UDC 521.597
DOI 10.52171/herald.239

Complex Air Heat Exchange of Disc-Shoe (Tubular Type) Brake of Drilling Winch

A.I. Volchenko[1], N.A., Volchenko[2], A.V. Voznyi[1], V.I. Snurnikov[1]

[1]*Kharkiv National Automobile and Highway University (Kharkiv, Ukraine)*
[2]*Kuban National Technological University (Krasnodar, Russia)*

For correspondence:
Voznyi Andrey / e-mail: andrii.voznyi@gmail.com

Abstract

Experimental design developments and theoretical studies of disk-shoe (tubular type) brakes of drilling drawworks with forced air cooling of their friction pairs made it possible to establish the following: improved wear-friction properties of friction pairs due to reduced metal consumption of the main disk and increased area of matte surfaces using an additional disk; forced air heat exchange with the environment of matte and polished surfaces of the main and additional disks by thermal conductivity, convection and radiation was taken into account, which made it possible to estimate the variable value of the brake heat balance; the surface-volume temperature gradient of the friction belts during braking by the main disk of the tubular design is insignificant, and the depth gradient is small in magnitude, which led to uniform wear of the brake friction pairs; the influence of the design parameters of the main and additional brake disks on the weight of the drill pipe string lowered into the well and its operating parameters, from which the braking torque was isolated.

Keywords: disc-shoe brake, metal-polymer friction pair, research model, convection, thermal conductivity, radiation, operating parameters, air cooling.

Submitted *16 Nov 2024*
Published *17 Mar 2025*

For citation:
A.I. Volchenko et al.
[Complex Air Heat Exchange of Disc-Shoe (Tubular Type) Brake of Drilling Winch]
Herald of the Azerbaijan Engineering Academy, 2025, vol. 17 (1), pp. 15-24

Qazıma bucurqadının diskli-kündəli (boru tipli) əyləcinin mürəkkəb hava istilik mübadiləsi

A.İ. Volçenko[1], N.A., Volçenko[2], A.V. Voznıy[1], V.İ. Snurnikov[1]

[1]*Xarkov Milli Avtomobil və Yol Universiteti (Xarkov, Ukrayna)*
[2]*Kuban Dövlət Texnologiya Universiteti (Krasnodar, Rusiya)*

Xülasə

Sürtünmə cütlərinin məcburi hava ilə soyudulması zamanı qazıma qurğularının diskli-kündəli (boru tipli) əyləclərinin təcrübi-konstruktor işlənməsi və nəzəri tədqiqatları aşağıdakıları müəyyən etməyə imkan verdi: əsas diskin metal tutumunu azaltmaqla sürtünmə cütlərinin yeyilmə-friksion xassələrinin təkmilləşdirilməsinə və əlavə diskin tətbiqi ilə parlaq səthlərin sahəsinin artırılmasına nail olunub; əsas və əlavə disklərin parlaq və cilalanmış səthlərinin ətraf mühiti ilə istilikkeçiriciliyi, konveksiya və radiasiya ilə məcburi hava istilik mübadiləsi nəzərə alınıb ki, bu da əyləcin istilik balansının dəyişən kəmiyyətini qiymətləndirməyə imkan verib; boru konstruksiyasının əsas diskində əyləmə zamanı sürtünmə kəmərlərinin səthi-həcmi temperatur qradiyenti aşağı səviyyədədir, dərinlik qradiyenti isə kiçikdir ki, bu da əyləc sürtünmə cütlərinin bərabər yeyilməsinə səbəb olmuşdur; əsas və əlavə əyləc disklərinin konstruksiya parametrlərinin quyuya endirilən qazıma borularının çəkisinə və onun əyləc momentinin ayrıldığı istismar parametrlərinə təsiri öyrənilmişdir.

Açar sözlər: diskli-kündəli əyləc, metal-polimer sürtünmə cütü, tədqiqat modeli, konveksiya, istilikkeçirmə, şüalanma, istismar parametrləri, hava ilə soyudulma.

Сложный воздушный теплообмен дисково-колодочного (трубчатого типа) тормоза буровой лебедки

А.И. Вольченко[1], Н.А., Вольченко[2], А.В. Возный[1], В.И. Снурников[1]

[1] *Харьковский национальный автомобильно-дорожный университет (Харьков, Украина)*
[2] *Кубанский национальный технологический университет (Краснодар, Украина)*

Аннотация

Опытно-конструкторские разработки и теоретические исследования дисково-колодочных (трубчатого типа) тормозов буровых лебедок при принудительном воздушном охлаждении их пар трения позволили установить следующее: достигнуто улучшение износо-фрикционных свойств пар трения за счет снижения металлоемкости основного диска и увеличения площади матовых поверхностей с применением дополнительного диска; учтен вынужденный воздушный теплообмен с окружающей средой матовых и полированных поверхностей основного и дополнительного дисков теплопроводностью, конвекцией и радиацией, что позволило оценить переменную величину теплового баланса тормоза; поверхностно-объемный градиент температуры поясов трения при торможении основным диском трубчатой конструкции является незначительным, а глубинный градиент по величине маленький, что привело к равномерному износу пар трения тормоза; влияние конструктивных параметров основного и дополнительного дисков тормоза на вес колонны бурильных труб, спускаемых в скважину, и его эксплуатационные параметры, из которых выделен тормозной момент.

