The Joule–Thomson effect and the non-equilibrium thermodynamics of sliding nano-contact

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***Abstract*—Dynamical systems, having the space-time-varying behavior, takes place in the range of processes. Especially interesting are those which affect the structure and properties complex materials during its formation because of thermal communication between the different parts of the system. One of the most important features of the study is the temperature behavior in the contact area under sliding interaction. This behavior results from the large contribution of the heat capacity to the entropy. We investigate the influence of the Joule-Thomson effect on the behavior and thermal characteristics of contact area formed by debris and lubricant between the sliding surfaces when they are brought into contact with one another in commutator-and-brush assembly as an example. The model reflecting the influence of the change in the third body temperature on the material properties, geometry of the debris and the surrounding environment is proposed. The result shows the strong correlations between Joule-Thomson effect and mechanical fluctuations of the wear particles that are responsible for the size of the contact area.**

Keywords— sliding surfaces; thermal fluctuations; wear particles; dynamic contact; surrounding medium

I. INTRODUCTION

Dynamic contact between two surfaces that are moving over each other is usually accompanied by many physical phenomena [1–6]. From a physical point of view, the dynamic contact is an impulse process having the space-time-varying behavior in contact area, so called spatio-temporal processes [4–13]. The probabilistic nature of the dynamics and the structure of material leads to the strong correlations between interaction and physical properties that are responsible for the dynamic equilibrium [2–5,9–13]. This takes place in the range of processes, including sliding contact [14]. However, despite of the secular study of the sliding contact [1,14–17], many research questions of the pure equilibrium of the dynamical interaction between moving bodies remain unexplored, in particular, the influence of surface properties on thermodynamics of the sliding contact layer. The structure and properties (physical, thermal, mechanical, etc.) of complex materials during its formation process have strong correlation with the surrounding medium [2–5,14–18]. Each of the material particles interacts with surroundings randomly, independently of each other, resulting from a probabilistic nature. This fact leads to the rich material properties with small changes in parameters [18–20].

An electrical contact pair is of interest [4,5,14,17] from the point of view of its structure due to material multivariance (carbon, metal, nanostructure, and others), which have a correlation [3–5] with environment formed by wear particles or lubricant under sliding interaction. These elements exemplify the strong correlations [7–11] between random mechanical fluctuations of the wear particles and temperature behavior of the contact area (air with wear particles or lubricant), in particular, the non-equilibrium thermodynamics [5,6,8–12,20–21]. The random mechanical fluctuations of the wear particles during interaction with the environment cause the Joule-Thomson effect [14,21–27] on the contact area. We could optimize the choice of material and evaluate the contacting pair durability taking into account the thermodynamics of interaction at the electrical contact.

The aim of this article is to investigate the measure of influence of the Joule-Thomson effect on the behavior and thermal characteristics of contact area between the sliding surfaces when they are brought into contact with one another. To achieve our research outcomes, we create the model reflecting the influence of the change in the contact area temperature on the material properties, geometry and surrounding environment.

II. METHODS OF RESEARCH

We assume that the dynamic contact area of surface sliding interaction is constant. Thereafter, one surface slides on another surface under the action of the normal loading force with a constant linear speed, for example [17], when the electric brush slides on a slip ring (collector) of electrical machine (Fig. 1). We ignore the destruction of the brush lateral surfaces inside the brush-holder because it has no real impact on the thermodynamics of sliding contact layer and could be negligible.

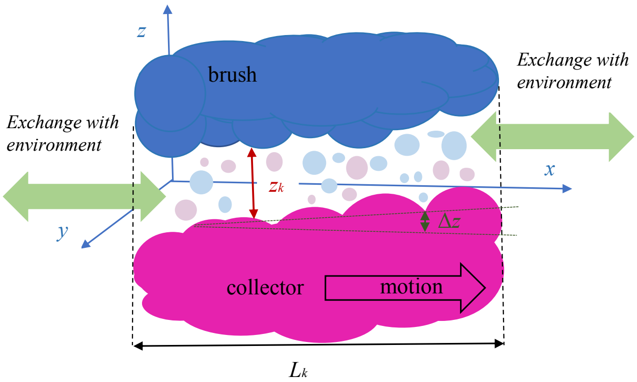

Fig. 1. A schematic of sliding contact area (z_k is an height of the contact area Δz is the change of the inclination)

