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Road and Rail Infrastructure III

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DEVELOPMENT OF A HEATING SYSTEM FOR HOLLOW SLEEPERS CONTAINING POINTS POSITIONING SYSTEMS

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Abstract

In winter, malfunctions of points on high speed routes can occur due to driving snow and ice. Existing heating systems, used to increase the availability of points positioning systems contained in hollow sleepers, cannot guarantee their operation under harsh environmental conditions. An optimized heating system is drafted using computational and experimental methods. The impacts of various designs of heating systems on the temperature profile at a positioning system are assessed using the thermal network method. A thermal network of the hollow sleeper and the positioning system equipped with an existing heating system is compiled and verified with experiments. The experimental verification is required to minimize the uncertainty of computed temperature profiles resulting from the uncertainty of flow and material parameters in the thermal network model. The efficiency of differently designed heating systems is calculated from computed temperature profiles of the points positioning system. A design with allocated heating elements is investigated experimentally in order to verify the computational results of that design. The temperature rise achieved with the optimized heating system is significantly higher than the one achieved with the original system, while the admissible temperatures are not exceeded.

Keywords: heating system, points, hollow sleeper, thermal network method, heat transfer, temperature rise

1 Introduction

Reliable carriage by rail requires a high availability of the infrastructure. In winter, malfunctions of points can occur due to snow and ice. On high speed routes, driving snow can ingress into hollow sleepers containing the points positioning system and impair its mobility. The preferred solution to increase the availability of points and in particular the availability of the positioning system in hollow sleepers is to apply heating systems. At all times in operation and especially under moderate environmental conditions, the maximum admissible temperature of the positioning system, which is determined by the hydraulic system, must not be exceeded at any spot in the points positioning system. Hence, the power of the heating system has to be limited in order to fulfil this task. Existing heating systems therefore cannot guarantee the operation of the positioning system under harsh environmental conditions like environmental temperatures as low as 20 °C in winter. Their capability of removing snow and ice does not suffice. Hence, an optimized heating system is required, which inherently does not exceed the admissible temperatures and provides an increased capability of removing snow and ice from the positioning system.

2 Thermal network method

The thermal network method [1] enables the investigation of temperature rise and temperature distribution within complex arrangements like points positioning systems contained in hollow sleepers. Within a thermal network, the heat transfer processes are simulated with the help of heat sources, temperature sources, thermal resistances and thermal capacities [2]. This method of computation is based on the analogy of the electric and the thermal flow field. The temperature ϑ of the thermal field is analogue to the electric potential ϕ of the electric field and the heat flow P is analogue to the electrical current I (Table 1).

Table 1 Analogy relations between the electric and thermal field

Electric field			**Thermal field**		
Magnitude	Symbol	Unit	Magnitude	Symbol	Unit
Potential	φ	V	Temperature	ϑ	°C
Potential difference voltage	$\Delta\varphi$ U	V	Temperature difference	$\Delta\vartheta$	K
Current	I	A	Heat flow	P	W
Resistance	R_{el}	$V\,A^{-1}$	Resistance	R_{th}	$K\,W^{-1}$

The heat flow is fed into the thermal network by heat sources, that e. g. mimic a section of the flat heating inside a hollow sleeper. The heat flow P is calculated with

$$P = I^2 R_{el} \tag{1}$$

The heat transfer processes in thermal networks are simulated by thermal resis-tances, defined as

$$R_{th} = \Delta\vartheta\, P^{-1} \tag{2}$$

The heat transfer processes of conduction, convection, thermal radiation and naturally driven volumetric flow occur in the hollow sleeper. The conductively transferred heat flow is described by FOURIER`s law of heat conduction [3], [4]:

$$P_d = -\lambda\, \vec{A}\, \mathrm{grad}\vartheta \tag{3}$$

λ is the thermal conductivity, A is the area of the heat flow and gradϑ is the gradient of the temperature field. The convective heat transfer is given by NEWTON'S law, with the convection coefficient α_{co}, the surface area A_{co} and the temperature difference $\Delta\vartheta$ between the surface and the fluid:

$$P_{co} = \alpha_{co} A_{co}\, \Delta\vartheta \tag{4}$$

The heat transfer coefficient α_{co} contains the physical flow processes and is determined by the similarity theory with the Nusselt number Nu, the Rayleigh number Ra and the characteristic length l_w [2]:

$$\alpha_{co} = Nu\, \lambda_{med}\, l_w^{-1} = c_1\, Ra^{n1}\, \lambda_{med}\, l_w^{-1} \tag{5}$$

