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Contactless turnouts' heating for energy consumption optimization

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Abstract: An electric turnout heating (ETH) system is an essential technical and economic issue. Uninterrupted operation of the turnouts is crucial to maintaining railway transport safety. The classic heating system is characterized by high energy consumption. The usage of it is extremely expensive, so the need to optimize the current system becomes more and more critical. At the same time, the progress in the contactless heating method has become a promising alternative. The paper presents the results of tests performed for electric turnout heating systems for two types of heaters. In the first place, the analysis of heat distribution was performed using the ANSYS Fluent v.16. The temperature fields in the turnout models filled with a model of semi-melting snow were analyzed. Thanks to cooperation with the Railway Institute in Warsaw the second stage of the research was possible to be completed. In this part, the models were implemented in the real world using the 49E1 railway turnout. The numerical solutions were validated by the experiments. The verification showed a high level of agreement among the results. The obtained results indicate the need for further tests of heating systems, to validate an optimal method of turnout heating. It was found that in the classic ETH, the working space area consumes a tremendous amount of energy. To ensure a higher efficiency of the heating process, the contactless heater is proposed as an alternative.

Key words: electric turnouts heating ETH, optimization of ETH system, temperature field simulations

1. Introduction

1.1. Electric turnouts heating systems

A railroad turnout is a crucial element of a railway road. It makes it possible for a train to change the direction of travel from one track to another. Maintenance of the turnout is necessary

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for ensuring safety in railway transport. The critical (working) area of the turnout contents: the space between a stock rail (fixed rail) and a point (moveable) rail, the surface of sliding saddles (chairs). The turnouts may be blocked during snowfall. In the winter-time, the critical elements of the turnout (Figure 1) must be cleaned or heated, so that its working area remains free of snow [3, 4, 8].

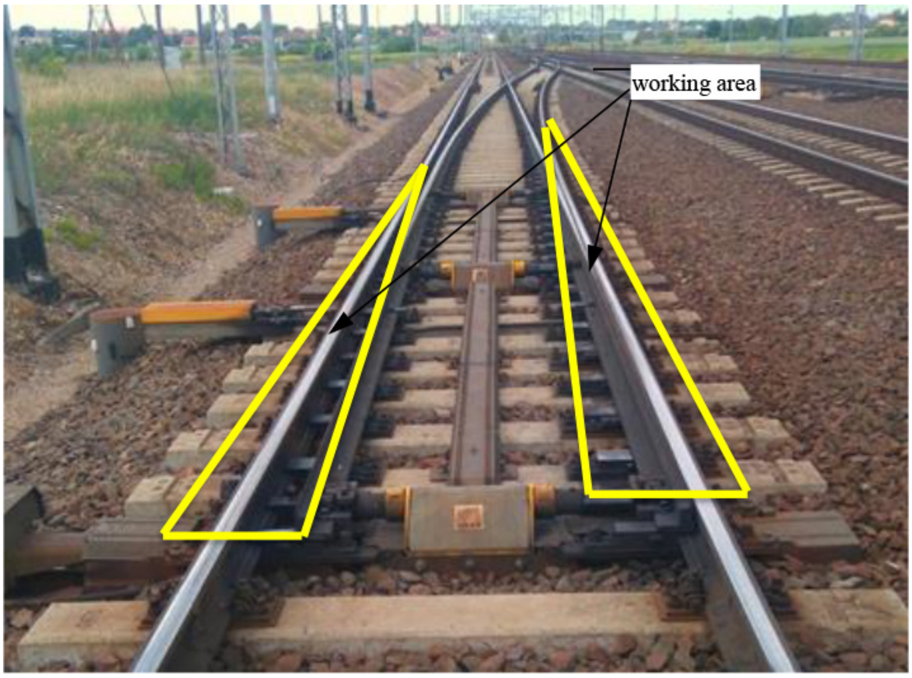


Fig. 1. Railway turnout working area (depicted by a yellow line)

Effective methods to prevent the turnouts from being blocked were developed since the beginning of the existence of railway transport. The central three systems used in the world are: pneumatic cleaning, gas heating, electric heating. The choice of one of them is determined by weather conditions in the installation area. The mostly applied system in Poland and Europe is an Electric Turnouts Heating ETH system [3, 4, 14, 15].