Any surface texture is rough; it is not ideally smooth on the nanoscale [5–8,18–20]. The surface roughness causes the wear damage processes, whilst the abrasive action is probably the most important factor affecting the surface wear. The geometry and size of the wear particles formed by the product of surface destruction (so called "the third body") are the random variables [14,17,28,29]. The random nature of the height of the layer between the surfaces is specified by the random geometric size and dimension of the wear particles

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and depends on theirs. Therefore, we assume that the average height of the contact area (z_k) is affected by the specific volume of the randomly packed particles between the surfaces: $V = s_{ca} \cdot v_{ca} \cdot t$, where s_{ca} is the cross-section through the contact area, v_{ca} is the average linear velocity of the particle stream along the surface (longitudinal) and t is the time period [14–17]. One thing that is evident from the existence of surrounding is that the wear particles dynamically interact with surrounding air or lubricating medium on the contact area. Meanwhile, the changing in height of the contact area leads to random mechanical fluctuations of the wear particles as a consequence of non-equilibrium state which can be altered by parameters such as pressure or temperature and correlate well with their values. Among the reasons for changes in the temperature are the mechanical fluctuations of the bodies during interaction which can result in the Joule-Thomson effect on the contact area [14,20–23]. This is exactly what stipulates the temperature-jump or the pressure-jump correlating with non-equilibrium state.

In the Joule-Thomson process a gas is forced through porous plug. In this paper, we consider the abundance of wear particles as the porous plug. To study this throttling process, we shall concern with the stream as a two-phase system, in particular, gas medium and wear particles in the sliding contact. This throttling process in the isenthalpic sliding contact layer can lead to either an increase (the Joule-Thomson coefficient is negative) or a decrease (the Joule-Thomson coefficient is positive) in temperature [14,20–26]. The Joule -Thomson coefficient (D_T) is defined as the ratio limit of the temperature change (ΔT) to the pressure change (ΔP): $D_T = lim\ [\Delta T / \Delta P] = D_T(T;\ \mathrm{P})$. It follows, that with choice of the surrounding gas, and suitable provided conditions, it should be possible to cool contact area for positive Joule-Thomson coefficient or to heat it for negative Joule-Thomson coefficient.

III. EQUATIONS

According the First law of thermodynamics the total amount of the heat is calculated through the formula $\Delta Q = \Delta Q_1 - \Delta Q_2 = dI - V\ dp$, where $\Delta\, Q_1$ is the external interchange of heat; $\Delta\, Q_2$ is the internal interchange of heat; dI is the sliding contact layer (third body) enthalpy; $V\,dp$ is the (third body) potential energy; p is the pressure in contact area; V is the contact area volume. This formula applies to the quasistatic process [14] in a homogeneous system. To calculate the external interchange of the heat $\Delta\, Q_1$ we can use the formula:

$$\Delta Q_1 = -\, k_{mo} \cdot L_k \cdot (t - t_0)\, dx \tag{1}$$

where k_{mo} is the heat transfer coefficients between the contact area and an external medium; L_k is the size of contact area surface; $(t - t_0)$ is the temperature difference.

After due calculation, the equation (1) takes the form:

$$\begin{aligned} k_{mo} \cdot L_k\, (t - t_0)dx =& c_p\, (mdt - mD_T\, (\Delta p / l\,)dx + \\ &+ mg(\Delta z / l\,)dx + md(v^2/2) \end{aligned} \tag{2}$$

where c_p is the specific heat capacity of the contact area; m is the mass flow rate; $\Delta p\, /\, l$ is the pressure variation per length l of the sliding surface; Δp is the distinction between the pressure at the beginning and at the end of the sliding contact area; $\mathrm{d}(v^2/2)$ can be neglected due to the rate of negligible speed. Furthermore, $dz \equiv (\Delta z / l\,)dx$, where Δz is the change of the inclination between two ends of a length l of the contact area. The contact layer has a random orientation and, thuswise, the coordinates of the entry and outlet ends of a length l can be described by the arbitrary orientation coordinates in a three-dimensional space (Fig.1).

