Bachelor Thesis

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CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY
OF MECHANICAL
ENGINEERING

Braking Resistor Design

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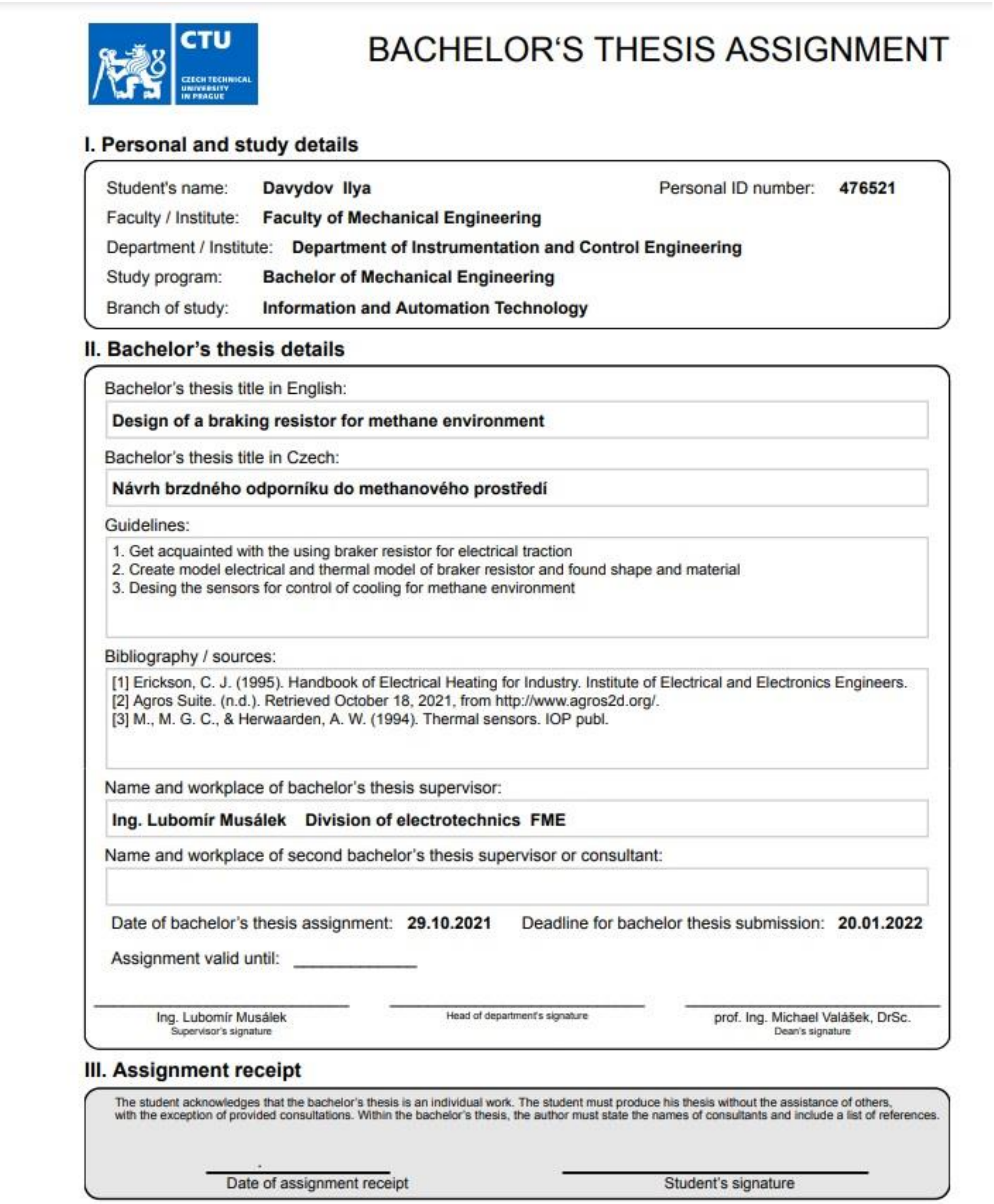

BACHELOR'S THESIS ASSIGNMENT

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Design of a braking resistor for methane environment

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Návrh brzdného odporníku do methanového prostředí

Guidelines:

1. Get acquainted with the using braker resistor for electrical traction
2. Create model electrical and thermal model of braker resistor and found shape and material
3. Desing the sensors for control of cooling for methane environment

Bibliography / sources:

[1] Erickson, C. J. (1995). Handbook of Electrical Heating for Industry. Institute of Electrical and Electronics Engineers.
[2] Agros Suite. (n.d.). Retrieved October 18, 2021, from http://www.agros2d.org/.
[3] M., M. G. C., & Herwaarden, A. W. (1994). Thermal sensors. IOP publ.

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

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Declaration

I declare that this bachelor thesis has been prepared independently under the guidance of my supervisor. Also, there’s an assumption that other practical work can be done based on this work. This has been done using the sources listed at the end, in the bibliography.

Acknowledgement

I would like to express my gratitude and sincerity to Ing. Lubomir Musalek for his guidance, knowledge, ideas and faith in me till the very end of my path called bachelor thesis.

Also, I would like to thank my parents for their faith in me and any kind of support.

Abstract

This bachelor thesis’s goal is to suggest a new idea of the design of braking resistor for a locomotive, operating in a methane environment, in other words – coal mines. The processes in braking will be described with details, as well as the effects of thermal and current fields. In the end it is necessary to select appropriate materials for both fields, specifically to protect the resistor from flowing cooling water, but to make sure the heat is conducted well.

List of figures

List of variables

α – heat transfer coefficient [W/(m^2*K)]

λ – thermal conductivity [W/(m*K)]

ϕ – potential [V]

ρ – density [kg/m^3]

σ – conductivity [S/m]

ε – emissivity [-]

γ – resistivity [Ω*m]

v – kinematic viscosity [m^2/s] or velocity [m/s]

w – flow velocity [m/s]

R – resistance [Ω]

V - voltage [V]

I – current [A]

J – current density [A/m^2]

Re – Reynolds number [-]

Pr – Prandtl number [-]

Nu – Nusselt number [-]

c_p – specific heat capacity [J/kg*K]

Q – volumetric heat [W/m^3]

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1. Introduction

1.1. Diesel locomotives for coal mines

1.1.1. Brief history

In underground mines, an ore locomotive with diesel power is used to transport ore cars. Early in the twentieth century, the first diesel mining locomotives were utilized in mines. The spread of diesel mining locomotives in the coal industry of the United Kingdom, Belgium, and other nations was aided by improvements in engines and the use of less expensive fuels.

Figure 1: A diesel locomotive for coal mines by LZH [3]

A typical setup for the diesel mining locomotive is a four-stroke diesel engine that powers it with water cooling. A mechanical gearbox controls speed, while a hydromechanical transmission controls speed on large diesel mining locomotives. Diesel mining locomotives are designed for routine mine operations as well as safe operation in areas where gas explosions are a risk. [1]

In time, the construction and functioning of locomotives for coal mines have changed. Nowadays, typical diesel ones (shown below in Fig.2) weigh up to 15 tons and consist of three parts: two cabins and a middle section with the engine and chassis. Cabins can be removed to make locomotives easier to transport into underground tunnels.

Figure 1: A Diesel Locomotive by PHS Strojarne

Speaking of technical characteristics, diesel engines range in power from 35 to 120 kW and are water cooled. Water-cooled exhaust manifold transports the exhaust gases. The torque force is transmitted from the engine to the axle gear via hydrostatic transmission, which ensures smooth operation. The chassis type is dual-axle, with an inter-axle cardan driveshaft ensuring transmission to the second axle. Interchangeable rims secure the travel wheels. The locomotives' suspension is provided by sagittal-shaped elastic rubber-metal blocks.[2]

1.1.2. Working principle

The most often-used way to transmit power is by means of converting the mechanical energy provided by a diesel engine into current for electric traction motors. Throughout most of the twentieth century, the common way was to connect the diesel engine to a direct-current generator, from which the current was delivered to the motors via proper controls. Beginning in the 1970s, tiny semiconductor rectifiers allowed the direct-current generator to be replaced by an alternator, which can produce more power and is less expensive to maintain than a direct-current machine. Static rectifiers converted the three-phase alternating-current output of the alternator to direct current for supply of series-wound direct-current traction motors.

Later, in the 1980s, European manufacturers began to use the three-phase alternating-current motor for diesel-electric traction units, looking forward to achieving the same benefits as electric traction. This creates a requirement in a thyristor-controlled inverter to convert the rectifier's direct-current output into a three-phase variable voltage and frequency supply for the alternating-current motors.