Currently, the most popular ETH system is a classic one. In this case, heat is generated in flat-oval resistive heaters (electric power of 330 W/m) that are installed directly on a rail's foot surface. Figure 2 shows the way of fitting a classic heater. The idea of the traditional ETH system is based on the assumption that the generated heat firstly is transferred into the rail, secondly from the rail's surface into the surrounding air. The main disadvantage of that solution is a result of the second heating stage. Only the heat that is directed into the working area causes the snow melting, and it's called "useable heat". The rest of the heat is dissipated outside the turnout's working space and is called "lost heat". In the classic ETH system, the process of snow melting lasts extremely long. The reason for this phenomenon can be explained on the basis of analysis provided for the first stage of the process under consideration. In this case, the long-time is a result of a vast thermal capacity of the fixed rail – it needs a significant amount of heat to warm up. Many turnouts heated by the classic ETH system are put at risk of insufficient temperature growth. As a consequence, the snow lying inside the working area may be only partially melted (Figure 3) [3, 4].

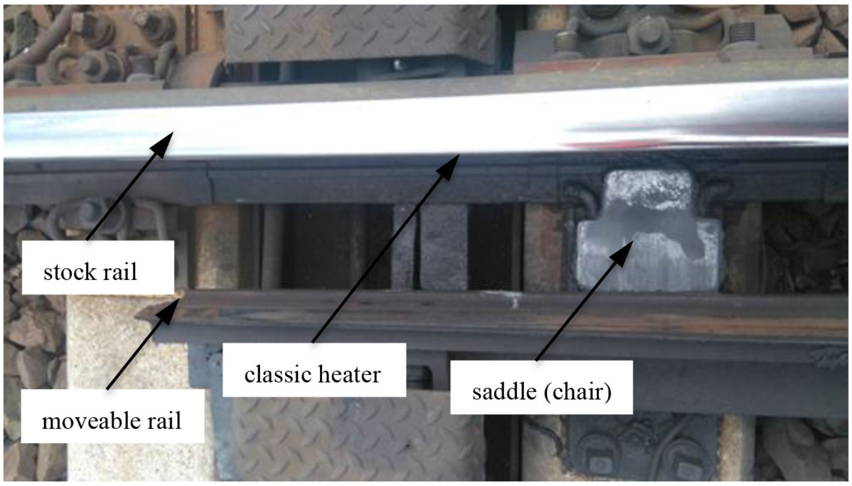


Fig. 2. An example of classic heater instalment

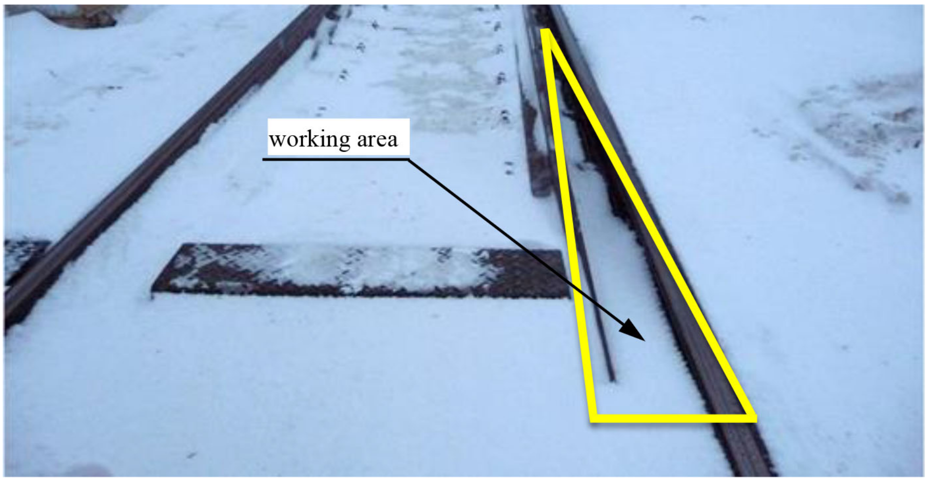


Fig. 3. Insufficient snow melting, a considerable amount of snow is present inside the working area

Classic ETH (Figure 3) heaters exploited in Poland have the following features:

- They are installed at 30% of turnouts,
- The number of heaters exceeds 100 000,
- The average time of operation during winter-time is about 300 h per one device,

- The total power of heaters per one turnout values from several to dozen or so kW,
- The absolute power of installed heaters is about 120 MW,
- It is the most energyconsuming element of the PKP SA infrastructure.

In Polish industry works are carried out aimed at reducing energy consumption and reduction of costs associated with the ETH operation [10]. Nowadays, electrical engineers face the new challenge of designing heating systems for new types of turnouts (e.g. turnouts characterized by a radius higher than before). Therefore, there is a need for intensive research in the field of searching for new, more effective and less expensive methods of removing snow from the turnout's working area [3, 4, 9].

