CETRA^{2024} 15-17 May 2024, Cavtat, Croatia
8th International Conferenceon Road and Rail Infrastructure

INDUCTIVE RAILWAY TURNOUT HEATING SYSTEMS – A REVIEW OF SCIENTIFIC PUBLICATIONS

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Abstract

Electrical heating rods are state of the art heating systems to keep railway turnouts clear from ice and snow. Installation, maintenance and procurement is easy. Operational experience of several decades show good efficacy up to moderate wintry weather conditions. However, the energy efficiency is low. A significant amount of heat does not contribute to snow and ice removal but is transferred directly to the environment. Anthropogenic climate change will most likely lead to less days with snowfall but increased short-term snowfall intensity. Future turnout heating systems therefore would need increased capabilities of snow and ice removal. In contrast, overall energy efficiency must be increased to reduce greenhouse gas emissions, explicitly required by the EU energy efficiency directive. Inductive heating of railway turnouts is considered a potential heating method to achieve higher energy efficiency in railway infrastructure. To obtain a well-founded overview of the current scientific knowledge and for future decision-making, this paper presents a scoping review of scientific publications of the last 14 years about inductive turnout heating systems. Technical design approaches and operating parameters of several inductive heating systems are compared. Expressed drawbacks of inductive heating used in railroad infrastructure and so far unanswered topics regarding electromagnetic exposition and health safety as well as electromagnetic interference are pointed out. Additional investigations need to be carried out before inductive heating can be considered as a preferred future heating method for railway turnouts.

Keywords: railway turnout heating, induction heating, efficiency of turnout heating

1 Introduction

As a crucial component of railway infrastructure, turnouts enable trains to pass between railway tracks. A turnout largely consists of fixed stock rails, two movable tongue rails, switching machine, locking system and frog (Fig. 1). For track changing, the switching machine moves the tongue rails between the stock rails. In final position, one tongue rail is pulled away from the stock rail and locked. The second tongue rail is push-locked to the inner side of the opposite stock rail. The frog guides the train wheel from the tongue rail to the stock rail of the following railway track. Frogs can be fixed or moveable.

Railway tracks are exposed to the weather. For wintry weather conditions, ice and snow can accumulate and block railway turnouts. Blocked turnouts cause delays leading to financial and public reputation damage and eventually pose a risk for safe operation. Heating turnouts is an essential technical measure to prevent snow and ice accumulation. About 13.000 turnouts are heated in Austria. Heating is mostly carried out by electrical heating rods and plates. Installed electrical heating power exceeded 76 Megawatts in 2022 (Fig. 1).

DOI: https://doi.org/10.5592/CO/CETRA.2024.1592

Recent research concluded that energy efficiency of heating rods is low as a high amount of heat does not contribute to snow and ice removal [1]. Facing the challenges of anthropogenic climate change, the Energy Efficiency Directive of the EU requires all members to increase energy efficiency [2]. Electrical turnout heating is seen to be prone for increased energy efficiency. In contrast, less days with snow are expected but intense snowfall events likely increase under future warming [3]. Then, a higher capacity of ice and snow removal would be needed. To bring together higher capacity of ice and snow removal with reduced energy consumption alternative heating methods need to be investigated, e. g. inductive heating. In this paper, a scoping review is carried out to gain a well-funded overview of state-of-the-art induction heating systems for turnouts.

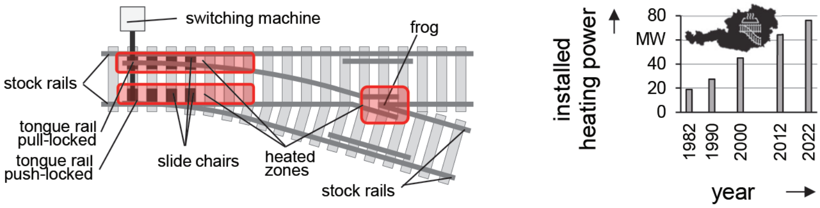

Figure 1 Railway turnout (left); Installed railway heating power in Austria (right)

2 Method

Google Scholar [4] was used to identify a first set of publications discussing inductive turnout heating. Publications were reviewed and references have been scanned with regards to inductive heating of turnouts. Through references identified additional set of papers was also reviewed and refences scanned. This method has been applied until papers reached publication dates before 2010 or initial papers were identified. Non-English literature has been excluded.