There are also alternative types to transmit power in diesel locomotives. One example, used for diesel railcars and multiple-unit train sets, is the hydraulic transmission. In this case, a centrifugal pump or impeller drives a turbine. The engine power is converted to kinetic energy in the oil impinging on the turbine blades by the pump, which is powered by the diesel engine. The lower the relative impinging speed of the oil, and the faster the locomotive runs, the faster the blades move.[4]

1.2. Braking in Locomotives

1.2.1. History of Braking

When diesel locomotives replaced steam ones, dynamic braking was used to make rail operations safer and more efficient. While safety will always come first, there are a growing number of aspects that must be optimized as time goes on. The need for choices to boost energy efficiency and minimize emissions is growing as fuel costs and environmental implications become more important.

In the beginning dynamic braking was meant to be a solution for mountainous areas, where wagon wheels were prone to burning on long downgrades. Dynamic braking was not available on diesel locomotives for trains operating on level ground or relatively light trains such as passenger trains. However, later it became highly demanded for overheating preventions, especially in the areas of fast development of railway industry, such as the state of Pennsylvania in the US.

1.2.2. Braking resistors

It is necessary to recall the principle of regular resistors to define the braking ones. Their basic property is consumption of a lot of energy and then its dissipation in a form of heat. When a mechanical system slows down, it starts acting as a generator, producing a huge amount of electrical energy that is transferred back into the power circuit. The resistor, which is included in a power circuit, consumes a considerable quantity of energy. The resistor transforms the consumed energy into heat and creates a braking effect at the same time. As a result, the resistor utilized for these 2 processes is called braking resistor, and the processes are referred to what’s called dynamic braking. The objective of a braking resistor is to produce a braking torque that will swiftly stop or slow down the mechanical system. Specifications for braking resistors include resistance and average braking power. The motors stop faster and dissipate more heat when braking resistors have lower ohmic values. Braking resistors are more reliable and require less maintenance. As a result, they have greater demand over friction brakes, when it comes to motors deceleration.

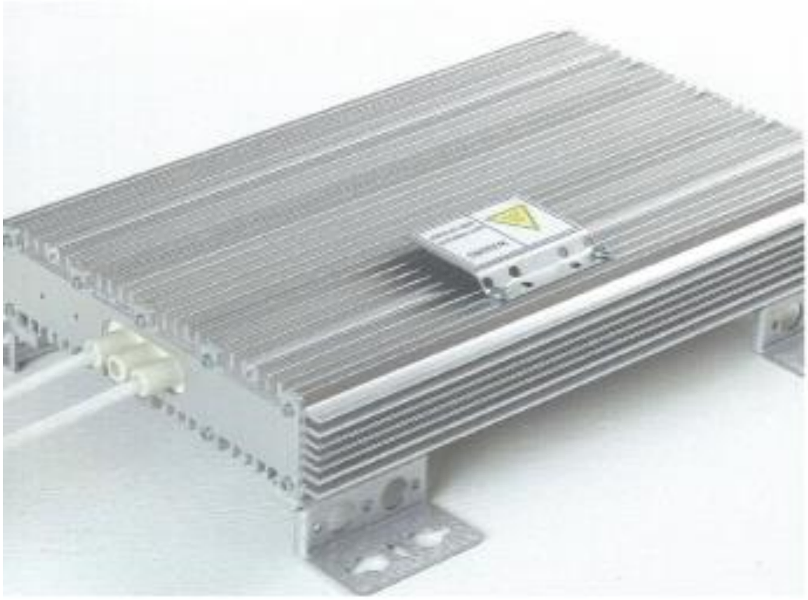


Figure 3: A wirewound “Nikkohm” braking resistor

Figure 4: A grid "Vishay" braking resistor

1.2.3. Braking Principles

Dynamic braking means the electric motor is used as a generator to slow down a vehicle. To be more precise, it's the use of an electric traction motor as a generator to dissipate excess energy in a vehicle like electric or diesel-electric locomotive. Depending on a situation or to what’s happening to this excess energy if more precise, there exist 2 terms to name dynamic braking. If the created electrical power is dissipated as heat in brake grid resistors, it is called rheostatic braking. However, if the power is returned to the supply line, it is called regenerative. Dynamic braking minimizes net energy consumption by reducing wear on friction-based brake components. Therefore, dynamic braking can be used in cases like railcars with multiple units, light rail vehicles, electric trams, electric and hybrid electric cars.

In case of regenerative braking generated electricity is either immediately reused by other locomotives or stored for later use. Electricity can be transmitted by overhead wires or an electrified third rail in the case of electric locomotives. Alternatively, a flywheel, battery, or other energy storage technology can be used to store it aboard.

When it comes to rheostatic braking, generated electrical energy passes through resistors and dissipated as heat energy. A rheostat is a device that changes the resistance of the current flowing through it to regulate it. This resistance generates a force against which work can be done in the event of rheostatic braking. Although regenerative braking makes a system more efficient by reusing energy, the infrastructure required for it is not always available.

Diesel-electric locomotives primarily operate on non-electrified rail. As a result, rheostatic dynamic braking is preferred. [5]

Also, specifically for diesel locomotives with hydraulic transmission, there exists a hydrodynamic braking type. Basically, braking energy heats the hydraulic fluid, which is then dissipated via the engine cooling radiator (via a heat exchanger). During braking, the engine is idle, therefore the radiator will not be overloaded. An earlier-mentioned locomotive by “PHS Strojarne” (Fig. 2) is a good example of such braking type, as it included hydraulic system with water cooling.

In this case locomotive braking is done on both axles independently by two separate systems: hydraulic and mechanical. Hydraulic braking refers to hydrostatic transmission via mechanical gears, while mechanical braking refers to mechanical action by direct coupling to the travel wheels. The maximum braking force/stopping power is self-adjustable, and the brake control is proportional. When the security system detects a failure mode or when the temperature and pressure limit values are exceeded, the locomotive engine is automatically stopped. The operator of the locomotive is notified of all circumstances via dashboard. [2]

1.2.4. Braking resistors maintenance and replacement

For the reasons of speed, general simplicity and costs of production and maintenance, replacing outdated resistors rather than replacing an entire drive system with modern drives is considered more effective in a sense of economics. This means that resistor suppliers should keep detailed records of all railway resistors made for all types of electric and diesel locomotives, electric multiple units, or metro vehicles.

Resistor manufacturers may create functionally similar replacements in many circumstances when original equipment designs are not accessible or are no longer manufactured. These replacements should be retested if necessary to make sure that they meet the same type-test criteria as the original parts primarily in a sense of electrical, thermal, and vibration performance.

Apart from the need to match resistance values, it's also equally necessary to make sure the active mass, material type, and electrical creepages and clearances all meet the requirements.[6]

2. Theory

2.1. General principle

As it may be concluded from the introduction part, simply speaking, the energy in the hybrid diesel-electric system may flow both ways – from the electric motor to the electric circuit with the braking resistor itself and a battery and opposite way. For the reason of energy conversion there must be an inverter on the path of the energy. Below, there is a simple illustration of how it's all happening. This concept is basically regenerative type of braking. The energy flow towards the diesel motor happens during motion/haulage, while the flow in opposite direction happens during braking and charges the battery.