In 2012 an innovative and revolutionary idea was proposed by the Termorad company from Poland [3]. By an expert method accomplished by experimental verification, the company team achieved favourable improvements in the working conditions of the ETH system. The engineers assumed that the development of railway turnout maintenance might be improved through:

- Instalment of thermal insulation between a rail and a heater, so that the rail is omitted in the heat distribution.
- Addition of a radiator to a surface of a classic heater. The radiators increase a surface that distributes generated heat directly into the working area [3, 5].

The innovative devices, namely contactless heaters integrated with radiator elements, were built and tested. The experimental results showed that the implementation of the described improvements was effective [3, 5]. The main changes introduced in the contactless heaters integrated with radiator elements that characterize the new method are described. Those changes are:

- Instalment of the heating element in a new way. It was proposed to thermally insulate the heater from the rail. It was assumed that this change would reduce the amount of heat absorbed by the rail. In consequence, this recovered heat would be directed into the turnout's working space. In practice, it is done by bending the heater's rod to provide 2–3 mm air space between the rail's foot and the heater's surface.
- Radiators instalment on the surface of traditional heating elements. In practice, it is done by screwing a piece of a plain 1–2 mm metal plate to the heater's surface.

The proposed method is believed to be effective. It is predicted that total heaters' power installed per meter of a turnout would be reduced. The technique may be successful because of the involvement of thermal insulation (air gap) between the heater and the rail. Additionally, radiator elements are added to the construction of currently exploited devices (Figure 4) [3].

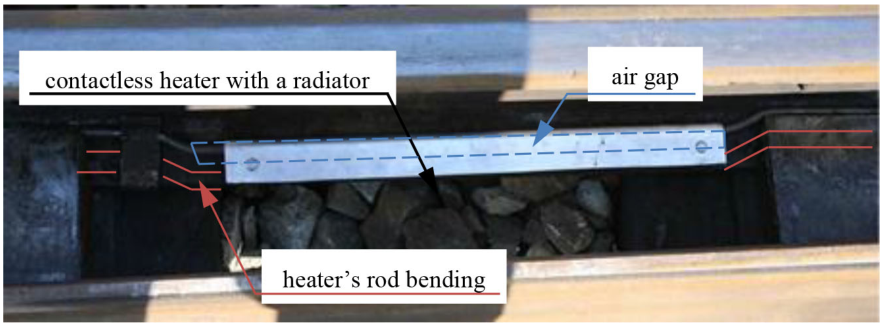


Fig. 4. Contactless heater with Termorad's radiator part

1.2. Thesis, aims and scope of the paper

The paper thesis

The use of thermal insulation (e.g. air gap) between a resistive heating element and a rail in a turnout increases the energy efficiency of the railroad heating process. As a consequence of energy consumption reduction, the operating costs of the railway infrastructure are suspected to decrease.

The article presents chosen issues that occur during exploitation of turnout systems. The first one is a theoretical analysis and description of the heat transfer mechanisms that play a significant role in the considered heating process. The second one is a discussion over a topic of energy consumption in the process. The author has showed results of a numerical investigation and compared them with gathered experimental data.

Aims of the paper

The purpose of the paper is to analyze the energy efficiency of heating railway turnouts. The analysis aims to describe the phenomena occurring when heating turnouts with various methods: a classic method (C) and an innovative method (I).

The objective of the work is accomplished by a numerical comparative case study of two types of heating systems: a classic method (model C) and a contactless method (model I). The results of the simulation tests were analyzed and confirmed experimentally.

The scope of the paper

This paper focuses on a comparative analysis of the energy efficiency related to the operation of two chosen ETH systems. The systems differ from each other in the way of heat distribution. The results obtained from the discussed in the paper experimental case studies are analyzed:

- Usage of classic heaters,
- Usage of heaters characterized by:
  - innovative profile shape,
  - the way of their instalment in a turnout.

2. Heat transfer modeling

2.1. Heat transfer mechanisms

Heat transfer is a physical phenomenon, which takes action as a result of temperature differences between two bodies. It can be realized by three mechanisms, such as: heat conduction, convection, heat radiation [1].

Heat conduction

In the turnout's case, the equation of thermal conduction describes heat transfer inside solid bodies and between the traditional heater and the base of the rail [1].

$$q_{cd} = -k\nabla T, \tag{1}$$

where: q_{cd} is the heat flux density [W/m^2], k is the material's conductivity [W/(m·K)], ∇T is the temperature gradient [K/m] [1].