Integrating (2) [30–32], we receive:

$$\begin{aligned} T = T_0 + \ell^{-k_c x} \cdot (T_b - T_0) - D_T\, (\Delta p / l\,) \cdot (1 - \ell^{-k_c x})/k_c - \\ - g\, k_c\, c_p \cdot (\Delta z / l\,) \cdot (1 - \ell^{-k_c x}) \end{aligned} \tag{3}$$

where T_0 is the background temperature; T_b is the temperature at the beginning a of the sliding contact area; $l \geq x \geq 0$ is x coordinate of the contact layer cross-sectional; a component $k_c = k_{mo} \cdot L_k\, /\, m$ denotes the proportion of surrounding gas (medium) leaving the contact area.

IV. RESULTS OF RESEARCH AND DISCUSSION

Let us denote the non-dimensional variation for a change of the relative inclination of the layer $a = \Delta z\, /\, l$. To calculate the temperature change ΔT for $k_c \cdot l < 1$ due to the Joule-Thomson effect, we need to estimate:

$$\begin{aligned} \Delta T\, /\, g\, c_p = k_c \cdot (\Delta z / l\,) \cdot (1 - \ell^{-k_c x}) = \\ k_c \cdot a \cdot (k_c \cdot l + 0.5 \cdot (k_c \cdot l)^2) = k_c{}^2 \cdot a \cdot l\, (1 + 0.5 \cdot k_c \cdot l) \cdot \end{aligned} \tag{4}$$

The expression (4) shows that a measure of the strength of association between the Joule-Thomson effect and the surrounding medium follows a parabolic law, likewise under a temperature gradient, the temperature in contact area is not constant, and it varies linearly with the coordinate of the beginning of a length l of the contact area. Specifically, the contribution of the Joule-Thomson effect (normalized on the component of the specific heat capacity $g \cdot c_p$) to the changing in temperature depends on the coefficient k_c.

In addition, we offer to provide insight into the coefficient kc, which is used in (3) to determine the heat exchange with the environment, and material removal factors and it depends on the size of the contact area L_k. To analyze the role of the coefficient k_c, we compare the changes in temperature (normalized on $g \cdot c_p$) occurring in the contact area (4) considering two cases $k_c = 1$ and $k_c = 0.2$ for the small change of the relative inclination of contact area $a = 0.1$, and rather more $a = 0.2$. The coefficient kc is a function of the size of the contact area. In the Fig. 2 one can see significant differences between the thermal response in the entry and outlet ends of the contact length l even though for the small change of the relative inclination $a = 0.1$, and more significantly for $a = 0.2$. The first is carried out on porous material composed of a slightly packing of the wear particles, the latter – at the material composed of close-packed particles [14,22–29]. Thus, we have a clear increasing trend in the influence of the Joule-Thomson effect in the both cases [21–27]. The comparison indicates a maximum difference of 30 percent of the thermal effect between the entry and outlet ends of the contact length l. This means that the strong correlations that are responsible for mechanical fluctuation leads to the increase in the dispersion of the temperature fluctuations in the outlet end of the contact area caused by the corresponding susceptibility to the surrounding medium [17,32–36]. It is also reasoned that the heat transfer to the environment and contact area extension can result in the gain in influence of the Joule-Thomson effect [21–27].

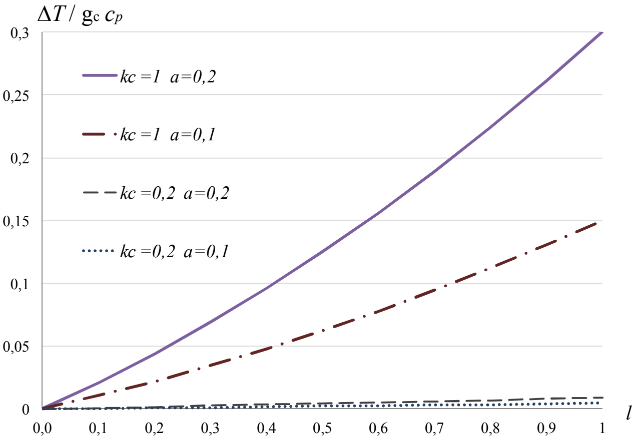

Fig. 2. The temperature change in the contact area as a function of $k_c = f(L_k)$ for the change of the relative inclination $a = 0.2$ and $a = 0.1$.