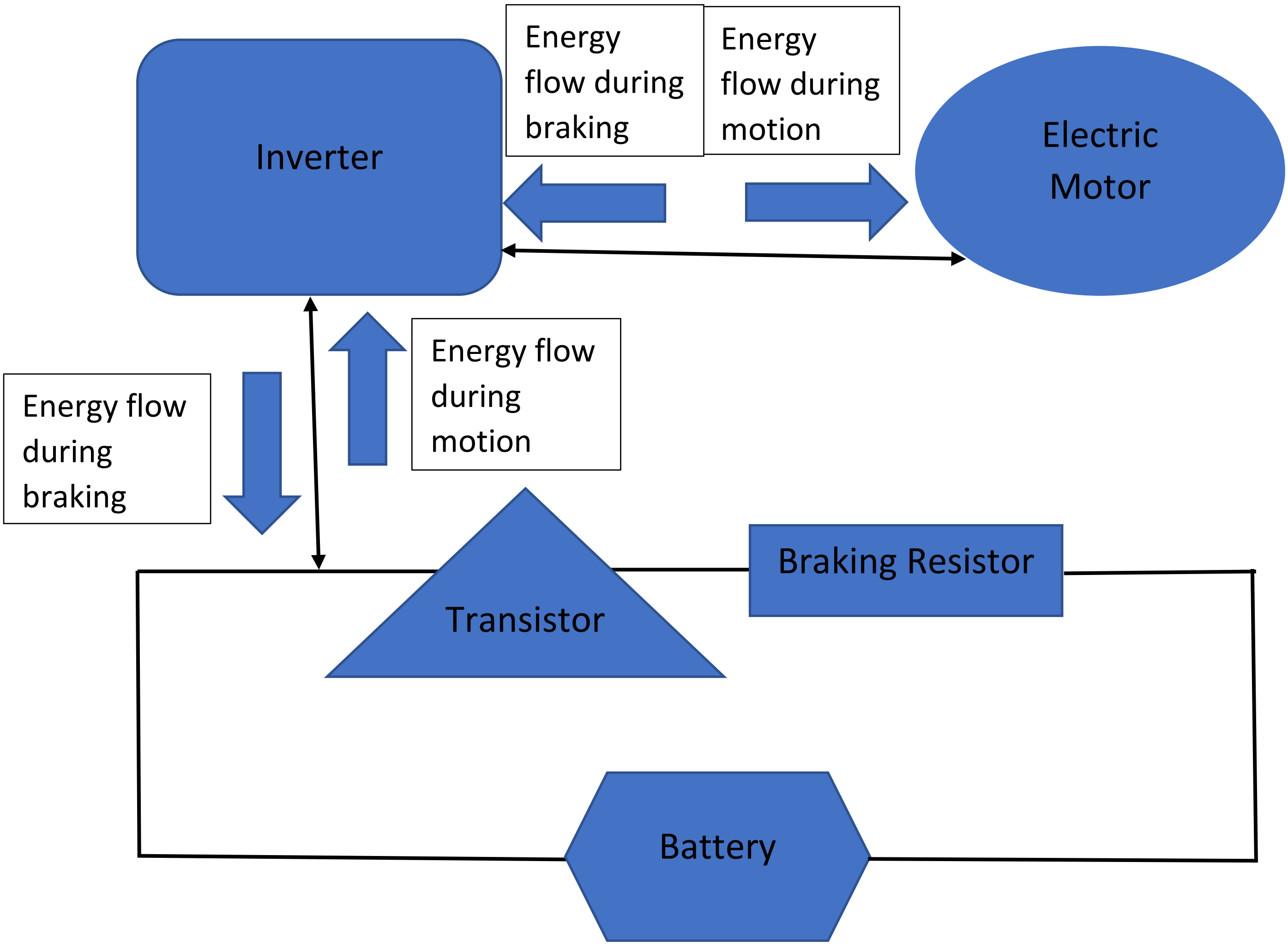


Figure 5: A simple scheme of energy flows both during regular motion and braking

As this principle is about energy being absorbed by braking resistor, which causes it to heat up, it is obvious that there’re thermal and electric field that are affecting the discussed part. It is necessary to take a close and detailed look on both present fields. To illustrate, simulate and calculate all that is necessary regarding the designed part, software called “Agros” is used.

2.2. Thermal field

2.2.1. Theory by means of principle

From the general principle and concept from introduction, the excess energy enters the braking resistor in an emergency case. Also, shouldn’t be forgotten that the water is closely flowing for cooling purpose. When this happens, it is necessary to consider several facts regarding the thermal field:

1. The water cannot get in contact with the resistor, obviously to avoid short circuit.
2. Therefore, the part should be covered by a certain other material.
3. The other material (from the reason of point 1) must have a very low electrical conductivity or a complete electrical isolator.
4. Also, for the need to cool down the resistor, this other material must have a proper thermal conductivity and mechanically sustain the flow of the water in the system, as this is what’s in direct contact with the water and not the resistor.

2.2.2. Theory by means of formulas

Selecting the material depends on overcoming the calculated value of heat transfer coefficient. It is expressed by the following formula:

$$\propto_{req} = \frac{P}{2 * S * \Delta t} \qquad (1)$$

Where:

- α_{req} - the heat transfer coefficient to overcome [W/(m^2*K)]
- P – maximum power generated by the battery [W]
- S - area of the cover plate that insulates the resistor. This area is what the water flow is in contact with. [m^2]
- Δt - temperature difference between the cooling water and cover plate [K]
- 2 is the coefficient, which shows that the water flows along 2 cover plates.

Before introducing the rest of the formulas, it is helpful to have the following illustration:

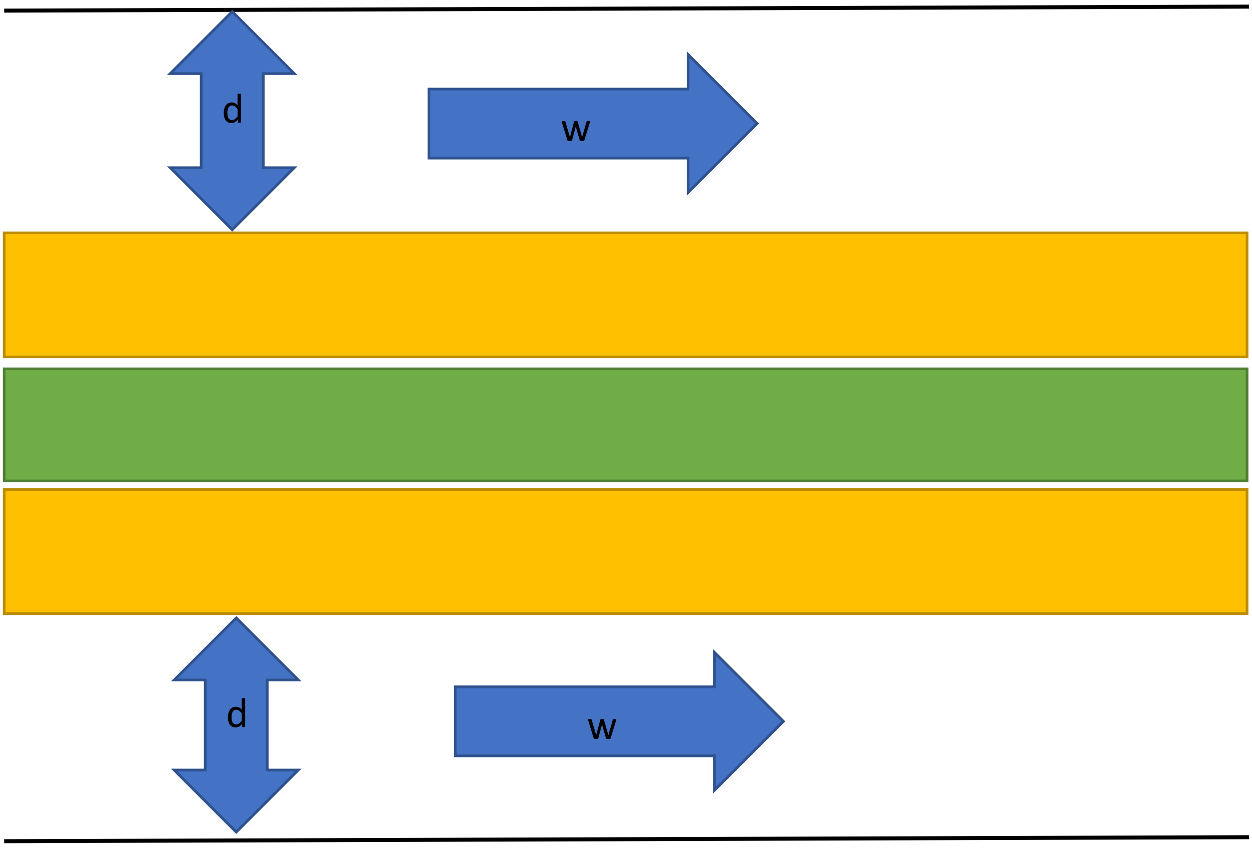


Figure 6: A side view on resistor and cover plates positions and water flow

Where:

- Green plate represents the side view on the braking resistor
- Yellow plates represent the protective cover plates

- Double-side blue arrow with a “d” label represents the diameter between the protective plate and the casing
- The arrow with a “w” label represents the water flow with a certain velocity.

Both variables d and w are used later in the other formulas.

Heat transfer coefficient that needs to overcome the calculated one is expressed as:

$$\propto = \frac{Nu * \lambda}{d} \tag{2}$$

Where:

- α – actual heat transfer coefficient [W/(m^2*K)]
- Nu - Nusselt number [-]
- λ - coefficient of thermal conductivity [W/(m*K)]
- d - the cross-section diameter the water flows through [m]. In this case it is the distance between the protective cover plate and the wall of the casing.

