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17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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EDITOR
Stjepan Lakušić
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Zagreb, Croatia

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SET UP OF A THERMAL NETWORK METHOD MODEL FOR THE CALCULATION OF TEMPERATURE DISTRIBUTION IN HEATED POINTS

Markus Schladitz, Robert Adam, Steffen Grossmann
Technische Universität Dresden,
Institute of Electrical Power Systems and High Voltage Engineering, Germany

Abstract

During winter season, the failure of point systems is a common problem in the rail sector. Snow and ice accumulate between stock rail and tongue rail; thereby, prevent a complete switching of the point. Electrical heating rods are installed to remedy this problem in order to avoid major restrictions of the rail traffic. Despite the established technical solutions for the heating of points, such as electric heating rods or gas heating systems, the heat transfer itself is not yet sufficiently understood. It must be determined under which boundary conditions (heat outputs, ambient temperatures, precipitation, etc.) the heating systems can ensure a reliable functioning of the switch. Therefore, a thermal model of a heated point has to be set up using the thermal network method (TNM). In order to gain a better understanding of the heat transfer processes, the first step is to develop the heating network of the stock rail and to calculate the heating under different ambient conditions. The stock rail constitutes one of the most important components in terms of the heating calculation. On the one hand, the heat flow is directly fed into the stock rail by the heating rod. On the other hand, the heat transfer within the stock rail has a big impact on the heating of the other components due to its large volume and surface. The usage of a TNM model has the advantage that the execution of calculations is less time-consuming and easily applicable to changing parameters. The single TNM models of various switch point components can be easily connected to each other. We used a FEM model to compare its results with the TNM model in order to verify the temperature distribution within the stock rail. Additionally we verified the heat conduction and emission to the ambience of our TNM model with an experimental setup. As a result, we obtained a TNM model that is able to calculate the heating of a stock rail under various ambient temperatures as well as heating powers and we verified it successfully with a FEM model and an experimental setup.

Keywords: Thermal network method, temperature calculation, stock rail

1 Introduction

Railway companies aim at reducing the amount of delays and train cancellations. Especially in the winter months, inoperable points represent a challenge for them. Currently, railway companies usually use electrical heating rods in order to ensure a failure free switching of points in the wintertime. If voltage is applied, the heating rods will warm up and transmit thermal energy to the switch point by heat conduction and heat radiation. Most of the time, this amount of thermal energy is sufficient to melt ice and snow that can accumulate between the stock rail and the tongue rail of a point. Nevertheless, sometimes various ambient conditions impede that. Thus, it is necessary to research the heating of a switch point.

2 Fundamentals of the Thermal Network Method

The Thermal Network Method (TNM) is predestined to compute the heating of a point due to easily changeable parameters and a short computing time even for big and complex geometries. It utilises the analogies between the electrical field and the thermal field (Table 1) [1].

Table 1 Analogies of electrical and thermal field

field type	electrical	thermic
current / heat	I	P
potential	φ	ϑ
resistance	R_{el}	R_{th}
potential difference	$\Delta\varphi = U = I \cdot R_{el}$	$\Delta\vartheta = P \cdot R_{th}$
capacity	C_{el}	C_{th}

A TNM model consists of heat sources, thermal resistors, thermal capacitors and temperature sources. The analogy to the electrical field offers us the possibility to calculate resulting temperatures for given heat flow and thermal resistance with:

$$P(\vartheta) = \frac{\Delta\vartheta}{R_{th}} \tag{1}$$

Thereby, the heat flow P always directs from one point with a higher temperature to another point with a lower temperature. The calculation of the electrical resistance depends on the type of heat transfer. Within a solid material, heat conduction transfers the thermal energy. The amount of heat transmitted by three-dimensional heat conduction can be calculated by FOURIER's law:

$$P_C(\vartheta) = -\lambda A_C \operatorname{grad} \vartheta \tag{2}$$

where λ is the thermal conductivity and A_c is the cross section area. For a rectangular cross section, we can simplify the conduction in a one-dimensional process and calculate the heat conduction resistance with:

$$R_C(\vartheta) = \frac{l}{\lambda A_C} \tag{3}$$

where l is the length of the considered section. Thermal energy is emitted to the ambience by convection and heat radiation on the surface of a body. Generally, we can calculate the power emitted by both processes with NEWTON's law [2]:

$$P(\vartheta) = \alpha(\vartheta) A_s \Delta\vartheta \tag{4}$$

A_s is the surface area. The heat transfer coefficient α describes the capability of a body to emit heat by convection or radiation. We can calculate the heat transfer coefficient for radiation αr by using the Stefan-Boltzmann constant σ (5).

$$\alpha_r(\vartheta) = \frac{\varepsilon_{12}\sigma(T_1^4 - T_2^4)}{\vartheta_1 - \vartheta_2} \tag{5}$$

ε_{12} is the resulting emissivity. We can calculate it by using the ratio of surfaces of the involved bodies (6).

$$\varepsilon_{12} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{A_{S1}}{A_{S2}}\left(\frac{1}{\varepsilon_2} - 1\right)} \tag{6}$$

It is evident that ε_{12} will correspond to ε_1 if the surface of body 2 is much larger than the surface of body 1 as long as ε_2 is not too small. It is possible to describe the convection by using the similarity theory. Therefore, the heat transfer coefficient for convection can be calculated with [1]:

$$\alpha_c(\vartheta) = Nu \frac{\lambda}{l_W} \tag{7}$$

The reference length l_W depends on the geometry and the definition of the Nusselt number Nu. There are different ways to calculate the Nusselt number. By using similarity functions, we calculate it with the following equation:

$$Nu = c_1 \left(k_s l_W^3 \Delta\vartheta\right)^{n_1} \tag{8}$$

This equation describes the Nusselt number for free convection. c_1 characterises the heat emitting geometry while the value of n_1 separates a laminar and a turbulent flow from each other.

3 Modelled switch point components

While a complete switch point consists of various components, we set up a TNM model for the heating rod and the stock rail in the first step. The heating rod is indispensable as it is the actual heat source and provides the thermal energy. The stock rail, on the other hand, is connected straight to the heating rod by clamps. Its heating affects strongly the heating of the other components due to the stock rail's big volume and surface.

The outer cover of the heating rod is made of a heat withstanding stainless steel. The size of the rod is relatively small in comparison with the stock rail., Thus we simplify the heating rod to a homogenous stainless steel body and assume a thermal conductivity λ_h = 15 W m^{-1} K^{-1}, to receive a model with an appropriate level of detail [1]. Furthermore, we approximate the geometry of the heating rod to a rectangular cross section to be able to describe it in the TNM model (Fig. 1).

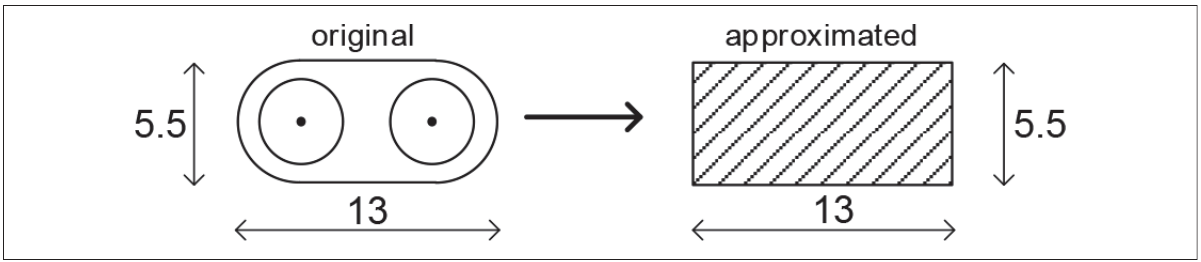


Figure 1 Original and approximated cross section of the heating rod

The stock rail is made of a special steel alloy. Various rail types exist for the railway traffic. The UIC 60 rail is one of the most used profiles and is therefore suitable for a TNM model. Its geometry is very complex, so that we have to simplify the cross section geometry of the UIC 60 profile significantly in order to set up a TNM model (Fig. 2).