Convection

In the analyzed case of ETH convection heat transfer, where convective heat transfer is calculated dynamically, describes heat transfer between solid bodies and fluids [1].

$$q_{cn} = h\left(T_s - T_f\right), \tag{2}$$

where: q_{cn} is the convective heat flux [W/m^2], h is the average convective heat exchange coefficient [W/(m^2·K)], T_s is the temperature of the solid [K], T is the temperature of the adjacent fluid [K] [1].

Heat radiation

In the model heat transfer by radiation describes heat radiated by all bodies [1].

$$q_r = \varepsilon\sigma T^4, \tag{3}$$

where: q_r is the emitted heat flux [W/m^2], ε is the object's surface emissivity coefficient [–], σ is the Stefan–Boltzmann constant [W/(m^2·K^4)], T is the radiating object's surface temperature [K] [1].

2.2. Melting process

A mathematical model of phase change, as an example of the highly non-linear phenomenon, is strongly complicated. Inside ANSYS Fluent, the enthalpy method for melting problems is implemented. When conduction, convection and a division surface between snow and air are present, the model consists of following equations [1, 2, 5, 6].

Conservation of mass

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0, \tag{4}$$

where: v_x, v_y, v_z are the velocity [m/s], x, y, z are the coordinates [1].

Conservation of momentum

$$\rho\frac{\partial v_x}{\partial t} + \rho v_x\frac{\partial v_x}{\partial x} + \rho v_y\frac{\partial v_x}{\partial y} + \rho v_z\frac{\partial v_x}{\partial z} = -\frac{\partial p}{\partial x} + \nabla\cdot(\mu\nabla v_x) + G_x + S_{vx} + F_{\sigma x}, \tag{5}$$

$$\rho\frac{\partial v_y}{\partial t} + \rho v_x\frac{\partial v_y}{\partial x} + \rho v_y\frac{\partial v_y}{\partial y} + \rho v_z\frac{\partial v_y}{\partial z} = -\frac{\partial p}{\partial y} + \nabla\cdot\left(\mu\nabla v_y\right) + G_y + S_{vy} + F_{\sigma y}, \tag{6}$$

$$\rho\frac{\partial v_z}{\partial t} + \rho v_x\frac{\partial v_z}{\partial x} + \rho v_y\frac{\partial v_z}{\partial y} + \rho v_z\frac{\partial v_z}{\partial z} = -\frac{\partial p}{\partial z} + \nabla\cdot(\mu\nabla v_z) + G_z + S_{vz} + F_{\sigma z}, \tag{7}$$

where: ρ is the density [kg/m^3], t is the time [s], p is the pressure [N/m^2], μ is the viscosity [kg/m·s], G, S_v, F_σ are the sources [kg/m^2·s^2] [1].

3. Heat transfer distribution in a railway turnout model

3.1. The semi-melting ETH model's description

The section presents the results of the numerical analysis of a temperature field in turnout models (Figure 5). The turnout consists of: a fixed and moveable rail, a heater and simplified snow. Two types of systems were investigated: a traditional system heated by a classic heater (model C), an innovative system using a contactless heater (model I). In both cases: the heater's power is 330 W/m, the turnout is located in the air, the reference temperature T_0 is 263 K, and the heat is transferred by the three mechanisms discussed above.

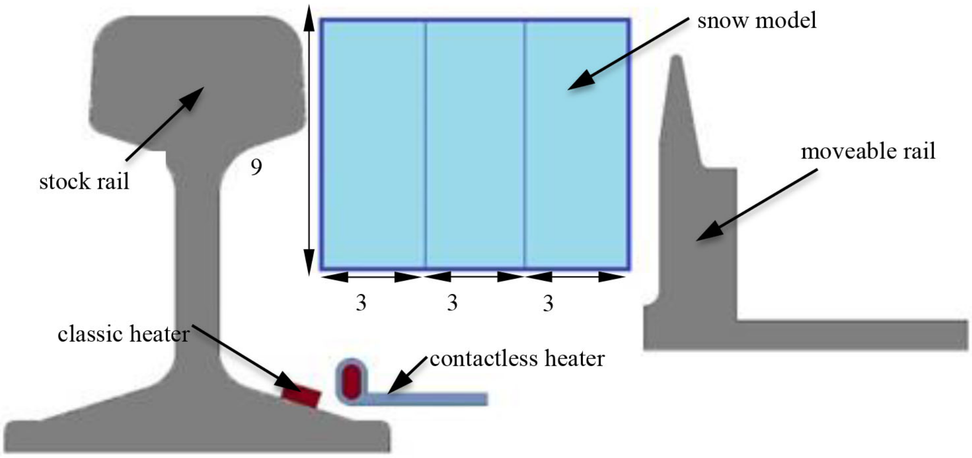


Fig. 5. The turnout model in semi-melting process analysis

In the two models, the working area of the turnout is filled up with a simplified snow model. It's assumed that for each one of them there are three degrees of the turnout's filling:

- Model 1 in which the snow's area is 9 cm × 9 cm,
- Model 2 in which the area is 6 cm × 9 cm,
- Model 3 in which the area is 3 cm × 9 cm.