Expression of the Nusselt number depends on the conditions. Considering the protective cover plate being flat and the flow being turbulent, it can be expressed as:

$$Nu = 0.037 * Re^{0.8} * Pr^{\frac{1}{3}} \tag{3}$$

Where:

- Re - Reynolds number [-]
- Pr - Prandtl number [-] [7]

Reynolds number – a ratio between inertial and viscous forces in a fluid – is expressed as:

$$Re = \frac{w * d}{v} \quad (4)$$

Where:

- w - the speed of the water flow [m/s]
- v – coefficient of kinematic viscosity of water [m^2/s]

Prandtl number – a ratio of kinematic viscosity and thermal diffusivity – is expressed as:

$$\mathrm{Pr} = \frac{v * c_p * \rho}{\lambda} \quad (5)$$

Where:

- c_p - specific heat capacity [J/(kg*K)]
- ρ - fluid density [kg/m^3]

The thermal field effect has been observed in Agros software, as mentioned above, therefore, it is necessary to show, how the software defines this effect formula-wise. Partial differential equation for the thermal field:

$$-div\ (\lambda\ grad\ T) + \rho * c_p * (v * grad\ T) = Q \quad (6)$$

Where:

- Q – generated volumetric heat [W/m^3]
- v – horizontal (linear) velocity [m/s]

In addition, Agros requires the boundary condition for heat flux, which is described as:

$$f = -\lambda \frac{\partial T}{\partial n_0} = f_0 + \quad (7)$$

$$\propto * (T_{ext} - T) + \varepsilon * \sigma * (T_{amb}^4 - T^4)$$

Where:

- f_0 and f – heat flux [W/m^2]

- ε – emissivity [-]
- T_{amb} – initial temperature of cooling liquid [K]
- T_{ext} – final external temperature after the cooling process

2.3. Current field

2.3.1. Theory by means of principle

The electrical part of the hybrid system has a battery that powers the whole system, which means there're certain power and certain current in the system. They are needed simply to calculate the current in the system and the so-called required resistance. Later, it is needed to choose a certain material with suitable resistivity/conductivity values to find the so-called calculated resistance which must relatively meet the required resistance. [17]

2.3.2. Theory by means of formulas

There are several simple equations, that are present in this theory.

$$I = \frac{P}{V} \tag{8}$$

Where:

- I - current in the system [A]
- V – voltage in the system [V]
- P – maximal power in the system from the battery [W]

$$R_{req} = \frac{V}{I} \tag{9}$$

Where:

- R_{req} is the resistance that the designed resistor must relatively meet [Ω]

From the ratios between these variables, required resistance can be calculated in a single step:

$$R_{req} = \frac{V^2}{P} \tag{10}$$

For the sense of representing how Agros defines the current field effect on the designed it is necessary to introduce more formulas. The partial differential equation for the current field:

$$-div(\sigma\, grad\, \varphi) = 0 \tag{11}$$

Where:

- σ – conductivity [S/m]
- ϕ – potential [V]

The Formula says that the scalar of the function in the brackets must be zero. Also, just like in case of thermal field, Agros requires boundary conditions for further calculations. There are 2 of them: for potential difference and current density.

$$\varphi = \ \varphi_0 \tag{12}$$

Where both ϕ_0 and ϕ stand for fixed potential or fixed voltage [V].

$$J_n = \sigma \frac{\partial \varphi}{\partial n_0} = J_0 \tag{13}$$

Where both J_n and J_0 stand for current density, and according to the condition there should be no flow.

2.4. Sensors

2.4.1. Overview

Many electronic components operate in a variety of temperatures. However, an increase in temperature above a set ambient can worsen the working performance of a component. The component gets damaged by heating or thermal runaway when the temperature passes the allowable maximum limit. As a result, thermal properties play an important role when selecting components for electrical circuits. Thermal sensors heavily help to maintain performance and reliability in automotive, industrial, and consumer electronics applications.

As all sensors measure the temperature of a certain system or ambient, which means their primary function is to prevent systems from overheating and to compensate for temperature-dependent changes in electrical parameters. The type of selected thermal sensor is determined by the system's requirements for responsiveness and accuracy. There are 4 basic types: RTDs, thermocouples, semiconductors, and thermistors. [8]

2.4.2. Resistance temperature detectors

During the measurement of the RTD’s resistance as its temperature is varied, the response is almost linear, behaving similarly to a resistor. Compared to an ideal linearity, there’s not much difference. [9]

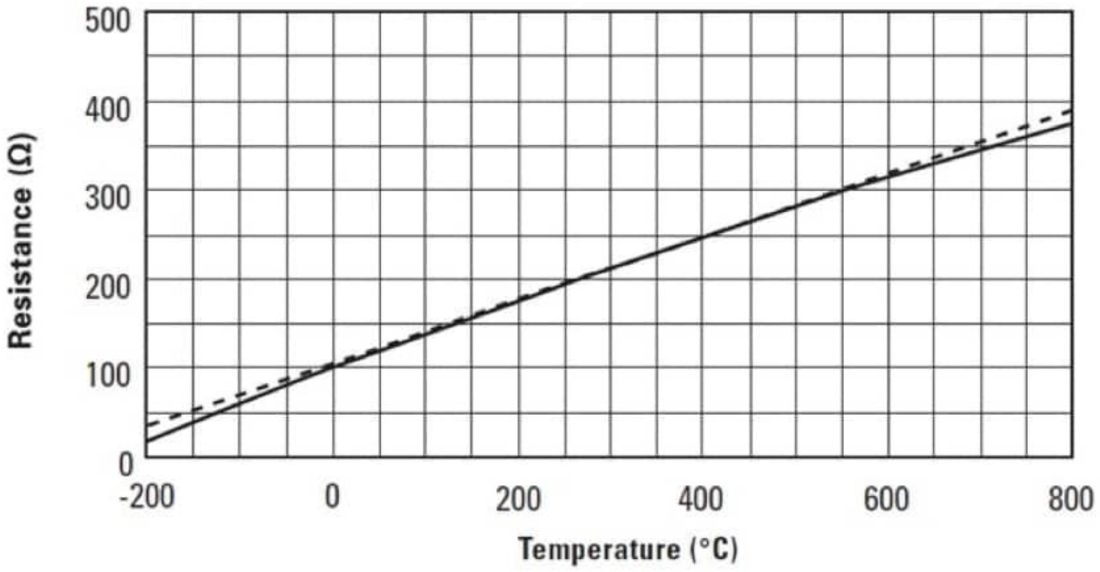


Figure 7: Resistance-Temperature dependency for an RTD

Most designers digitize the observed resistance value and add correction factors using a lookup table within the microcontroller to compensate for the small nonlinearity. RTDs are helpful in high-precision applications, such as detecting the temperature of fluid or gas in pipes and tanks, because of their repeatability and stability throughout a large temperature range (approximately -250°C to +750°C). [9]

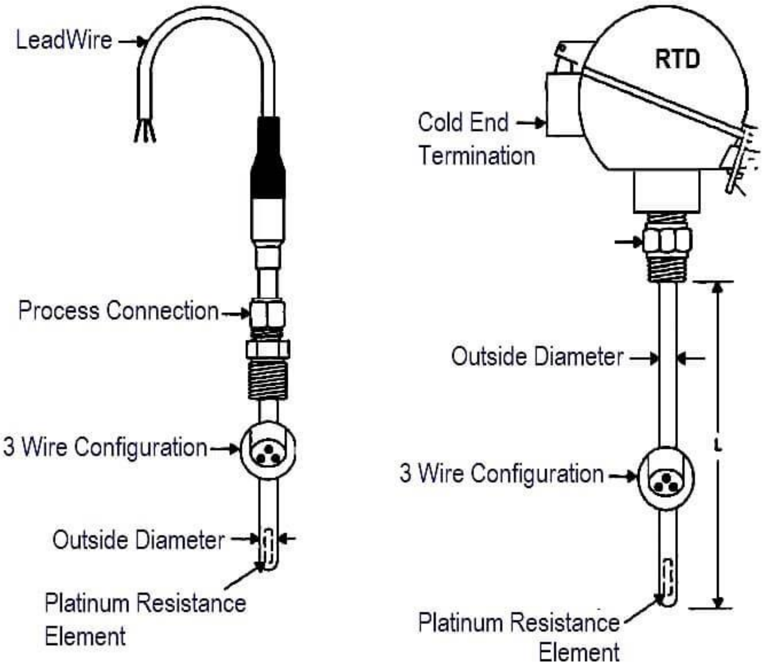


Figure 8: An example of an RTD thermal sensor [10]

2.4.3. Thermocouples

Unlike the RTD, this sensor type is non-linear. The thermocouple's sensitivity and temperature ranges differ depending on the metals linked together. The accuracy of thermocouples is poor, but they have a wide temperature range of -200°C to 1750°C. [8]