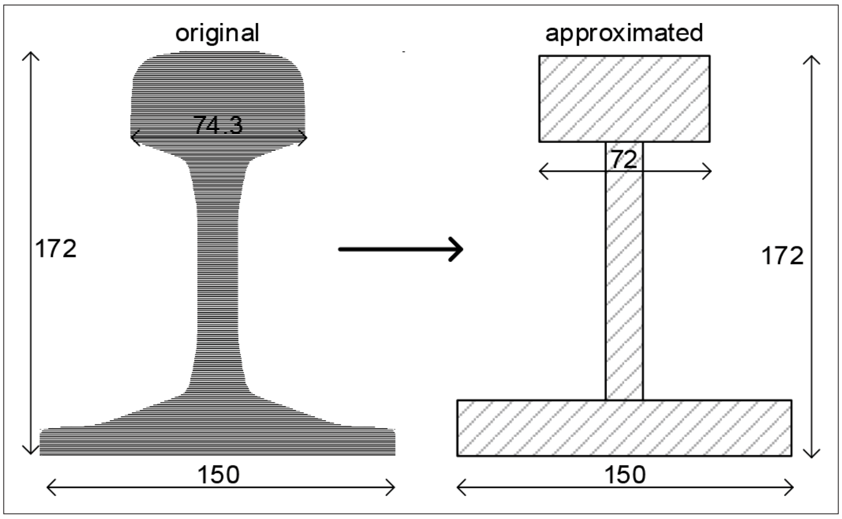


Figure 2 Original and approximated cross section of the stock rail

There is an obvious difference in the shape between both geometries. While a change in the cross section area can have an impact on the thermal conduction, a change of the surface area might affect heat radiation and convection. Comparing the cross section area and the perimeter size of both geometries shows a non-significant difference (Table 2).

Table 2 Cross section area and perimeter size for original and approximated geometry

	Original	Approximated	Approximated / original
Cross section Area	7617 mm²	7718 mm²	1.013
Perimeter	678 mm	746 mm	1.100

The deviation of the cross section areas amounts to 1.3 %, the perimeter, by contrast, has a difference of 10 %. Taken together, the deviation between original and approximated geometry is acceptable and we can use the approximated geometry to set up the TNM model for the heating calculation.

4 Set up of the thermal network

A thermal network consists of a number of nodes. Every node has a potential and consequently also an assigned temperature. Thermal resistors connect the nodes to each other. Heat conduction resistors realise the connection within a body. Resistors for convection and radiation represent the interface between the body and the ambience (Fig. 3).