The parameters c_1 and n_1 are a function of the flow geometry and are given for basic assemblies in e. g. [2]. The radiation heat flow P_{rad} between two bodies i and j is given by the STEFAN BOLTZMANN Law:

$$P_{rad} = \varepsilon_{i,j} \, C_s \, A_i \left[T_i^4 - T_j^4\right] \tag{6}$$

It contains the resulting emissivity $\varepsilon_{i,j}$, the radiation coefficient C_s of the black body, the radiating surface area A_i and the absolute temperatures T_i and T_j.

$$\varepsilon_{i,j} = f(\varepsilon_i, \varepsilon_j, A_i, A_i, F_{i,j}) \tag{7}$$

The resulting emissivity $\varepsilon_{i,j}$ is a function of the emissivity ε the surfaces areas A of the radiating bodies and the view factor $F_{i,j}$ [3], [4], [5]. The heat transfer P_V via volumetric flow is a function of the specific heat capacity c_p, the fluid density δ_0, the volumetric flow rate $\dot{V}$ and the temperature difference $\vartheta_i - \vartheta_j$ between the entering and exiting fluid.

$$P_V = c_p \, \delta_0 \, \dot{V} \left(\vartheta_i - \vartheta_j\right) \tag{8}$$

The volumetric flow rate $\dot{V}$ is a function of the buoyancy height h between the inlet and outlet apertures, the coefficient of volumetric thermal expansion β_0 and the flow resistances [2], [4]. The determination of flow parameters is generally not trivial and subject to uncertainty. Experimental verification is hence required.

3 Thermal network of positioning system in hollow sleeper

In this chapter the steps of modelling a points positioning system with the thermal network method as well as the compilation, structure, parameters and experimental verification of the model are described.