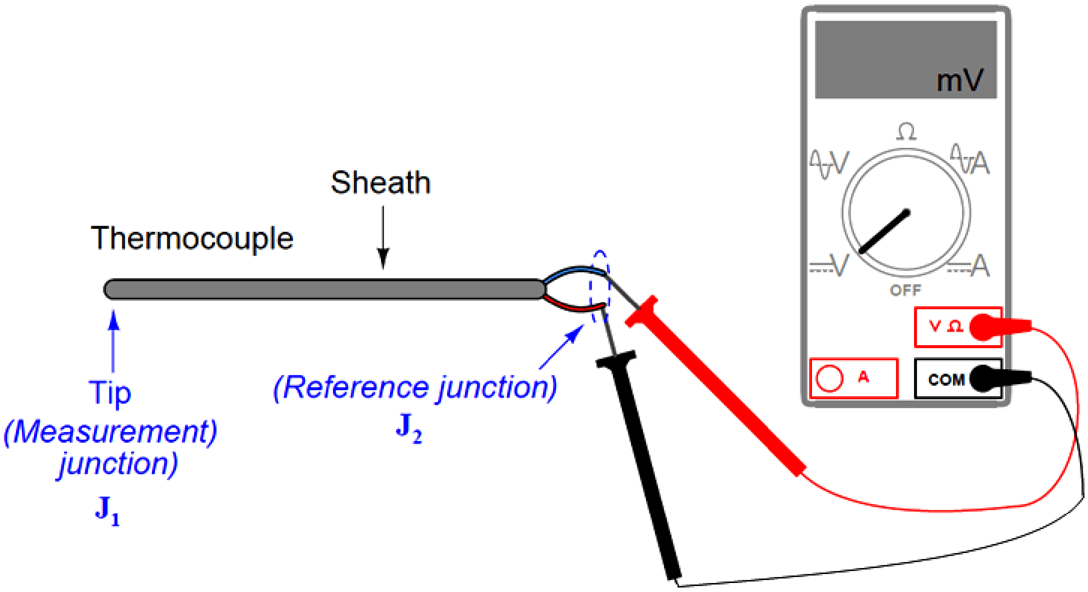


Figure 9: A schematic example of a Thermocouple thermal sensor [11]

In industrial, automotive, and consumer applications, thermocouples are the most often used thermal sensors. Their operating principle is so-called Seebeck effect, which is the phenomenon when a potential difference is produced by a temperature difference between two unlike metal wires. The voltage difference is proportional to the temperature change. The voltage difference is converted to temperature data using a look-up table.[8]

2.4.4. Semiconductors

Also known as IC sensors. Temperature variation is detected by these ICs through changes in output quantities like as current, voltage, resistance, and so on. Over the temperature range of 55°C to 155°C, semiconductors are very precise and linear.[8]

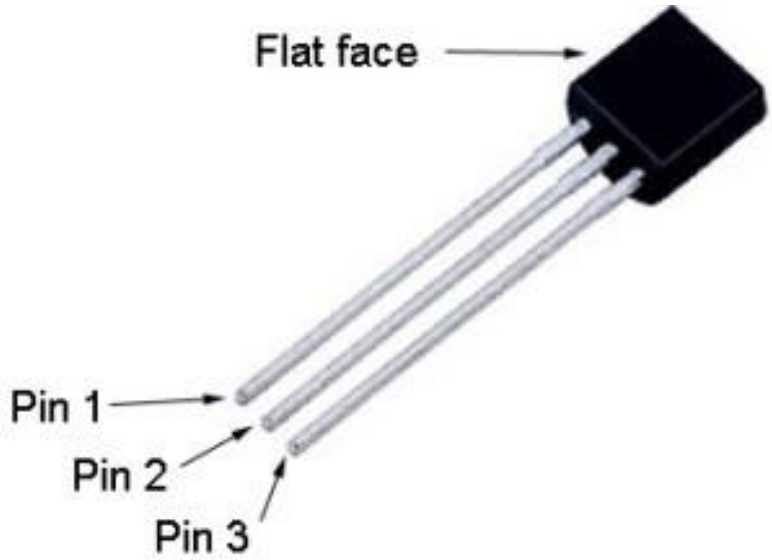


Figure 10: An example of semiconductor with 3 diodes, depending on different quantities [12]

IC thermal sensors have a variety of advantages such as low power consumption, small package sizes, and low device cost. In addition, since these sensors are calibrated during production testing, no additional calibration is required. Fitness trackers, wearables, computing systems, data loggers, and automotive applications all employ them.[9]

2.4.5. Thermistors

Just like RTDs, thermistors use resistance when reading the temperature variations. While RTDs are made of platinum, nickel or copper, thermistors are made of polymer or ceramic materials, therefore they’re cheaper but less accurate. There are two categories of thermistors:

- Negative temperature coefficient (NTC) thermistors – when the change in resistance is inversely proportional to the temperature change.
- Positive temperature coefficient (PTC) thermistors – when the change in resistance is directly proportional to the temperature change.[8]

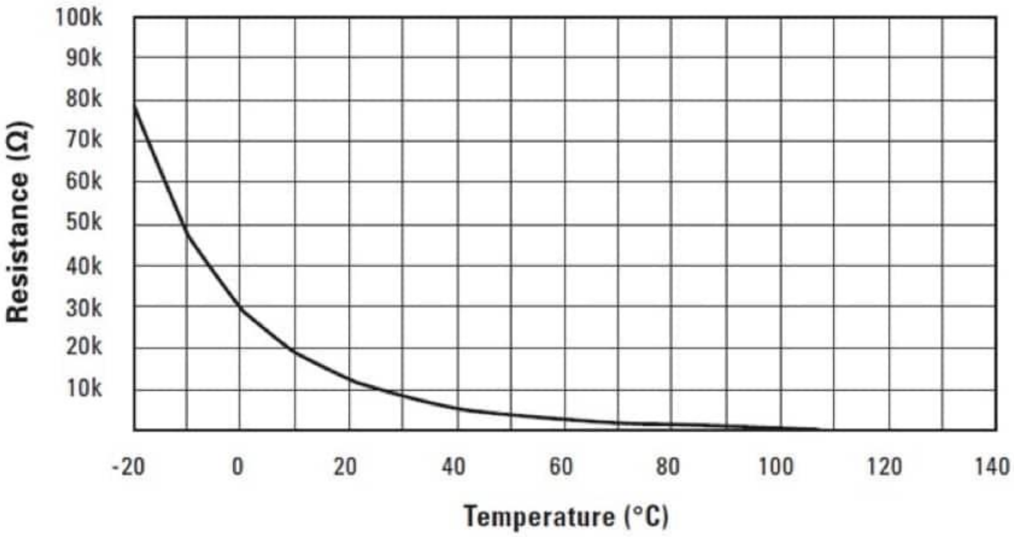


Figure 11: Resistance-Temperature dependency for a thermistor [9]

Considering how far this dependency is from being linear especially comparing to RTD, there may be needs in extra calibrations and other measures if linearization is required. [19]

Figure 12: An example of an NTC thermal sensor (copper casing) [13]

3. Construction

3.1. Design aspects

The design of the resistor is unique: a plate with a cut of a certain length, cross-section area and thickness, which is considered as a path for current flow. It shall be discussed in more detail from the perspective of both fields mentioned earlier.

3.1.1. Thermal field

As has been stated and illustrated in the theory part, from the side view (by side view the y-z side is assumed, if speaking by means of coordinate system) the resistor plate must be covered with protective solid plates for short-circuit prevention. Another illustration of that is shown below.

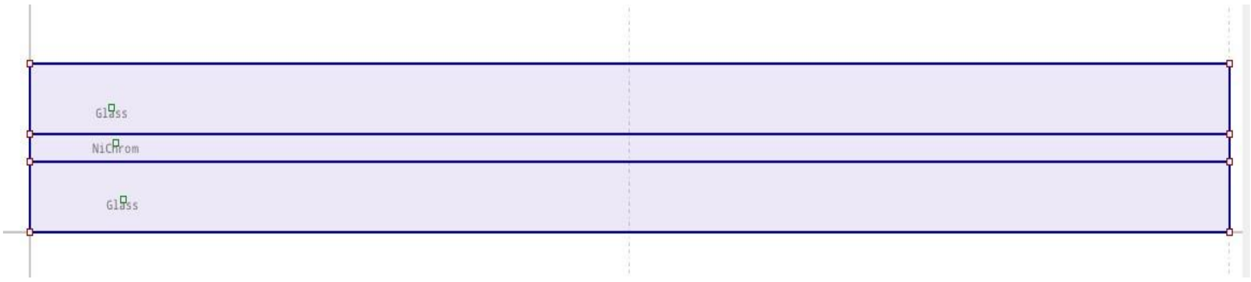


Figure 13: General Illustration of thermal design aspect in Agros software

3.1.2. Current field

The area the plate resistor can occupy is limited and is equal to 0.8 by 1 m. However, it’s been decided to make it 0.7 by 0.9 m and leave some space as tolerance, for example, in case of thermal expansion. Obviously, the illustrations of the design are shown in the front view (by means of coordinate system – x-y side).