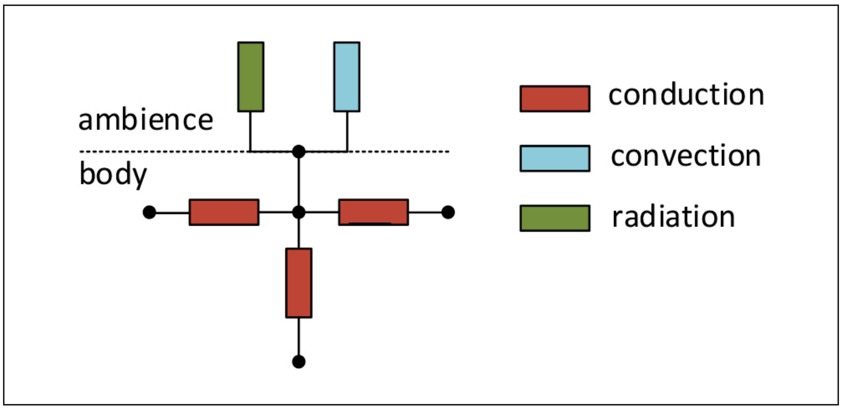


Figure 3 Small extract from a TNM model

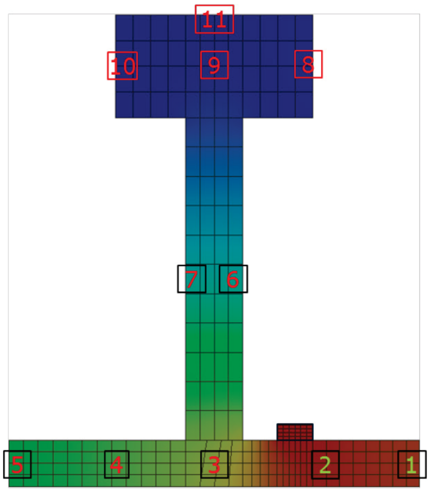
In this way, we set up a TNM model for a two-dimensional heat flow and the thermally steady state. That means this model does not cover a time-based heating. In hindsight, it will be possible to link several of those models considering the thermal conductivity to get the longitudinal temperature distribution additionally. The heat transport to the ground was not taken into account. A thermal conductivity of a carbon-manganese steel for the stock rail was assumed as a first approach. The emissivity amounts to 0.9 and we chose geometrical parameters for free convection by using the ones for vertical and horizontal plates (Table 3) [1]. The TNM model still has to be verified. We use a FEM model and an experimental set up to execute that.

Table 3 Chosen thermal parameters for first approach to a TNM model

		Stock rail	Heating rod
Thermal conductivity		$\lambda_s = 25$ W / (m K)	$\lambda_h = 15$ W / (m K)
Emissivity		$\varepsilon_s = 0.9$	$\varepsilon_h = 0.9$
Convection parameters	**Vertical surfaces**	$c_1 = 0.15$; $n_1 = 0.33$	
	Horizontal surfaces	upward: $c_1 = 0.17$; $n_1 = 0.33$ downward: $c_1 = 0.095$; $n_1 = 0.33$	
Heating power		P = 300 W / m	
Ambient temperature		$\vartheta_a = 0$ °C	

4.1 Verification with a FEM model

The number of nodes of a TNM model affects strongly its accuracy. A higher number is able to calculate the heat conduction depending on the geometry more detailed for a two-dimensional or three-dimensional heat flow in particular. FEM calculations achieve very precise results for heating calculations. The model geometries can be very complex and the results are almost independent on the mesh size except for very low number of nodes. However, it is a crucial disadvantage that the computing time will significantly increase if the model size expands. It is consequently not expedient to set up a FEM model for an entire switch point. Nevertheless, we can use the FEM to receive information if the number of nodes of the TNM model is sufficiently high enough by comparing the calculation results.



Reference point	ϑ_{FEM} / °C	ϑ_{TNM} / °C	$\Delta\vartheta$ / K
11	29.3	28.9	0.4
10	29.2	28.7	0.5
9	29.7	29.3	0.4
8	29.2	28.7	0.5
7	40.5	40.2	0.3
6	40.5	40.2	0.3
5	48.8	49.4	0.6
4	50.7	51.3	0.6
3	55.4	56.0	0.6
2	67.2	68.7	1.5
1	64.9	66.3	1.4

Figure 4 Heating calculation results by FEM and TNM

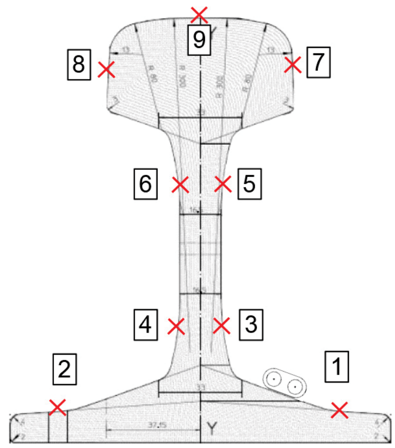
Therefore, we build up the simplified geometry of stock rail and heating rod in FEM and assign the same parameters for heat transfer as in the TNM model. Subsequently we vary the mesh size of the FEM until the nodes of the FEM model and the TNM model are located at the same positions of the geometry. In order to evaluate the results, we chose eleven reference points, at which the temperature values will be compared (Fig. 4).
The deviation of the heating calculation between both models is higher next to the heating source concomitant with higher static temperatures. All in all the results of both models only differ from a minor extent and thereby the number of nodes is chosen sufficiently high enough for the TNM model.