The snow's model undergoes a semi-melting process, whereas the "semi" definition is "the first part of the compound word "melting" that creates the melting phenomena only partly, which the second part of the submission indicates". The other simplifications in a melting process are:

- The snow doesn't undergo a phase change,
- The computation process in each case is stopped when the temperature of the snow's boundary reaches 273 K,
- The influence of wind isn't considered.

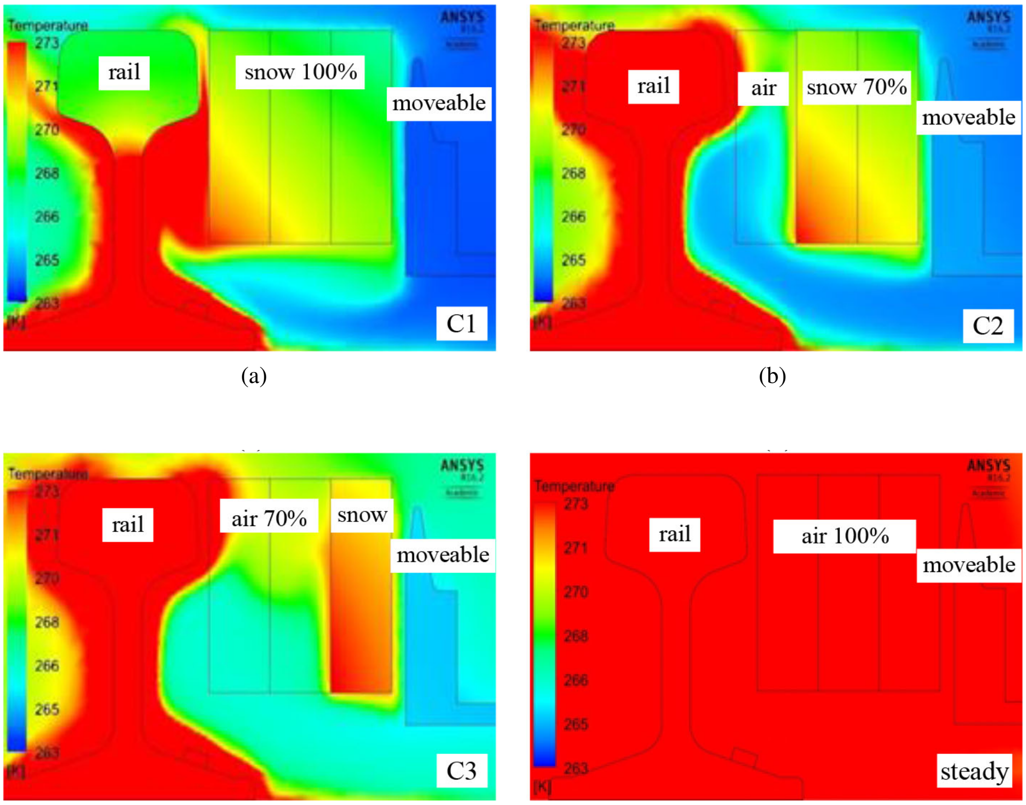
Thermal materials' properties are listed in Table 1 [1]. The set of parameter values gathered in Table 1 are subject to variability, e.g. due to different types of snow, the content of water in snow, climatic conditions, weather conditions, pollution, etc. It's extremely difficult to indicate the expected variability of the values. There are many types of snow available in nature. It is suspected that whether the impact on the results would be significant depends on the materials' parameter values. So that it is essential to take care of providing a satisfactory agreement between the weather conditions and the boundary conditions used in the computation analysis. In addition, an important condition is the ambient temperature of the turnout. The tremendous impact of wind speed and wind direction is observed during snowfall.