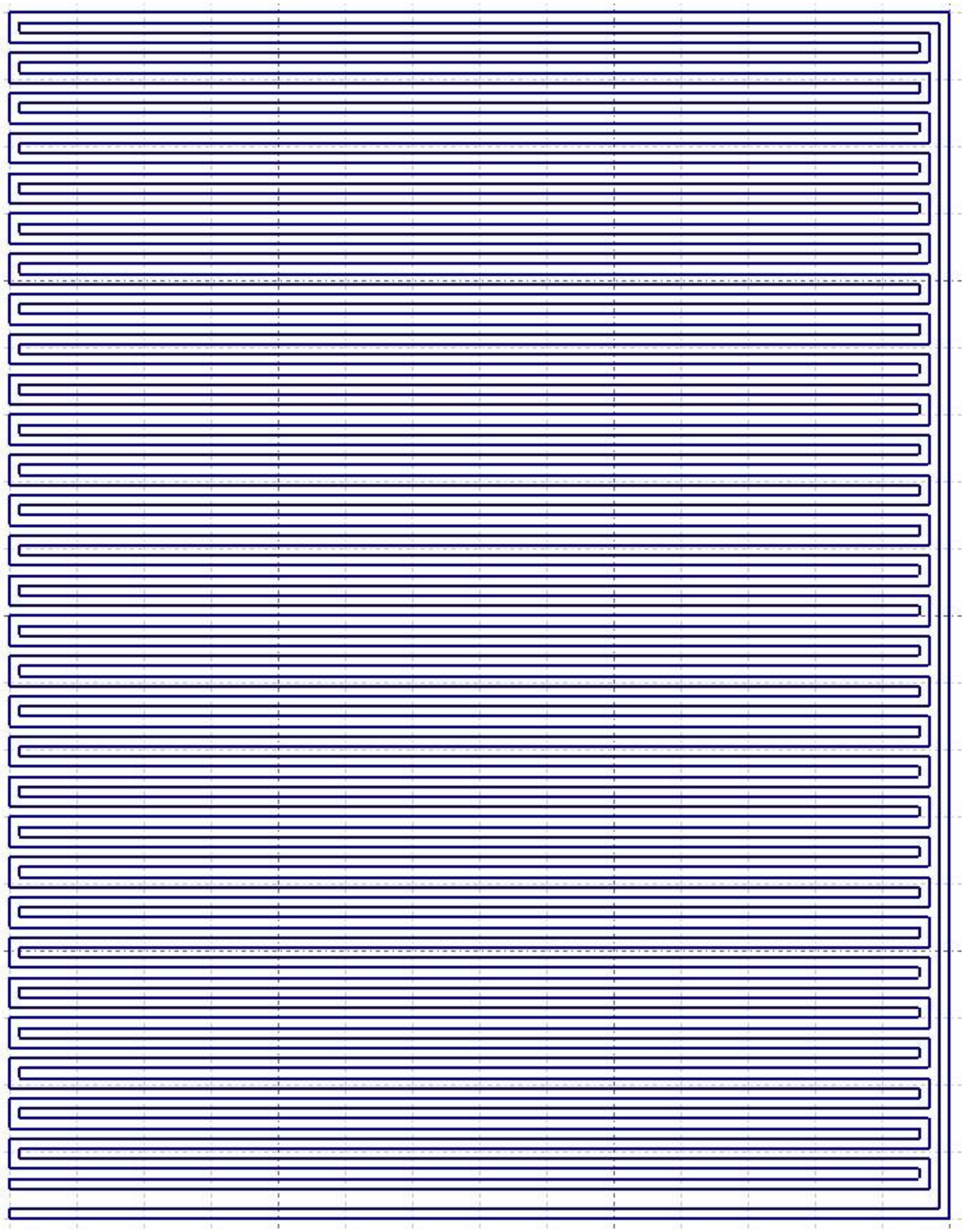


Figure 14: General illustration of the electrical design aspect in Agros software

For this aspect, 3 factors are important when designing the part:

- Resistivity/electric conductivity value of the selected material
- Length of the cut

- Cross-section area of the cut

Since length of the flow path plays huge role, such path has been chosen, because it occupies significant amount of space on the plate.

Therefore, the following formula is introduced:

$$R_{calc} = \frac{1}{\gamma} * \frac{l}{A} \tag{14}$$

Where:

- R_{calc} – calculated resistance, which must meet the required one
- γ – resistivity of the selected material [Ω*m]
- l - length of the path for current flow [m]
- A – cross-section area that the current flows through [m^2]

However, due to the cut having non-constant diameter along its whole path, the stated formula cannot be applied. Though, there is an alternative way. It makes sense, that the greater is the cross-section, thus diameter of the cut (y-dimension on the illustrations) more current can flow through. Same way works with thickness of the cut (z-dimension, non-visible on electrical field illustrations). If the cut is thicker – more current flows through and the other way around. Based on this logic, the following formula is introduced:

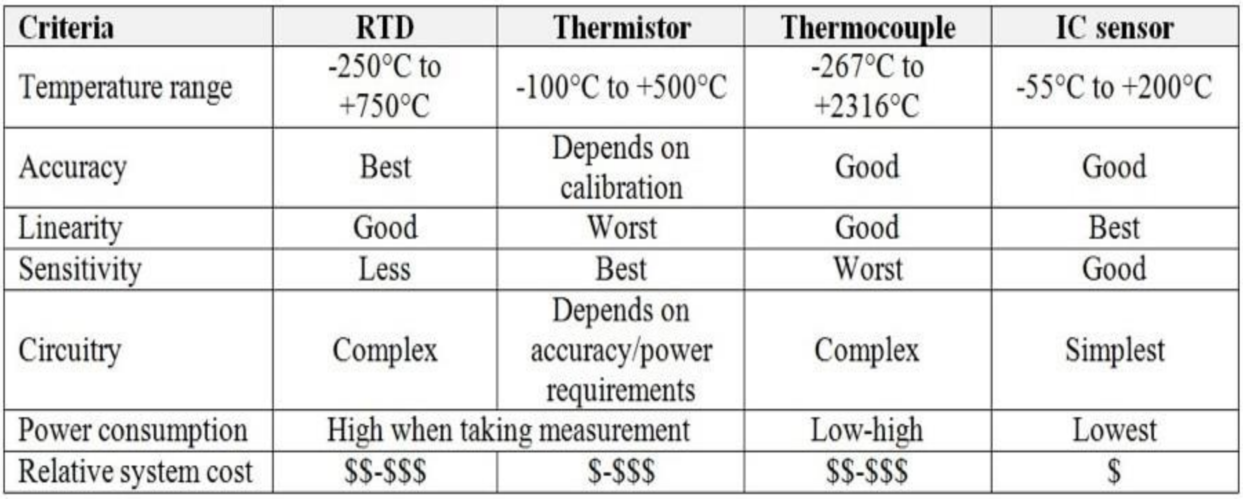
$$R_{calc} = \frac{V}{I} * \frac{1}{th} \tag{15}$$

Where:

- V – potential difference [V]
- I – real value of current flowing in the resistor [A] (from Agros)
- th – a thickness of the cut of the path for current flow [m]

3.1.3. Sensors

At the start and the end of the path for the water flow, there's a need to mount a thermal sensor. That's the main purpose, sensors have been discussed in the theory chapter, and the main purpose of the sensors is to control the temperature of flowing water. To be more precise, the temperature of the flowing water should not get higher than 90 degrees Celsius, otherwise the water has high chances to start vaporizing. In that case, the locomotive must perform an emergency stop, therefore there won't be that much power to dissipate.



