1. Introduction

The efficiency of friction elements of the rolling stock brake system has a significant impact on traffic safety and possibility of speed increase. This helps to improve freight capacity and throughput [1 - 5].

During braking, kinetic energy of the train is transformed into other forms of energy, mostly to heat. This process is accompanied by increase in the friction element temperature. Effective braking depends on the friction coefficient, which is influenced by temperature changes in the friction contact. Accordingly, the topical issue in the rolling stock operation is stabilization of the temperature in the braking element interaction zone [6 - 7].

Due to the friction forces wheel and brake pads contact is heated up during braking. This adversely affects the surface of the wheel rolling (the temperature in the contact zone reaches 700 - 800 °C) [2 and 8]. It is proven that the heat load is inversely proportional to the disc and pad interaction square. A temperature field with a significant gradient is an indispensable physical phenomenon of mechanical energy into heat conversion. This leads to decline in friction and strength properties due to structural changes in materials. Prolonged exposure to high temperatures promotes the release of thermal cracks into the outer surface. Due to high temperature friction the surfaces of brake elements wear relatively quickly. The rate of wear is determined by the occurrence and development of high temperatures in the friction zone [9]. The increasing temperature of the brake disk can lead to its deformation and surface misalignment. Thermal deformation in the rib area causes the waviness or roughness of the friction disc surface, thereby increasing the pressure on the friction linings and creating local temperature spots on the friction disc surface [10].

2. Temperature control methods of tribo-loaded brake elements

Providing stabilization of friction element operation is a multifaceted problem which cannot be solved by the application of a single method. It requires solutions of technical-economic, technological, metallurgical, and tribological tasks.

To solve this problem, combinations of various methods have to be implemented (ceramic discs with high temperature resistance, perforation application, etc.) and cooling air has to be supplied. In designing brake elements for means of transport, following methods for temperature control of friction pairs are currently implemented [1 - 2, 6 - 8, and 10 - 18]:

1. Temperature control based on heat absorption or release by metallic or non-metallic friction elements of brakes.
at periodic heating and cooling making use of unequal thermal expansion of individual sections of the pad.

Innovative methods which can be implemented in modern braking systems in the future are as follows:

- forced air flow supply into the contact area of two friction elements;
- forced air supply with temperature control depending on conditions and modes of operation;
- pads with porophore inserts;
- pads with cooling ribs;
- brake pads with outer surface covered with heat dissipating material;
- friction activator supply to the friction contact zone;
- brake elements with phase transition material inserts.

3. Impact assessment of vehicle movement resistance caused by disc brake operation

The most common construction solution for ensuring stable operation of the brake elements is the use of ventilated discs (Fig. 1). The main advantage of these designs is the cooling surface of the disc when braking up to a certain speed. The disadvantages include the movement resistance from the ventilation channels. At vehicle’s high speeds the brake disc vent blades create additional resistance to movement, which leads to certain losses of locomotive power capacity, especially for high-speed locomotives, for which the resistance increases due to significant speeds. So 3000 – 4000 m³/h of air that cools the disc is pumped through the ventilation channels. This leads to costs that depend on the rolling stock speed and length, number of discs on the wheelset axis. For example, according to the research performed by A. I. Turkov [1], diesel trains of DR-type which were equipped with sets consisting of eight brake discs will consume for self-ventilation 19.1 kW at the speed of 200 km/h. Electric trains of ER-type will consume 48 kW for self-ventilation. For diesel train DR1 total power is reduced by 2.6%. The study presented in the Table 1 shows that for modern high-speed trains, this number increases several times.
4. Technical solution for eliminating self-ventilation of disc brakes during a vehicle running

To eliminate the self-ventilation of the disc brakes resulting in the vehicle resistance against movement and against the startup of a standing vehicle, it is necessary to close the ventilation channels of the disc brakes. The developed disc brake design contains elements for closing the ventilation openings during the movement. This phenomenon is achieved by the design illustrated in Fig. 2. During the movement, the shape memory alloy plates (Fig. 2) located at each vent blade, block the ventilation ducts. During braking, the temperature of the brake disc rises. Under high temperature the material of the plate shifts from the martensitic state $T_{M}$ to austenitic $T_{A}$ (Fig. 2). This changes a crystal lattice and a shape of the plate. The angle of inclination $\alpha$ of the plate to the ventilation blade decreases from 90° to 0° and the ventilation channels open. Under the action of centrifugal forces the air in the ventilation ducts moving from the brake disc center to its periphery in the radial direction, as a result, forms the ventilation air flow that removes heat from the disc.

Analysis of the brake discs influence on the train power loss

| $t$ | Manufacturer | Train Series | Power output, $P$, kW | Speed, $v$, km/h | Aerodynamic (pumping) power loss for one brake disc $Q_{aero}$, kW | Aerodynamic (pumping) power loss for all brake discs of the train $\sum Q_{aero}$, kW | Loss of power train due to operation of disc brakes, % |
|-----|--------------|--------------|---------------------|-----------------|-------------------------------|----------------------------------|-----------------------------------------|
| 1   | Alstom       | TGV POS      | 9 280               | 320             | 3.15*                         | 88.15*                           | 1*                                      |
| 2   | Siemens      | CRH380B      | 9 200               | 350             | 3.83*                         | 245.39*                           | 3*                                      |
| 3   | Talgo Bambordier | AVE Class 102 | 8 800               | 330             | 3.37*                         | 141.48*                           | 2*                                      |
| 4   | Hitachi Kawasaki Nippon Sharyo Tokyo Car | E2 SERIES SHINKANSEN | 9 600               | 275             | 2.26*                         | 180.44*                           | 2*                                      |
| 5   | Alstom       | ED250 Pendolino | 5 664               | 200             | 1.12*                         | 47.01*                            | 1*                                      |
| 6   | Hitachi      | BR Class 395 | 3 360               | 225             | 1.45*                         | 69.62*                            | 2*                                      |
| 7   | Hyundai Rotem | KTXIII       | 9 840               | 350             | 3.83*                         | 184.04*                           | 2*                                      |