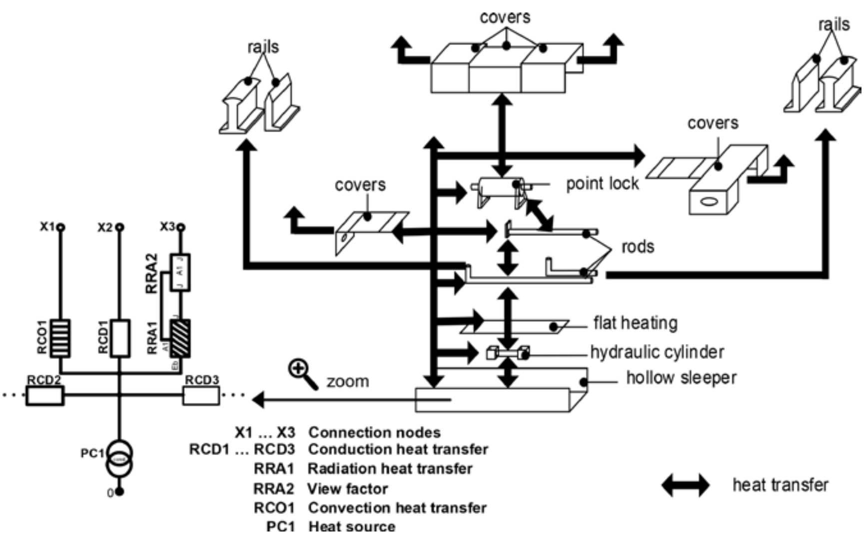

Figure 1 Thermal network model of the points positioning system

3.1 Classification of assemblies

The regarded points positioning system is a complex group of altogether 17 assemblies made of several materials with differing thermal material properties and surface qualities. The assemblies are: 9 different covers, 3 different rods, the hydraulic system, the rails, the point lock, the hollow sleeper and the flat heating. The thermal network model is compiled for each assembly separately and the resulting assembly models interact via conduction, convection and radiation heat transfer. Each assembly is modelled with several nodes (Figure 1), which interact with each other via conduction and with the other assemblies and the environment via convection and radiation. The radiative interaction between surfaces of several assemblies is a function of the geometry, temperature distribution and surface quality and it is described using view factors [4], [5]. The number of required nodes per assembly results from each assembly's dimension and its spatial constant of temperature distribution [2]. The heating system is modelled with spatially distributed power sources. The model requires several input parameters besides its structure to be defined. Input parameters are geometric (cross sections A, surface areas A, distances and view factors F_{ij}), material and surface properties [6] (thermal conductivity λ, emissivity ε) and flow parameters [2].

3.2 Verification

The material and surface properties depend on the chemical composition of the used steel alloys and their manufacturing procedure. An experimental verifica-tion of the thermal network model is necessary to limit the uncertainty of the computational results caused by the uncertainty of material and surface properties. The cover of the hollow sleeper exhibits several apertures, which enable a naturally driven volumetric flow between the inner air of the hollow sleeper and the environment. Flow parameters describing the volumetric flow and the convective heat transfer are given for basic assemblies [2] but need to be verified experimentally for complex assemblies. The verification process is performed in two steps in order to separately investigate convection flow parameters together with material and surface properties on the one hand and volumetric flow parameters on the other hand. The flat heating is operated with three different powers which are normalized with the power of the original heating system. The apertures in the cover of the hollow sleeper are closed and proofed in the experiments of the first step. A volumetric flow from the inside of the hollow sleeper to the environment cannot occur in this case (Figure 2).

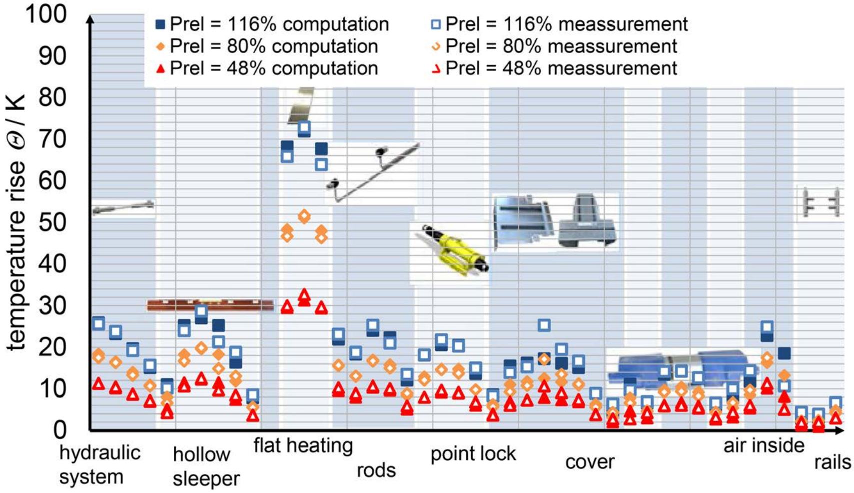

Figure 2 Experimental verification of thermal network with proofed apertures

In the experiments of the second step, the apertures are open and a volumetric flow from the inside of the hollow sleeper to the environment can establish. Its parameters are derived from the experimental results and complete the thermal network model of the entire positioning system contained in the hollow sleeper (Figure 3).