Criteria	RTD	Thermistor	Thermocouple	IC sensor
Temperature range	-250°C to +750°C	-100°C to +500°C	-267°C to +2316°C	-55°C to +200°C
Accuracy	Best	Depends on calibration	Good	Good
Linearity	Good	Worst	Good	Best
Sensitivity	Less	Best	Worst	Good
Circuitry	Complex	Depends on accuracy/power requirements	Complex	Simplest
Power consumption	High when taking measurement		Low-high	Lowest
Relative system cost	\$\$-\$\$\$	\$-\$\$\$	\$\$-\$\$\$	\$

Figure 15: Simple summary table regarding the discussed sensor types comparison [9]

Considering general information about each sensor type discussed in the theory chapter as well as the summary listed in Fig.15, the sensor type that suits best seems to be IC sensor or semiconductor. First, there's no need to operate an extremely high temperature, the temperature must not exceed 90 degrees Celsius. The rest of criteria looks suitably good, therefore combined with low costs semiconductor looks most preferrable for this situation.

Another option can be a Pt100 sensor. It is a variation of an RTD sensor, a platinum-based sensor that by default operates when the device's resistance is 100 Ω at temperature of 0°C. The right scheme in Fig.7 is a typical example of a Pt100.

4. Results

4.1. Thermal field

4.1.1. Material selection

As was mentioned in the theory, the plates that cover the designed part should be manufactured of such material, that serves as electrical isolator for short circuit prevention and a decent heat conductor for simplifying the cooling process of the part, during or after braking. Again, what should also be kept in mind is its mechanical strength against the flowing water pressure. Glass-ceramic looks to be an appropriate choice for these conditions. It is mechanically strong and sustains high temperatures. Considering, that the temperature shouldn't go higher than 90°C, that's more than enough.

Figure 16: Glass-ceramic used for an electric stove

4.1.2. Corresponding values

Referring to formula 1, it's necessary to find out the value of heat transfer coefficient, that must be exceeded. From construction part of the theory the x-y dimensions of resistor plate are 0.7 by 0.9 m, and so are the dimensions of the cover plates. The condition for braking is that so the resistor is heated up to 70°C and since the resistor is one of least parts of the system to get cooled down, the cooling water temperature is 40°C, therefore $\Delta t = 30°C$. Based on what's known, the required heat transfer coefficient:

$\alpha_{req} = 582.011\ W/m^2K$

To find the actual heat transfer coefficient, first, it is necessary to find Reynolds, Prandtl and Nusselt numbers with help of formulas 4,5 and 3 respectively.

For Reynolds number calculation, the parameters w and d are up to designer, therefore they were decided to be both 0.1. Higher speed of flow isn't really preferrable because there's a single pump that maintains this velocity, and additional ones would cause design-related troubles. Another value for the formula is water's kinematic viscosity: $\nu_{water(40°C)} = 0.658*10^{-6}\ m^2/s$ [15].

Therefore, with these assumptions and knowledge of kinematic viscosity of water at 40°C:

$Re = 15197.56839$

For Prandtl number:

- $c_{p(water)} = 4200\ J/kg*K$
- $\rho_{water} = 1000\ kg/m^3$
- $\lambda_{water(40°C)} = 0.62586\ W/m*K$ [14]

Therefore, using formula 5:

$Pr = 4.3967$

Using formula 3:

Nu = 134.31

In the end, using Nusselt number and formula 2, the actual heat transfer coefficient:

$\alpha = 844.213\ W/m^2*K > \alpha_{req}$ => requirement is fulfilled

4.1.3. Simulation

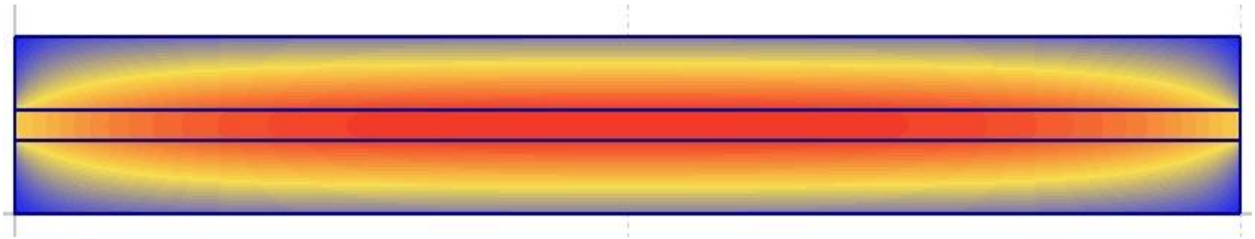


Figure 17: Thermal field simulation in Agros software

Simulation in Fig. 17 has been achieved by plotting the known results into the equation for the thermal field for both Nichrome and Glass-Ceramic plates as well as the boundary condition equation in Agros software. Those formulas are 6 and 7 respectively. However, 2 new values should be introduced:

- $\lambda_{Nichrome} = 17\ W/m*K$
- $\lambda_{Glass\text{-}ceramic} = 1.1\ W/m*K$

These values were used for simulation in formula 6 for Nichrome and glass-ceramic respectively.

4.2. Current field

4.2.1. Material selection

As was mentioned earlier, the selected material for the braking resistor plate itself is Nichrome allow. The main reason is its conductivity value, which allows to match the required resistor, in other words the material shouldn't be too much electrically conductive (like copper or aluminum).

4.2.2. Corresponding values

The electric circuit part of the hybrid system has the following variables given:

- $P = 22$ kW
- $V = 530$ V

Using formula 10, required resistance can be calculated in a single step, however they value of the current is needed too for other calculations, therefore formulas 8 and 9 are used:

- $I = 41.51$ A
- $R_{req} = 12.77\ \Omega$

To calculate the actual resistance, which should relatively match the required one, formula 15 is used. The thickness parameter should be designed. The current in formula 15 is taken from Agros and is different from the current in formulas 8 and 9. It is because the value of current is known from surface integration in Agros and the value isn't constant everywhere on the path. The value of current that is needed is on both ends of the path. As a boundary condition, to simplify the calculation the potentials were chosen to be 1 and 0, therefore potential difference is 1 V. The value of electrical conductivity of Nichrome alloy is $9.09*10^5$. [16]

Current field

Length	l	7.500e-03	m
Surface	S	7.500e-03	m^2
Current - conductive - real	I	1.622e+02	A

Figure 18: Real current value on one of the ends of the current flow path

Considering the knows information from Agros, and designing the cut to be 0.5 mm or 0.0005 mm thick:

$R_{calc} = 12.33\ \Omega$

It is necessary to admit that though formula 14 isn't used in the calculation, cross section area still matters when it comes to the amount of flown current and, therefore – resistance. The actual resistance is calculated at diameter of 0.75 mm. As mentioned earlier, the diameter is the thickness of the path on the x-y plane. [18].