3 Applied fundamentals of turnout heating

Blocking of turnouts is caused by formation of ice and accumulated snow. Icing causes the tongue rail or the movable frog to freeze on the stock rail or slide chairs and prevent switching [5, 6]. Ice and snow drop from rolling stock and accumulate in the gap between tongue rail and stock rail [7]. Then, a switched tongue rail cannot be moved to its final position. Snow accumulates in the gap between the stock rails and tongue rails. Switching will compact the snow and eventually impair movement of tongue rails [8, 9]. Accumulation of drifting snow in hollow sleepers is also observed. It is assumed that switching will compact the snow and eventually block the mechanical or hydromechanical system [10, 11]. Heating stock rails with heating rods prevent from freezing and snow compaction between stock rail and tongue rail. For additional distributed heating power, tongue rails can be heated. Heat transfer from the heating rods along the rails to the slide chair prevents from freezing tongue rails to slide chairs. Heating rods used by ÖBB-Infrastruktur have a power from 330 W/m (stock rails, tongue rails) up to about 400 W/m (movable frog). Due to their primitive design, heating rods can easily be procured from several suppliers. Heating rods are clamped on the rails foot enabling easy replacement and maintenance (Fig. 2). Heating of hollow sleepers is carried out with heating plates of up to 400 W. Wet surface temperatures of rails, slide chairs and enveloping surfaces of critical gaps must be maintained above 0 °C.

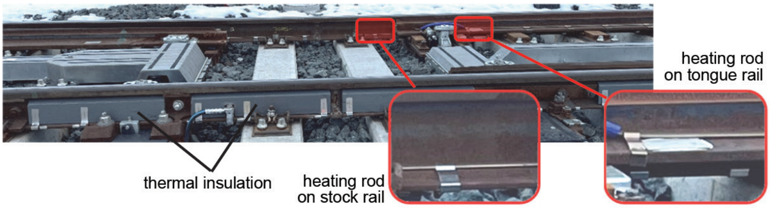

Figure 2 Full turnout heating installation at new railway track “Koralm” in Austria

ÖBB-Infrastruktur uses a control system that measures precipitation, ambient air temperature and stock rail temperatures. When precipitation is detected and ambient air temperature is below 4 °C, heating starts and maintains stock rail temperatures between 8 °C and 10 °C. Additional non-electrical equipment such as snow brushes or thermal rail insulation can be added to reduce snow accumulation or direct heat dissipation to ambiance.

4 Inductive heating

4.1 Mathematical formulation

With inductive heating, a conductive and ferromagnetic part is exposed to an alternating magnetic field . The magnetic field is usually created by an alternating current with a frequency . Heat in the part is then generated mainly from ohmic losses due to induced eddy currents in combination with the part’s electrical conductivity . Hysteresis losses due to magnetization occur to a limited extend. Eddy currents result from induced voltages by the alternating magnetic field penetrating the part and are described by Maxwell-Faraday equation for induction

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1}$$

equation for Ampère-Maxwell circuital law

$$\vec{\nabla} \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \tag{2}$$

material laws

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \tag{3}$$

$$\vec{B} = \mu_0 \vec{H} + \vec{M} \tag{4}$$

and Ohm’s law

$$\vec{j} = \sigma_{el} \vec{E} \tag{5}$$

It is $\vec{E}$ the electric field, $\vec{B}$ the induction, $\vec{j}$ the current densitiy, $\vec{D}$ the displacement field, t the time, $\vec{P}$ the polarization, $\vec{M}$ the magnetization, ε_0 the vacuum permittivity, ν_0 vacuum permeability and σ_{el} the electrical conductivity.

4.2 Direct inductive heating of rails and slide chairs

Szychta et al. [12] discussed the phenomenon of inductive heating by developing an analytical model of eddy current loss applied to rails (Table 1). The efficacy will strongly depend on the penetration depth of the magnetic field associated with the magnetic permeability. An analysis of UIC60 rail profile showed changing material structures between rail head, web edge and foot. Measurement from these sections determined different magnetic permeabilities.