* when calculating the formula according to Turkov: $N_{t1} = 0.1624 \cdot V^{2.2}$

** when calculating the formula according to Turkov: $N_{t3} = 0.03594 \cdot V^{3}$

Due to limited information we assume that all types of bogies will have wheelsets equipped with two brake discs. Though in operation, one wheelset can have more brake discs.
When the brake disc cools, the reverse occurs - the plate material passes from the austenite state to martensite. When the plate temperature reaches martensitic condition $T_m$ it flexes, taking the original position ($90^\circ$) - the ventilation channels close (Fig. 2); this reduces the additional power cost caused by airflow in the ventilation ducts of the brake disc during movement.

Thus during movement the ventilation channels are closed and during braking they are open. Upon the brake disc reaching ambient temperature, the plate returns to its initial position. In this case the ventilation channels are closed until the next braking.

### 5. Innovative design of rolling stock brake elements

The disadvantages of the known brake disc constructions include:

- The complexity of brake disc replacement for the use in railway transport. When the disc is to be replaced and a standard brake disc is placed between the wheels of the wheelset, it is necessary to press both the wheel and the disc from the axle. Then both a new disc and wheel are pressed on the axle.
- High brake disc replacement costs.
- Insufficient cooling of the contact surface.
- Crackles.

To eliminate these disadvantages and take advantage of the known disc structures an innovative brake disc design is proposed [15]. The main idea of the design is making the disc in the form of two wound plates, one of which is frictional the other is heat removing (Fig. 3). The brake disc is formed by winding and fixing these plates on the wheelset axis. A strip of the outer contact plate side has projections for cooling on the outer, and...
grooves for placing the strips of the inner heat removing plate on the inner side. Ventilation channels for cooling are formed between the strips of the outer contact plate. Strips can have a constant width or their width can widen from the disc center to its periphery, which enables to make use of greater amount of air in the ventilation channels.

A strip of the inner heat sink insert 7 is made of material with higher conductivity than the external strip material of the contact plate 4.

A strip of the outer contact plate 4 must be made of steel with high resistance to wear caused by friction material of the brake lining.

Before winding the strips of the outer contact plate 4 into the grooves 6, the inner heat conducting strip insert 7 is attached to the contact plate strips. The inner strip thickness 7 is greater than the depth of the groove 6, and its width is less than the one of the outer strip 4. This ensures the formation of ventilation channels 10 in the disc across its friction surface. The edges of the outer contact plate strip 4 are rounded to reduce wear of the friction pair “brake disc 3 - friction pad 2". Both strips are provided with holes 8 for attachment to the wheelset axis 9.

The mounting of the brake disc 3 is done by winding strips on the wheelset axis 9. Then the brake disc 3 is fixed on the wheelset axis 9. To ensure the acceptable level of the brake disc 3 imbalances, the run-out value must not exceed the set limit. The diameter of brake disc 3, the thickness of both strips and the width of air channels depend on material properties, rolling stock type, operating conditions, and maximum permissible speed of train.

During braking, the brake shoes 1 are pressed to the brake disc 3. The heat removal from the friction zone is due to:

1. Different heat conductivity of a bimetallic couple of the external strip of the contact plate 4 and the inner heat sink strip insert 7 which causes heat flow gradient in these sections of the brake disc 3. The inner heat sink strip insert 7 provides a more rapid transfer of heat through its cross-section than the outer strip of contact plate 4. As a result, on the border “strip of the outer contact plate 4 - internal heat sink inserts 7" there is a temperature difference. Less heated surface of the inner heat sink strip insert 7 serves as a refrigerator for the corresponding surface of the strip to the outer contact plate 4, accelerating the outflow of heat from its scope and, consequently, of the friction zone.

2. Convective transfer of heat formed on the surface of the strips through the vent channels 10.

Lowering the temperature of friction surface heating allows maintaining the friction coefficient output values for a long time and, therefore, braking efficiency. However, the decrease in temperature contributes to the preservation of the mechanical properties of the contact surface layer, thereby increasing its resistance to wear.

The acceleration of heat outflow from the zone of inhibition leads to a decrease in the temperature of the heating strip of external contact plate 4 of the brake disc 3 in 1.5 - 2.0 times depending on the size and material of the insert strip 7. The result is improved braking efficiency and reduced wear of the contact surface.

The use of the wound design of the brake disc allows reducing the probability of cracks in the depth of the disc, thus increasing the reliability of its operation.

The proposed design use will provide additional cooling surfaces of the brake disc to reduce the friction surface wear, improve resistance to crack propagation in the depth of the disc, simplify the technological process of the brake disc replacement, due to the fact that it is not necessary to dismantle the wheels.

6. Conclusion

An effective braking system is an important part of safety and resource saving in rolling stock operation. The article considers braking elements interaction problem. Basic and advanced methods for the temperature stabilization of the brake element friction contact are presented. Based on the analysis we can conclude that the most widely used way of temperature stabilization is the implementation of a disc with ventilation channels. The design of discs with ventilation channels improves braking effect but, at the same time, it increases the vehicle running resistances. The study of vent disc movement resistance effect on different formulations showed that depending on the disc structure, their quantity and train speed, reduction of power ranges from 1% to 23%. In conclusion, disc elements with a shape memory design are proposed; they allow opening and closing the vents depending on the disc temperature and thereby eliminate the phenomenon of self-ventilation. The proposed innovative brake disc design takes into account the advantages of existing structures.

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