0.103637000000083;
% airhumidity(2) = 48;
% airhumiditytime(2) = 0.103627000000083;
% airhumidity(3) = 68;
% airhumiditytime(3) = 0.103622000000083;
% airhumidity(4) = 88;
% airhumiditytime(4) = 0.103618000000083;
% airhumidity(5) = 100;
% airhumiditytime(5) = 0.103615000000083;
%
% altitude(1) = 0;
% altitudetime(1) = 0.103630000000083;
% altitude(2) = 500;
% altitudetime(2) = 0.103625000000083;
% altitude(3) = 1000;
% altitudetime(3) = 0.103621000000083;
% altitude(4) = 1500;
% altitudetime(4) = 0.103616000000083;
% altitude(5) = 2000;
% altitudetime(5) = 0.103615000000083;
%
% hold on
%
% x1 = subplot(3,1,1);
% p1 = plot(roomtemperature,roomtemperaturetime, '-', 'LineWidth', ...
    5, 'Color', [128/255 128/255 0/255]); L1 = "room temperature";
% p4 = yline(0.103622000000083, ':', 'LineWidth', 5, 'Color', [0/255 ...
    0/255 0/255]); L4 = "original result";
% legend([p1,p4], [L1,L4], 'Location', 'northeast','NumColumns',2);
% set(gca,'FontSize',35)
% ylabel('Time (s)')
% xlabel('Temperature (oC)')
% ylim([0 0.5])
```

```
% grid on
%
% x2 = subplot(3,1,2);
% p2 = plot(airhumidity,airhumiditytime, '--', 'LineWidth', 5, ...
    'Color', [0/255 128/255 128/255]); L2 = "air humidity";
% p4 = yline(0.103622000000083, ':', 'LineWidth', 5, 'Color', [0/255 ...
    0/255 0/255]); L4 = "original result";
% legend([p2,p4], [L2,L4], 'Location', 'northeast','NumColumns',2);
% set(gca,'FontSize',35)
% ylabel('Time (s)')
% xlabel('Humidity (%)')
% xlim([-2 102])
% ylim([0 0.5])
% grid on
%
% x3 = subplot(3,1,3);
% p3 = plot(altitude,altitudetime, '-.', 'LineWidth', 5, 'Color', ...
    [255/255 0/255 255/255]); L3 = "city's altitude";
% p4 = yline(0.103622000000083, ':', 'LineWidth', 5, 'Color', [0/255 ...
    0/255 0/255]); L4 = "original result";
% legend([p3,p4], [L3,L4], 'Location', 'northeast','NumColumns',2);
% set(gca,'FontSize',35)
% ylabel('Time (s)')
% xlabel('Altitude (m)')
% xlim([-100 2100])
% ylim([0 0.5])
% grid on
%
% hold off

%% 2
% wirediameter(1) = 0.04;
% wirediametertime(1) = 10.207033999112573;
% wirediameter(2) = 0.05;
% wirediametertime(2) = 5.271341000382913;
% wirediameter(3) = 0.06;
% wirediametertime(3) = 3.354168000114934;
% wirediameter(4) = 0.07;
% wirediametertime(4) = 2.361385999976165;
% wirediameter(5) = 0.08;
% wirediametertime(5) = 1.769129999944644;
% wirediameter(6) = 0.09;
% wirediametertime(6) = 1.383752999976348;
% wirediameter(7) = 0.1;
% wirediametertime(7) = 1.117522999998250;
% wirediameter(8) = 0.5;
% wirediametertime(8) = 0.103622000000083;
```