Magnetic permeability also showed a sharp decrease for frequencies above 1 kHz. Szychta et al. and Kiraga [12-14] established simplified models of an UIC60 rail profile with a current carrying conductor at the rails foot to study basic distribution of magnetic field, magnetic induction, and eddy current density by means of the Finite Element Method (FEM). Formation of eddy currents and hence possibility of induction heating were proven with the FEM-model. A current carrying conductor as a source of the magnetic field was determined as suboptimal. This arrangement does not form a closed magnetic circuit. It is assumed that electric and magnetic properties of rails can change with each batch of rail production. Properties from several areas of a UIC60 rail were then measured [13, 15, 16]. An advanced FEM-model was established and set-up with measured electric and magnetic parameters for further analysis [16]. The FEM model is divided into sections for rail head, edges of rail web and rail core according to zones of same measured magnetic permeability. Computed induction was low. It is concluded that air gaps between the current carrying wire and the rails foot must be avoided. Oblong flat and oblong cup inductors to heat rails were developed by Szychta et al. [17]. Both inductors failed to provide a closed magnetic loop. The rail did not heat up from eddy currents. In 2016, experiments with a coil (150 windings) with a U-shaped ferrite core forming a closed magnetic circuit placed on a fragment of a rail were carried out. After 30 min this set-up reached a temperature-rise of about 20 K for frequencies from above 200 Hz to 1000 Hz and 60 Watts power supply. It is stated that a current converter with resonant circuit and total power of 4 kW per turnout should be sufficient for field application. Operation at the optimal frequency of 650 Hz requires costly capacities. Therefore, reasonable operation frequency should be between 1.5 kHz and 10 kHz [13, 18, 19]. Szychta et al. [5, 6] present a review of designs for inductive rail heating, where patents of several inductors are referenced. Further research into these inductors was not carried out. Uferev et al. [20] present a study of a trivial inductor coil made from single core wire placed around a slide chair. The inductor coil is run with a frequency of 10 kHz, a voltage of 100 V and an apparent power of 900 VA from a power source. The active power consumption of the power source is about 350 W. Tests with a slide chair covered in snow at -23 °C show the surface of the slide chair was cleared from snow after 2 h while the temperature rise was about 68 K.

Table 1 Approaches of turnout heating by direct inductive heating

Ref.	Approach	Parameters	Results/Remarks
[12]	· Analytical model induction heating		· f > 50 Hz · μ essential
[12-16]	· FEM-calculations for UIC60 rail with current-carrying conductor at rail foot	· μ_r for rail head, web edge, center and foot from measurement · σ = (3,50 – 3,88) MS/m from measurement · f = (0.1 – 1) kHz	· B_{max} = 0.037 T · no closed magnetic circuit · eddy currents proven
[17]	· oblong inductors as source for magnetic field	· P = 60 W · f = (0.05 – 1) kHz	· no heating observed
[13, 18, 19]	· U-shaped ferrite core with coil on a fragment of a rail	· n = 150 windings · t = 0.5 h · f = (0.05 – 1) kHz · P = 60 W	· ΔT = (8 – 20) K · inverter-design: f = (1.5 – 10) kHz and P = 4 kW per turnout
[20]	· inductor coil from single core wire around slide chair	· f = 10 kHz · U = 100 V · S = 900 VA · t = 2 h	· P = 350 W · ΔT = 68 K · slide chair cleared from snow

4.3 Dedicated induction heaters

Oh et al. [21] designed an induction heater consisting of a heating plate, a ferrite sheet as core and a coil placed inside a case. The coil was designed as printed circuit board (PCB) to satisfy the heaters limit size of 20 mm width and 6 mm thickness (Table 2). A 200 W resonant inverter with 250 kHz functions as power source. Heating performance is analysed by the means of numerical calculations. The induction heater does not heat up the rail but only its heating plate and reaches a surface temperature-rise of 30 K after 37 seconds. Subsequently, designs of induction heaters with and without a ferrite core were compared [22]. Both designs consist of a heating plate and a coil with 100 windings. It is shown with numerical calculations that surface eddy current density of the heating plates of both induction heaters rise linearly with increasing output voltage of the power source. The eddy current density of the induction heater with ferrite core is about 35 % higher. The surface temperature-rise increases with the square of the output voltage. For 20 V output voltage, a steady state-temperature-rise of 98 K is reached with ferrite core and 58 K without core. Oh et al. [23] present detailed development and tuning of prototypes of a PCB induction heater and a power inverter. Measured and numerically calculated temperature rise of the tuned induction heater correspond well. For actual application, surface temperature is capped at 50 °C by frequency-shifting from the resonant frequency of 250 kHz (high power mode) to 350 kHz (low power mode). Waveform of the supply voltage is rectangular. Efficacy of the tuned prototype including frequency shifting has been proven with an outdoor test at 4 °C. The gap-facing side of a snow-covered stock rail is cleared after 55 min of heating.