Table 1. Thermal materials' properties [1]: ρ is the density [kg/m^3], c_p is the specific heat [J/kg·K], k is the thermal conductivity [W/m·K], T is the air temperature [K]

Turnout's part	**Thermal material's properties**
Stock and moveable rail	$\rho = 8\,030$ [kg/m^3], $c_p = 502$ [J/kg·K], $k = 16$ [W/m·K]
Classic and contactless heater	$\rho = 8\,900$ [kg/m^3], $c_p = 461$ [J/kg·K], $k = 92$ [W/m·K]
Snow	$\rho = 90$ [kg/m^3], $c_p = 2\,100$ [J/kg·K], $k = 2.2$ [W/m·K]
Air	$\rho = 353/T$ [kg/m^3], $c_p = 1\,006$ [J/kg·K], $k = 0.024$ [W/m·K]

3.2. Discussion of the results obtained in the semi-melting models

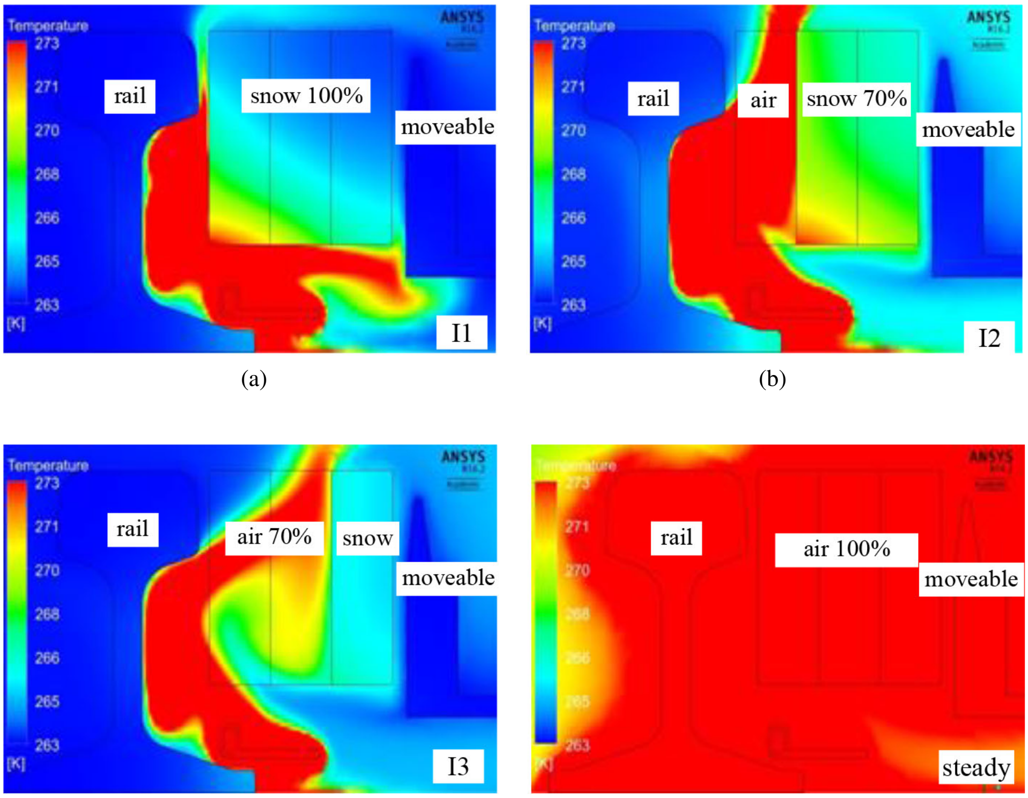
Figures 6, 7 present temperature fields obtained in the transient solution. The scale of the temperature is bordered by 273 K. The figures allow one to observe how the hot air is penetrating the working area of the turnout.



(a) (b)

(c) (d)

Fig. 6. Semi-melting in C ETH: (a) model C1; (b) model C2; (c) model C3; (d) steady solution



(a) (b)

(c) (d)

Fig. 7. Semi-melting in I ETH system: (a) model I1; (b) model I2; (c) model I3; (d) steady solution

The time was normalized as follows: t_s is the normalized time, T_{real} [s] is the time which was needed for each case separately to get 273 K at the snow's border and $T_{\max}$ [s] is the maximum time noted in the performed simulations:

$$t_s = T_{\text{real}} 100\%/T_{\max}\,, \tag{8}$$

The time t_s for the following C (classic, traditional) cases is:
- C1 – 0%,
- C2 – 13%,
- C3 – 59%,
- C4 (steady-state) – 100%.

Respectively, for the considered I (innovative, contactless) cases the time is:
- I1 – 0%,
- I2 – 7%,
- I3 – 12%,
- I4 (steady-state) – 13%.

Those results show that the time of the (I) process is several times shorter than the (C) one.