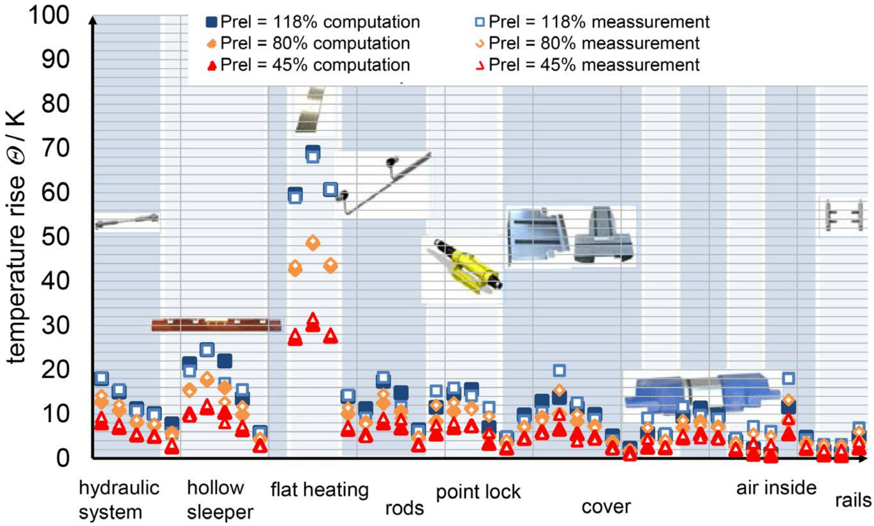

Figure 3 Experimental verification of thermal network with open apertures

4 Optimized designs of heating systems

As a result of the temperature rise tests (Figure 3) an uneven temperature distri-bution is evident along the hydraulic system, the hollow sleeper, the rods, the covers, the point lock and the flat heating. While the admissible temperature rise is exceeded at the flat heating, the temperature rise is less than 20 K in most of the positions. Therefore, high availability at winter conditions with outside temperatures as low as -20 °C cannot be ensured. By optimizing the heating system design, the temperature distribution in the entire hollow sleeper shall be homogenized. Increasing the surface area of the flat heating would obviously increase the heat transfer to the positioning system while reducing the surface temperature of the flat heating. Nevertheless, a flat heating with increased dimensions cannot be mounted in the hollow sleeper, as only limited room is available. Instead, the radiation heat transfer from the flat heating could be intensified by varnishing the surfaces of the flat heating, the gears and the inner surfaces of the hollow sleeper. Varnished surfaces have a higher emissivity of thermal radiation than blank metal surfaces [2], [6]. The usage of several allocated heating elements could homogenize the temperature distribution as well as directed heat transfer via a radiant heater combined with varnished surfaces. Alternatively, warm air can be fanned into the hollow sleeper. The impact of the introduced design alterations on the temperature distribution is assessed computationally (Figure 4) using the compiled thermal network model. The computational model considers an environmental temperature of 5 °C, which is the highest value to be expected in winter condition. Solar radiation is also taken into account for assessing the admissible power of the heating system.

Table 2 Parameters of the computed temperature rise distribution

Design	Mean value of temp. rise / K	Coefficient of variation
Original design	25.3	0.58
Varnished surfaces	27.4	0.54
Allocated heating elements	33.9	0.51
Flat + radiant heater	28.1	0.51
Warm air fan	19.7	0.47

The efficiency of the heating system designs is measured by the mean value of the temperature rise, while its homogeneity is measured by its coefficient of variation (Table 2). Only the temperatures of the hydraulic system, the hollow sleeper, the heating elements, the rods and the point lock are taken into account. The cover is not likely to impair the positioning systems mobility and the rails are separately heated which is not considered in the present investigation.

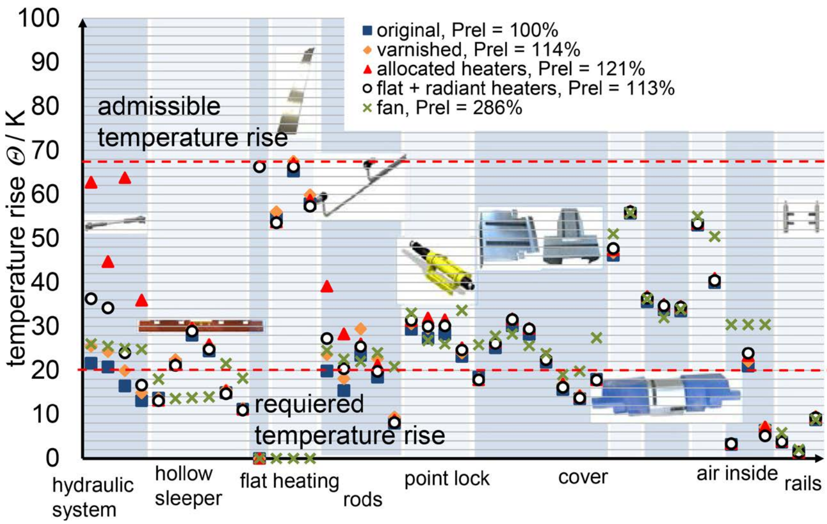

Figure 4 Computed temperature distribution for various designs of the heating system