Table 2 Approaches of turnout heating with dedicated induction heaters

Ref.	Approach	Parameters	Results/Remarks
[21]	· PCB-induction heater · FEM-calculations	· 20 mm width · 6 mm thickness · $P = 60$ W · $f = 250$ kHz	· $\Delta T = 30$ K after 37 s · rail not heated
[22]	· FEM-calculations · PCB-induction heater with and without ferrite core	· $n = 150$ windings · $U = (10 - 120)$ V · heating plate: 2 mm thickness · heating plate of SUS430	· with ferrite core: $\Delta T = 98$ K @ 20 V · no ferrite core: $\Delta T = 58$ K @ 20 V
[23]	· PCB-induction heater and inverter · FEM-calculations · outdoor test	· $f = 250$ kHz (high power mode) · $f = 350$ kHz (low power mode) · $\vartheta_{limit} = 50$ °C	· stock rail cleared from snow after 55 min heating @ 4 °C ambient temperature
[5]	· reference to market-ready design	-	· $\vartheta = 135$ °C after 5 min heating
[5]	· climate chamber test · induction heater inside slide chair	· $\vartheta_{ambient} = -5$ °C · $P = 450$ W · turnout frozen	· 2 h until steady state temperature-rise · $\Delta T = (16 - 25)$ K · slide chair de-iced after 5 min · switching after 30 min
[9]	· multi-turn coil with radiator plate · experimental verification	· ice block on top · $\vartheta_{ice} = -10$ °C · $f = 50$ kHz and 90 kHz	time to melt ice block · 1219 s @ 50 kHz · 4751 s @ 90 kHz

Szychta et al. Error! Reference source not found.[5] present a review of designs of induction heaters. One market ready design is referenced for its short time to heat up (up to 135 °C in 5 min). This induction heater is placed under the stock rail and heats the critical gap between the stock and tongue rails. Experimental research on another induction heater placed inside a slide chair was carried out in a climate chamber. For -5 °C ambient temperature and 450 W heating power, the induction heater reaches steady state temperature-rises after about 2 hours. The steady-state temperature-rise of the slide chairs vary between 16 K and 25 K depending on the position of temperature sensors and tongue rails. Significant temperature-rises at the rails were not observed. From the measured temperatures and from additional experiment with snow it is concluded, that heating of the critical gaps between the rails was entirely sufficient. Further tests for -5 °C and iced turnout were carried out. Frozen slide chairs were de-iced after 5 min. For a tongue rail frozen to the stock rail, shifting was possible after 30 min of heating even though icing was still present. A prototype of an induction heater and its experimentally verified efficacy is presented by Żelazny et al. [9]. The induction heater is mounted at the bottom of the gap between the stock rail and the switch rail. It consists of a multi-turn coil placed inside an enclosure with high permeability and a radiator plate on top. Temperature rise with ice on top was numerically calculated with FEM for magnetic field frequencies from 40 kHz to 90 kHz and experimentally verified at 40 kHz. Experiments were carried out. An actual ice block placed on top of the prototype melts within 20 min at 50 kHz and 10 °C initial temperature. At 90 kHz impedance increases, current drops, and the time to melt the ice block increases to 79 min.