4. Experimental research on melting in turnouts systems

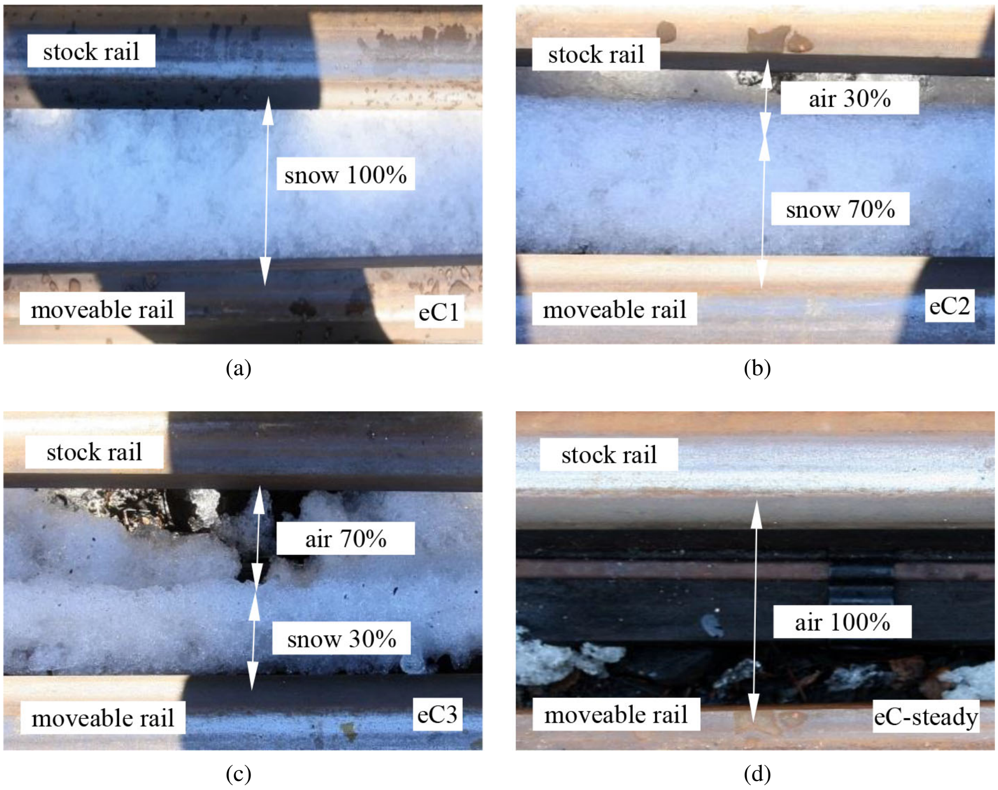
4.1. Description of the experimental model of a turnout

In 2010–12, the Railway Institute in Poland performed tests of contactless heaters with different heating element's shapes and equipped in different radiator types. The results of the research have been published in technical information sheets by D. Brodowski, the Railway Institute in Poland. In the publication [3], he described the heating using a few contactless radiators. The tests were carried out in winter conditions in the junction with 49E1 rails.

This paper is concentrated on the analysis of one chosen modified heating element, as named before – a contactless heater integrated with radiator elements.

4.2. Conclusions based on the experiment

Based on the experiment with a classic heater, it was found that snow melting is a long-term process. In a short time, the snow melted only to a small extent. It was measured that in the steady-state the temperature of the rail was about 45°C, the lowest temperature of the heater was 80°C, and the highest temperature was 160°C.



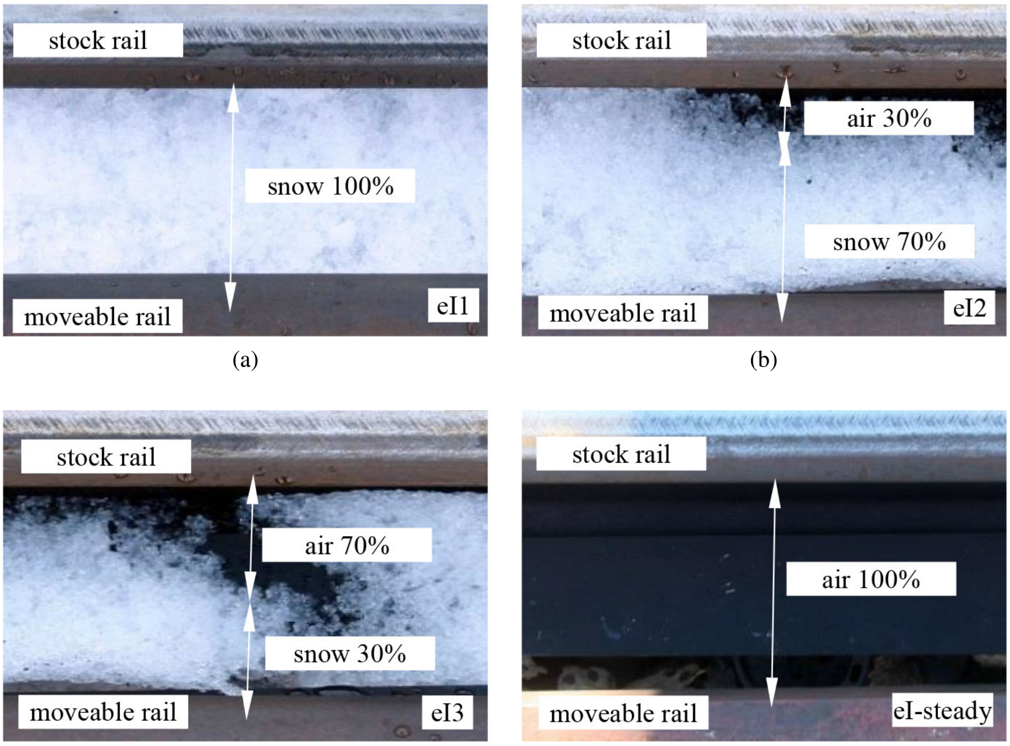
(a) (b) (c) (d)