The computational results only indicate a moderate effect of varnished surfaces on the temperature distribution within the positioning system. Fanning warm air into the hollow sleeper leads to a relatively homogenous temperature distribution but requires excessive power, because most of the heat is carried away by the warm air. Radiant heaters and allocated heating elements result in higher temperature rise and more homogenous temperature profiles than the original configuration.

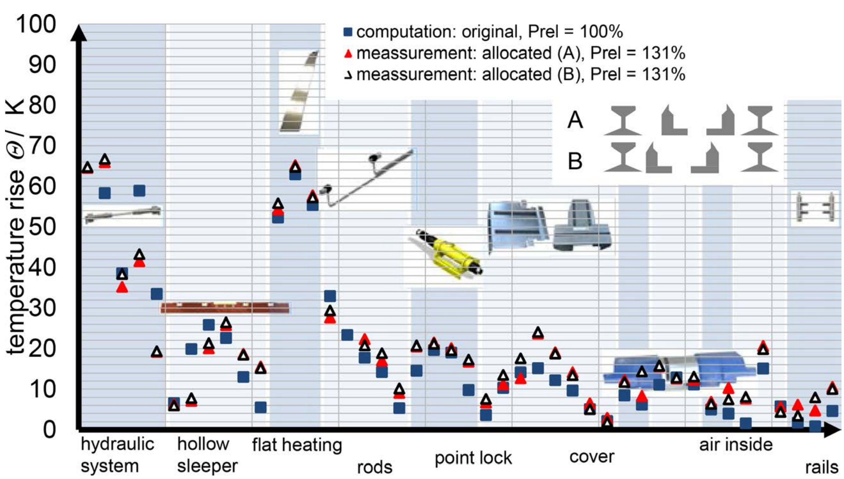

Figure 5 Experimental temperature rise with several allocated heating elements

The increase of the temperature profile homogeneity and temperature rise due to allocated heating elements is approved by experimental investigations (Figure 5). The temperature profile hardly depends on the position of the switch rails. The impact of the heating system optimization therfore does not depend on the switch rail position either. The power consumption of the optimized heating system with allocated heating elements is P_{rel} = 121 % and slightly higher compared to the original configuration. An increased effictivity of the optimized heating system can strictly be approved only under the conditions of investigation (no wind, no percipitation, environmental temperatur approximately 20 °C) and cannot be reasonned directly for realistic operational conditions. This is due to the impact of the environmental conditions, that has not been assessed experimentally. Wind increases the heat transfer to the environment and percipitation lowers the temperatures at the hollow sleeper. Therefore, a temperature rise of 20 K under laboratory conditions is only a necessary but not a sufficient condition for operation at environmental temperatures as cold as -20 °C. Nevertheless, the increase of mean temperature rise and the homogeneity of the temperature profile at least indicates a better availabillity of the points positioning system in winter conditions. It is not admissible to increase the power of the heating system in order to further increase its effectivity, because the admissible temperatures may be exceeded. Either higher admissible temperatures or a controll system could create the possibility for a further increase in heating power.

5 Conclusions

In order to assess the impact of various designs of heating systems on the tem-perature distribution at a points positioning system contained in a hollow sleeper, a thermal network model has been established and verified experimentally. Various modified designs of an existing heating system have been investigated by computational and also experimental means. A heating system composed of allocated heating elements provides for a relatively homogenous temperature distribution, while the admissible temperatures determined by the hydraulic system are not exceeded. In order to approve the effectivity of the drafted heating system, tests under harsh outdoor conditions have to be performed.

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