4.4 Efficiency and efficacy

Luft et al. [18] and Szychta et al. [13, 19] refer to induction heating of rails in Poland in 1978/1979. They conclude energy efficiency was 30 % higher as well as efficacy was higher while operation and maintenance costs were lower. For direct rail heating, the U-shaped ferrite core shows high heating efficiency in laboratory testing [18, 19]. Wołoszyn et al. [24] compare efficiency and efficacy of a heating rod with the induction heater placed at the bottom of the gap between stock and tongue rail by the means of numerical calculations. An ice block is modelled in the gap between stock and tongue rail. While induction heating takes 4 min to heat surfaces of the ice block from -23 °C to o °C, the heating rod takes 70 min at the same heating power. It is concluded that the induction heater transfers heat mainly from its surface to the ice block but not the rail. Therefore, efficacy and energy efficiency are higher. Szychta et al. [5] experimentally compare the induction heater placed inside a slide chair with heating rods and conclude that results point to a higher heating efficiency of induction heating. Because with heating rods, a high portion of heating power is transferred directly to ambience but not the critical parts and surfaces. Żelazny et al. [9] experimentally conclude the induction heater placed between the stock and tongue rails safes up to 70 % of energy compared to classic heating with heating rods. Uferev et al. [20] state heating the slide chair with an inductor coil is significantly more energy efficient than classic electrical heating. Main reason is a more directed heating of critical parts with inductive heating while with classic electrical heating non-critical parts are also heated. Oh et al. [23] compare the energy consumption of the prototype of high frequency induction heating system witch PCB inductor in an outdoor test to heating wires with 400 W/m. Taking frequency shifting into account, with inductive heating 87% of electrical energy can be saved during the 55 min it takes to heat up the stock rail and clear the inner facing rail surface from snow.

4.5 Electromagnetic compatibility

To ensure safe and reliable function of rail control systems, electromagnetic compatibility of inductive heating must be designed in respect to regulations of design and construction of rail application systems, communication systems, data processing and traffic control defined by standards EN 50126, EN 50128 and EN 50129 [18, 19]. It is stated that the DC/AC-converters must have sinusoidal waveforms of the inductor's voltage and current and absence of impact on communication, data processing and rail traffic control. Magnetic flux density measurements in the vicinity of the prototype of the inductive heater designed by Żelazny et al. [9] were carried out. Measured flux density directly at the top of the device vary from 4.5 µT at 40 kHz to 1.7 µT at 100 kHz. Magnetic flux density decreases with higher distance. At 12 cm only remaining background noise of 0.17 µT to 0.32 µT is measured. It is concluded that the magnetic flux density is very low and should not interfere with any nearby infrastructure. For the high frequency induction heating system with PCB-coil, Oh et al. [23] state the operation at 250 kHz resonant frequency was chosen to avoid electromagnetic interference with track and signal frequencies of Korean railways. in the study from Oh et al. [21] on de-icing with induction heating it is mentioned that a filter has been added to the input of the 200-W-250-kHz-resonant inverter to avoid electromagnetic interference.

5 Discussion

Recent research about a lower efficiency of turnout heating with heating rods is congruent to findings by various papers comparing inductive heating to heating rods. Heating with dedicated induction heaters seem to be more efficacious than direct inductive heating of rails or slide chairs. Electric and magnetic properties of rails are mostly unknown and may vary with manufacturer, production batch and zones of the rail, which hinders correct dimensioning of direct inductive heating systems. Two kind of induction heaters were developed. First kind of induction heaters can be placed at the foot of rails comparable to heating rods, which is advantageous for installation and maintenance. Second kind of induction heaters are placed in the gap between stock rail and tongue rail near or under the rails foot. This should enable highly efficient snow and ice removal within the gap. Installation and maintenance seem to be more complex. Also tamping may be affected. For further decision-making, systematic research of efficiency and efficacy of the two kind of induction heaters should be carried out for each type of turnout blocking scenario and benchmarked to heating rods. Design rules for electromagnetic compatibility are pointed out. While Luft et al. [18] and Szychta et al. [19] state, that sinusoidal waveforms are required, Oh et al. [23] describe a rectangular waveform for the output voltage at 250 kHz to avoid electromagnetic interference. Absence of interaction with rail control and communication systems must be verified experimentally. The author did not find any publications researching electromagnetic emissions for health safety assessments. It is assumed this topic will be publicly questioned in detail when induction heaters would be rolled out.

6 Conclusion

Current applied fundamentals of turnout heating within Austrian ÖBB-Infrastruktur were briefly elaborated. Overview of scientific state of the art of inductive turnout heating was compiled by the means of a scoping review. Inductive heating is possible. Findings indicate that inductive heating is more energy efficient and more efficacious than heating rods. Dedicated induction heaters are more efficacious than direct inductive heating of rails or slide chairs. For a shift to application, further research should focus on benchmarking induction heaters to heating rods. Research on electromagnetic emissions for health safety assessments was not found by the author.

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