```
% wirediameter(9) = 1;
% wirediametertime(9) = 0.070451000000050;
% wirediameter(10) = 2;
% wirediametertime(10) = 0.058105000000037;
% wirediameter(11) = 3;
% wirediametertime(11) = 0.054426000000034;
% wirediameter(12) = 4;
% wirediametertime(12) = 0.052654000000032;
%
% wirelength(1) = 5;
% wirelengthtime(1) = 0.026691000000006;
% wirelength(2) = 10;
% wirelengthtime(2) = 0.047531000000027;
% wirelength(3) = 15;
% wirelengthtime(3) = 0.072940000000052;
% wirelength(4) = 20;
% wirelengthtime(4) = 0.103622000000083;
% wirelength(5) = 30;
% wirelengthtime(5) = 0.130824000000110;
%
% platewidth(1) = 1;
% platewidthtime(1) = 0.087126000000066;
% platewidth(2) = 2.5;
% platewidthtime(2) = 0.092270000000072;
% platewidth(3) = 5;
% platewidthtime(3) = 0.103622000000083;
% platewidth(4) = 7.5;
% platewidthtime(4) = 0.116597000000096;
% platewidth(5) = 10;
% platewidthtime(5) = 0.130824000000110;
%
%
% figure; hold on
%
% x1 = subplot(3,1,1);
% p1 = plot(wirediameter,wirediametertime, '-', 'LineWidth', 5, ...
    'Color', [128/255 128/255 255/255]); L1 = "wire diameter";
% p4 = yline(0.103622000000083, ':', 'LineWidth', 5, 'Color', [0/255 ...
    0/255 0/255]); L4 = "original result";
% legend([p1,p4], [L1,L4], 'Location', 'northeast','NumColumns',2);
% set(gca,'FontSize',35)
% xlabel('Diameter (mm)')
% ylabel({'Time (s)'; ''})
% ylim([0.00 2.00])
% xlim([-0.5 5])
% grid on
%
```

```
% x2 = subplot(3,1,2);
% p2 = plot(wirelength,wirelengthtime, '--', 'LineWidth', 5, ... 'Color', [255/255 128/255 128/255]); L2 = "wire length";
% p4 = yline(0.103622000000083, ':', 'LineWidth', 5, 'Color', [0/255 ... 0/255 0/255]); L4 = "original result";
% legend([p2,p4], [L2,L4], 'Location', 'northeast','NumColumns',2);
% set(gca,'FontSize',35)
% xlabel('Length (cm)')
% ylabel('Time (s)')
% xlim([0 32])
% ylim([0.00 0.5])
% grid on
%
% x3 = subplot(3,1,3);
% p3 = plot(platewidth,platewidthtime, '-.', 'LineWidth', 5, ... 'Color', [255/255 128/255 255/255]); L3 = "plate width";
% p4 = yline(0.103622000000083, ':', 'LineWidth', 5, 'Color', [0/255 ... 0/255 0/255]); L4 = "original result";
% legend([p3,p4], [L3,L4], 'Location', 'northeast','NumColumns',2);
% set(gca,'FontSize', 35)
% xlabel('Width (mm)')
% ylabel('Time (s)')
% xlim([0 12])
% ylim([0 0.5])
% grid on
%
% hold off

%% 3
% electricalpower(1) = 1.5;
% electricalpowertime(1) = 4.896622000330535;
% electricalpower(2) = 3.0;
% electricalpowertime(2) = 1.134212999996877;
% electricalpower(3) = 4.5;
% electricalpowertime(3) = 0.523107999994205;
% electricalpower(4) = 6.0;
% electricalpowertime(4) = 0.312805999998549;
% electricalpower(5) = 7.5;
% electricalpowertime(5) = 0.214471000000194;
% electricalpower(6) = 9.0;
% electricalpowertime(6) = 0.159920000000139;
% electricalpower(7) = 10.5;
% electricalpowertime(7) = 0.126166000000105;
% electricalpower(8) = 12;
% electricalpowertime(8) = 0.103622000000083;
%
% xx = 1.5:.25:12;
```

```
% yy = spline(electricalpower,electricalpowertime,xx);
%
% figure; hold on
% p1 = plot(xx,yy, '-', 'LineWidth', 5, 'Color', [64/255 128/255 ...
    64/255]); L1 = "wire diameter";
% p4 = yline(0.103622000000083, ':', 'LineWidth', 5, 'Color', [0/255 ...
    0/255 0/255]); L4 = "original result";
% legend([p1,p4], [L1,L4], 'Location', 'northeast');
% set(gca,'FontSize',40)
% xlabel('Voltage (V)')
% ylabel('Time (s)')
% ylim([0 5])
% xlim([0 15])
% grid on
% hold off
```