Fig. 8. Melting process in experimental classic (eC) ETH system: (a) model eC1; (b) model eC2; (c) model eC3; (d) eC-steady state solution

The research showed that in the case of the new heater:

- The snow inside the working area was melted much faster in comparison to the traditional system.
- The snow inside the working area was melted to a greater extent than in the classic case.

Indeed, in the case of the Termorad S.C. prototype, the snow in the turnout's working area melted faster. In a relatively short time, an amount of melted snow (Figure 9(c)) reached a level as high as 70%. Consequently, just only 30% of the snow was still present. The temperature of the rail's foot was about 20°C, while the radiator's one was about 170÷200°C.



(a) (b)

(c) (d)

Fig. 9. Melting process in experimental innovative contactless (eI) ETH system: (a) model eI1; (b) model eI2; (c) model eI3; (d) eI-steady state solution

There can be found good agreement between presented numerical analysis results and experimental data. Qualitatively, the results obtained by two different research methods (simulation and experiment) seem to be almost the same in both studied cases. The melting process time was normalized, it was assumed that t_e is the normalized time, T_{real} [s] is the time which was needed for each experiment case separately to get 273 K at the snow's border and $T_{\max}$ [s] is the maximum time value noted in the performed experiments:

$$t_e = T_{\text{real}} 100\% / T_{\max} . \tag{9}$$

Quantitative analysis, based on Figures 8, 9, shows that times of the melting in the respective cases noted in the experimental part of the paper were:

- classic heater:
  - eC1 (Figure 8(a)) – at the beginning of the heating ($t_{eC1} = 0\%$) a percentage of the melted snow was 0%,
  - eC2 (Figure 8(b)) – after $t_{eC2} = 15\%$ of the heating time a percentage of the melted snow was 30%,
  - eC3 (Figure 8(c)) – the snow was melted in 70% after the time $t_{eC3} = 60\%$,
  - eC-steady (Figure 8(d)) – the snow was completely removed (100%) from the working space at the end of the experiment at the time $t_{eCs} = 100\%$.
- contactless heater:
  - eI1 (Figure 9(a)) – respectively, $t_{eI1} = 0\%$ and melted snow percentage is 0%,
  - eI2 (Figure 9(b)) – respectively, $t_{eI2} = 4\%$ and melted snow percentage is 30%,
  - eI3 (Figure 9(c)) – respectively, $t_{eI3} = 14\%$ and melted snow percentage is 70%,
  - eI-steady (Figure 9(d)) – respectively, $t_{eIs} = 18\%$ and melted snow percentage is 100%.

5. Final conclusions and further research prospects

The thesis of the article was proved. The operation of the current heating systems is not optimal. The comparative analysis showed that the contactless system is much more effective than the traditional one. Nevertheless, further investigation is needed to find the optimal shape of the heater element.

It was shown that in thermal problems, FEA analysis is characterized by high accuracy [11, 12]. Unfortunately, the calculation time of the phase change problems is extremely long, so it was decided to analyze the semi-melting of snow.

The use of ETH systems is a severe financial barrier for railway infrastructure managers. This factor justifies the need to look up for new alternatives in the field of turnouts' heating systems.

Right now, the author of this paper is working under the development of a device predicted to be implemented in railway transport. The device would restrict the amount of snow laying inside the turnouts area [13]. The prospect of this project is to build the next solution for energy consumption reduction.

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