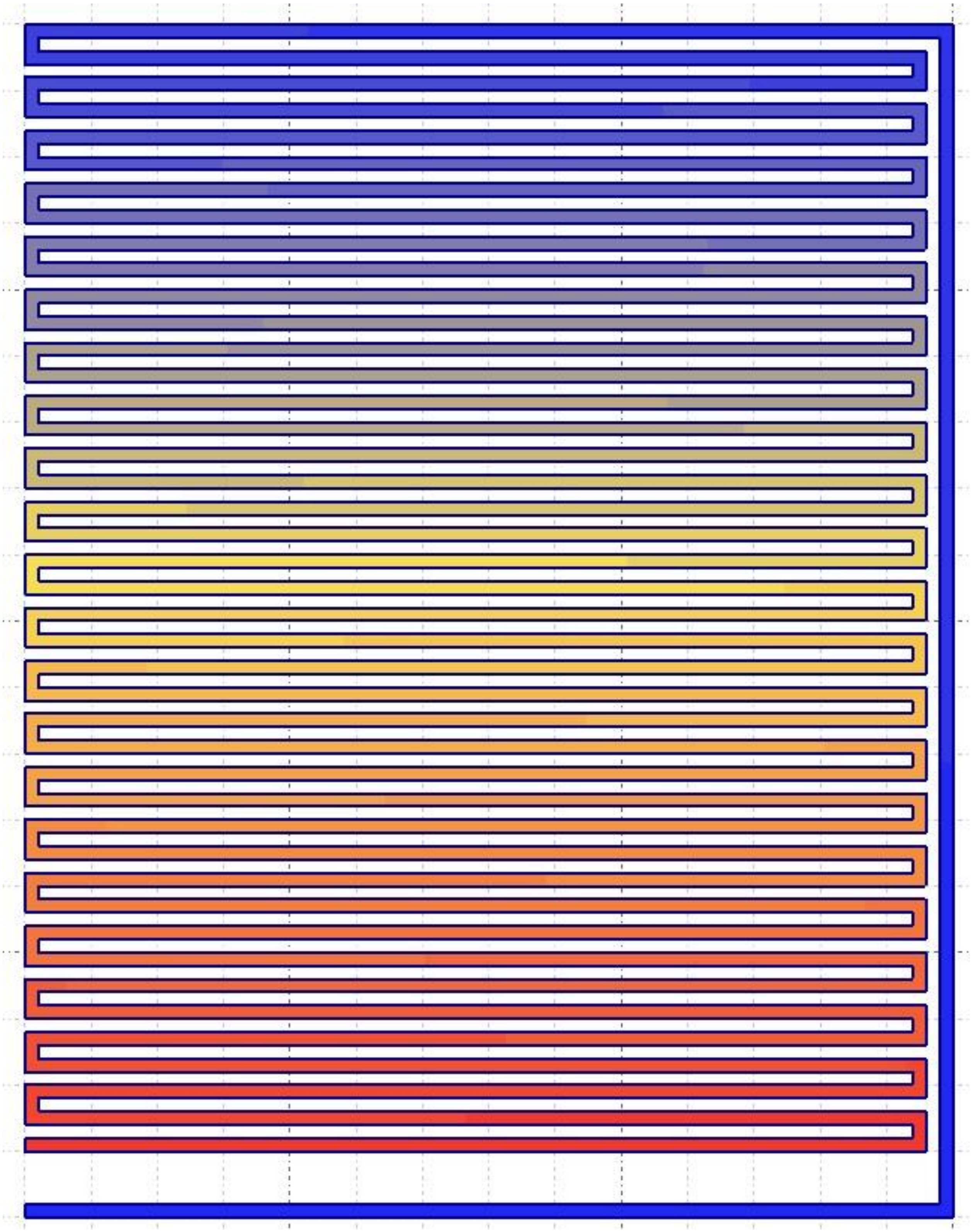


Figure 19: Electrical field simulation in Agros software

Fig. 19 shows the simulation of the current field effect. It basically represents the potential difference.

4.3. Future working possibilities

As has been stated in the theory, the best types are semiconductor and Pt100. So, due to the small temperature range and the fact that the peak temperature won't go above 90°C, semiconductor is the appropriate choice. Though there may be uncertainties of 3-4°C, but it's not that significant.

Figure 20: IC sensor KTY 81/120, 112 by "Farnell" [20]

The sensor shown in Fig. 20 is a good example of a semiconductor sensor. Just like stated in the summary about all basic sensor types, it has decent accuracy, appropriate temperature range (from -55 to 150°C) and has low cost (50 CZK).

5.Conclusion

5.1. Results overview

Generally, design fulfills all conditions and scientific requirements.

In a sense of thermal field, the main condition is fulfilled, the actual heat transfer coefficient is greater than the minimal required one, which means the braking process can charge the battery with enough power if the braking is regenerative.

In a sense of a current field, the requirement is fulfilled too. The actual resistance with a designed Nichrome resistor placed into the circuit is slightly less than the required one, however, unlike the case of thermal field, in current field actual resistance should be close to the required one. Therefore, it can be stated that this condition is fulfilled, too, since the difference in 2 resistance values isn't significant.

However, the design has several assumptions regarding calculation, but this doesn't mean there shouldn't be any. Designing is an engineering process, so some parameters should be selected, assumed and later check simulate if they work.

5.2. Future working possibilities

The purpose of this thesis is to design the resistor and check by means of calculations and simulations. However, this work may be used in the future to manufacture an actual resistance. Possibly, this design work can simplify the approximation towards manufacturing. The tests of the actual part will show if it truly works or not.

Bibliography

[1] PARKHOMENKO, A A. Diesel mining locomotive. *The Free Dictionary* [online]. [Accessed 10 February 2022]. Available from: https://encyclopedia2.thefreedictionary.com/Diesel+Mining+Locomotive

[2] Mining Locomotives - PHS. *News - PHS* [online]. [no date] [viewed 10 February 2022]. Available from: http://www.phs-strojarne.sk/index.php?id=mining-locomotives

[3] Lokomotivy LZH « Ortas. *Ortas |* [online]. [no date] [viewed 10 February 2022]. Available from: https://www.ortas.cz/lokomotivy-lzh/

[4] SHEDD, Thmas Clark. locomotive - Diesel traction. *Encyclopedia Britannica* [online]. [no date] [viewed 10 February 2022]. Available from: https://www.britannica.com/technology/locomotive-vehicle/Diesel-traction

[5] What Are Brake Resistors? Braking Resistor Solutions — ES Components. *ES Components* [online]. [no date] [viewed 10 February 2022]. Available from: https://www.escomponents.com/whatare-braking-resistors

[6] SMYTH, Louise. Braking resistor technology makes railways more energy efficient | Engineer Live. *Engineering News & Opinion | Engineer Live* [online]. 15 January 2019 [viewed 10 February 2022]. Available

from: https://www.engineerlive.com/content/braking-resistor-technology-makes-railways-more-energy-efficient

[7] Laminar vs Turbulent - Nusselt Number | Correlations | nuclear-power.com. *Nuclear Power* [online]. [no date] [viewed 10 February 2022]. Available from: https://www.nuclear-power.com/nuclear-engineering/heat-transfer/convection-convective-heat-transfer/laminar-vs-turbulent-nusselt-number/#:~:text=Dittus-Boelter%20equation+-,For%20fully%20developed%20(hydrodynamically%20and%20thermally)%20turbulent%20flow%20in%20a,number,%20which%20is%20Pr%20=%200.89

[8] The Different Types of Thermal Sensors. *Electromechanical, Micro, & Power Systems Engineering | Cadence Blog* [online]. [no date] [viewed 10 February 2022]. Available from: https://resources.system-analysis.cadence.com/blog/msa2021-the-different-types-of-thermal-sensors

[9] SOLTERO, Manny. Find Electronic Components – Mouser Europe. *Electronic Components Distributor - Mouser Electronics Europe* [online]. 25 November 2015 [viewed 10 February 2022]. Available from: https://www.mouser.com/blog/what-are-you-sensing-pros-and-cons-of-four-temperature-sensor-types

[10] STAFF, Editorial. What is an RTD? - Components of RTD - InstrumentationTools. *Inst Tools* [online]. [no date] [viewed 10 February 2022]. Available from: https://instrumentationtools.com/components-of-rtd/

[11] STAFF, Editorial. Manually Interpreting Thermocouple Voltages. *Inst Tools* [online]. [no date] [viewed 10 February 2022]. Available from: https://instrumentationtools.com/manually-interpreting-thermocouple-voltages/

[12] Temperature Sensor : Various Types with Examples. *WatElectrical.com* [online]. [no date] [viewed 10 February 2022]. Available from: https://www.watelectrical.com/6-different-types-of-temperature-sensors-with-their-specifications/

[13] NTC Thermistor Sensor - Senstech. *Senstech* [online]. [no date] [viewed 10 February 2022]. Available from: https://senstech.cn/ntc-thermistor-sensor/

[14] Machinable Glass-Ceramic :: MakeItFrom.com. *MakeItFrom.com: Material Properties Database* [online]. [no date] [viewed 10 February 2022]. Available from: https://www.makeitfrom.com/material-properties/Machinable-Glass-Ceramic

[15] Water - Density Viscosity Specific Weight. *Engineers Edge - Engineering Reference Data and Tools | GD&T ASME Training | DFM DFA Training* [online]. [no date] [viewed 10 February 2022]. Available from: https://www.engineersedge.com/physics/water__density_viscosity_specific_weight_13146.htm

[16] D, Anne Marie Helmenstine, Ph. A Table of Electrical Conductivity and Resistivity of Common Materials. *ThoughtCo* [online]. 26 December 2012 [viewed 10 February 2022]. Available from: https://www.thoughtco.com/table-of-electrical-resistivity-conductivity-608499

[17] Erickson, C. J. (1995). Handbook of Electrical Heating of Industry. Institute of Electrical and Electronics Engineers

[18] Agros Suite. (n.d). Retrieved October 18, 2021, from http://www.agros2d.org/.

[19] M., M. G. G., & Herwaarden, A. W. (1994). Thermal sensors. IOP publ.

[20] [no date] [viewed 10 February 2022]. Available from: https://cz.farnell.com/nxp/kty81-120-112/temperature-sensor-1k02-sod-70/dp/2776059?gclid=Cj0KCQiAjJOQBhCkARIsAEKMtO2mhKGxJ_lsKVIw__x295yhGG8o5lgInTKyQ1wkSaQJyU1EmCwHGeIaAgpQEALw_wcB&mckv=szGAykWEH_dc|pcrid|490629366850|plid||kword||match||slid||product|2776059|pgrid|109298444042|ptaid|pla-301371110069|&CMP=KNC-GCZ-SHOPPING-Whoop-HI-31-Aug-20&gross_price=true