Due to the facts that k_c is a measure of heat output from the sliding contact, and degree of compaction is usually assessed through the density or specific volume reduction of the particles, the case of $k_c = 1$ corresponds to the maximum porosity for close-packed particles or, in other words, the lake of surroundings in the contact layer. In our opinion, in this case there is accumulation of heat due to the rolling and sliding friction under zero heat current [14,17].

As noted earlier, the changes in the contact area temperature under Joule-Thomson effect has resulted from mechanical fluctuations of wear particles which directly depend on the size of the wear particles, associated with the change of the relative inclination a of the sliding contact. The Figure 3 shows the correspondence between the change of the relative inclination of the contact layer and its thermodynamics, normalized on $g{\cdot}c_p$, for $k_c = 1$ and $k_c = 0.2$. Both lines depict reasonably linear correlations of these parameters, and moreover the temperature 8-fold increases in the average with increasing coefficient a. This fact means that the correlation between thermal effects in the sliding contact and wear damage caused by the different type of abrasion must be strong [3,37–39].

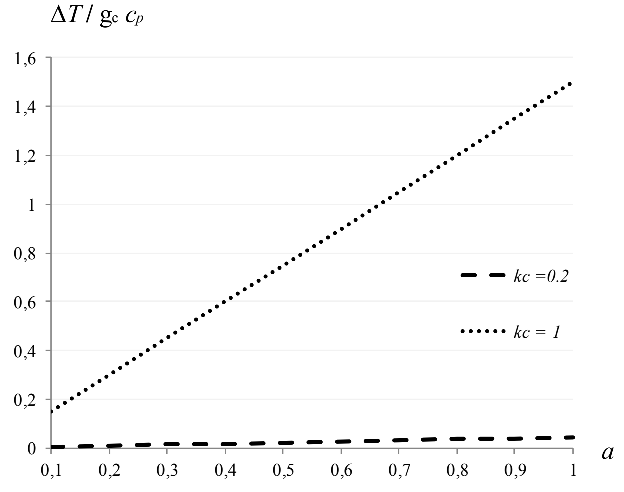

Fig. 3. The influence of the change of the relative inclination of the contact layer on its thermodynamics for $k_c = 1$ and $k_c = 0.2$.

Fig. 2 and 3 indicate that there is significant impact of the Joule-Thomson effect on the increase of the average temperature. It is interesting to note that larger wear particles have a greater temperature increase because of Joule-Thomson effect. It follows, that more porous material has a greater damage rate because of the large size of wear particles and possibly their mechanical fluctuations leads to the greater change in the temperature.

V. CONCLUSION

In this paper, we have attempted to explain the phenomenon underlying the occurrence of the Joule-Thomson effect in the consequence of differential change (decrease or increase) in the temperature of the contact area using the sliding contact in commutator-and-brush assembly as an example. The significance of the material properties dependency of temperature, in particular the Joule-Thomson effect was also evaluated. The coefficient which strong correlates with temperature changes in the contact area could have dramatic consequences on material properties due to the interaction or lack of interaction with a surrounding environment. Increasing the coefficient will decrease the influence of the Joule-Thomson effect. It can be expected that the more densely particles become closer packed, the less surrounding can penetrate into the contact area result in a reduction in the rate of heat exchange having as a consequence dramatic change in the temperature. The results presented in this paper show the strong correlations between Joule-Thomson effect and mechanical fluctuations that are responsible for the size of the contact area which leads to the conclusion that as the size of the contact area is significantly reduced, the Joule-Thomson effect could be negligible [14].

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