4.2 Experimental verification

An experimental verification enables the verification of the heat conduction within the stock rail and the heat emission to the ambience. The used heating rod with a length of 2.87 m and an electrical power of 900 W transfers heat into the 3.63 m long piece of a stock rail. Clamps connect both parts and thermocouples measure the temperatures at various positions. Around 7 h are required for the stock rail to reach the thermic steady state. Initially the differences of the measured temperatures and the calculated ones were considerable.
The emissivity was reconsidered at first to reduce those differences. A reference measurement with an infrared camera compared with measured temperatures by thermocouples delivered a mean emissivity of the stock rail $\varepsilon_s = 0.835$ and of the heating rod $\varepsilon_h = 0.23$.
The material of the examined stock rail is the steel alloy R350HT. Previous research has shown that values for the specific thermal conductivity are still not existing. Nevertheless, we can estimate the actual thermal conductivity by looking up physical parameters of other low-alloyed steels with a high carbon content. The steel CSN 42 2736 has almost the same proportion of carbon and manganese. Its thermal conductivity amounts to 36.8 W m^{-1} K^{-1} and will be assumed for the stock rail [3].
We used a fog machine in order to make the airflow visible at the thermal static state. The fog showed that a laminar flow mainly participates at the convection. That leads to the factor $n_1 = 0.25$ for the convection. A significantly higher measured temperature at the heating rod suggests the presence of additional heat transfer resistances R_t between heating rod and stock rail in the TNM model. From the experimental measured temperatures, we determined the missing values of the heat transfer resistance R_t and of the convection c_1 (Table 4). To simplify the TNM model and the parameter verification, the same convection parameters were set for every surface. Hence, the orientation of the surfaces does not affect the convection any more. Consequently, we chose nine reference points for the comparison between calculated and measured points on the surface of the stock rail (Fig. 5).

Table 4 Final thermal parameters for TNM model

	Stock rail	**Heating rod**
Thermal conductivity	$\lambda_s = 36.8$ W / (m K)	$\lambda_h = 15$ W / (m K)
Emissivity	$\varepsilon_s = 0.835$	$\varepsilon_h = 0.23$
Convection parameters	$c_1 = 0.2$; $n_1 = 0.25$	
Reference length	$l_{ws} = 0.172$ m	$l_{wh} = 0.0055$ m
Heat transfer resistance	$R_t = 4$ K / W	
Heating power	P = 900 W / m	
Ambient temperature	$\vartheta_a = 17{,}1$ °C	



Reference point	ϑ_{cal} / °C	ϑ_{meas} / °C	$\Delta\vartheta$ / K
1	92.7	86.9	-5.8
2	80.6	80.4	-0.2
3	75.4	79.0	3.6
4	75.4	78.5	3.1
5	67.2	69.1	1.9
6	67.2	67.6	0.4
7	62.3	65.4	3.1
8	62.3	64.8	2.5
9	62.5	64.8	2.3

Figure 5 Calculated and measured temperatures at different reference points on the rail

Obviously, the biggest temperature difference occurs at reference point 1. That position is located close to the heating rod. The higher the temperatures are, the higher the acceptable deviation is for the model.

5 Conclusion

The verification with a FEM model confirmed a sufficient number of nodes of the TNM model. Furthermore, an experimental set up helped us to adjust the parameters of the heat transfer to the ambience mostly. For further researches, it will be expedient to measure the heat conduction of the stock rail material with a separate test setup. The convection should also be reconsidered and various ambient factors e.g. wind, precipitation taken into account. Overall, we received a TNM model that is able to calculate the static temperatures at the cross section of a stock rail for various heating powers and ambient temperatures with a sufficient accuracy.

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