Ключевые слова: дисково-колодочный тормоз, металлополимерная пара трения, модель исследования, конвекция, теплопроводность, излучение, эксплуатационные параметры, воздушное охлаждение.

Introduction

The surface-volume temperatures achieved in the friction pairs "disc friction belt - working surfaces of the linings" depend on: the weight of the drill pipe string lowered into the well; the braking mode; the design of the disc and linings; the materials of the disc and linings. Due to the stress-strain state of the locally frictionally interacting micro-protrusions of the disc and linings, the energy transfer is not uniform. In overheating zones (burn spots), the surface-volume temperatures and the equivalent stresses in the brake disc caused by them exceed the permissible ones. At a maximum design surface-volume temperature of 500 ° C in the burn zone of the working surfaces of the friction pairs, the actual temperature reaches 800-100 ° C. Based on the above, it is necessary to intensify forced air cooling of the friction pairs of the disc-shoe brakes of drilling drawworks when lowering drill pipes into the well.

Analysis of literary data and problem statement

According to fragments of a new type of disc-shoe brakes with a forced air-nano-liquid cooling system, we have the following [1]. The design is tubular. The main brake disc with friction belts rests on a solid and non-solid slit ring. The overlap zones of friction linings are also located here. The main and additional discs have chambers, the volumes of which are connected to each other on semi-circles by diffusers and confusers.

In [2] it was proved that the thickness of the brake disc has an uneven effect on the surface-volume temperatures and equivalent stresses arising in the process of electrothermomechanical friction. In a 45.0 mm thick disc, the surface-volume temperatures are somewhat lower due to its metal content than in a 35.0 mm thick disc. In the first disc, high equivalent stresses arise due to a more uneven distribution of the surface-volume temperature in it. In the second disc, the surface-volume temperature was higher, but lower equivalent stresses arise in it.

Forced liquid cooling of the tribosystem of the band-shoe brake of a drilling winch is given in the work [3]. The system consisted of a chamber located under the rim of the pulley. Water was used as a coolant. The efficiency of such a system was no more than 12.5%. In addition, no assessment was given of the efficiency of forced forced cooling of the friction pairs of the brakes.

In the work [4] the operational parameters of foreign models of disc-shoe brakes of drilling rigs were analyzed. However, the influence of the coefficient of mutual overlap of friction pairs depending on the number of supports located along the perimeter of the brake discs was not established.

A.V. Chichinadze in his numerous studies [5] noted that the dynamic coefficient of mutual overlap of friction pairs is the local sum of their contact areas.

The work [6] is devoted to methods of studying the contact interaction of thermoelastic bodies, based on the condition of local friction taking into account frictional heating and wear. It was necessary to introduce forced and forced air cooling into the research, which would increase the practical value.

The aim of the work is to determine the operating parameters of friction pairs of a new disc (tubular type) brake with forced air cooling of a drilling winch.

Complex heat exchange processes in friction pairs of brake devices

The traditional source of information on temperature, convective, radiation and heat-conducting fields during friction interaction of brake friction pairs are theoretical and experimental studies, which are carried out on full-scale samples and models. It should be said that due to the presence of accompanying transfer processes, complex heat exchange is much more complex than purely conductive, convective and radiation heat exchange, which significantly complicates its analytical and experimental studies. In this regard, complex heat exchange processes are currently relatively poorly understood.

From the point of view of nonequilibrium thermodynamics, the main task of describing the transfer process is to establish a relationship between the magnitude of the specific flow q *and* the surface-volume temperatures *t* that it causes in the metal friction elements of the brakes. With regard to the heat exchange process , the main task is to establish a relationship of the form

$$q = f(t). \qquad (1)$$

The general nature of this connection is determined by one of three possible forms of heat transfer. The first of them - thermal conductivity (conduction) - is connected with the transfer of thermal energy by microscopic elements of a physical system (molecules, ions, electrons). Thermal conductivity of gases is the transfer of energy by molecules through collisions; in a solid body, heat transfer is carried out by oscillating ions of the lattice of the substance and the "electron gas", in a liquid - by all the listed mechanisms.

Heat transfer, carried out due to the movement of macroscopic volumes, is called convection. There are two types of convection - free, when elements of mass move in the field of gravity due to the density of the system varying in volume, and forced, in which the movement of mass is carried out due to external forces.

The third form of heat exchange - radiation - is associated with the ability of bodies to absorb, reflect, transmit and emit electromagnetic field energy. Unlike thermal conductivity and convection, heat exchange by radiation between bodies is also possible in a vacuum. When meeting absorbing media, the energy of electromagnetic waves is converted into heat. The determination of heat exchange thermodynamic parameters of friction pairs of braking devices, based on conductive (a), convective (c) heat exchange and thermal radiation (b) is presented in Fig. 1.

The following symbols are used in Table 1: t_{n1}, t_{n2} are the surface temperatures of the metal-polymer friction pair; the remaining symbols are given in Table 2. What is surprising in Table 1 is that there are no boundary conditions for the radiative heat exchange of the metal friction element.

Fig. 2 presents a model of frictional interaction of friction pairs of a drilling winch disc-shoe brake.

Based on the above, we will move on to assessing the operational parameters of metal-polymer friction pairs of the disc-shoe (tubular type) brake of a drilling winch.

Forced air cooling of metal-polymer friction pairs of disk-shoe (tubular type) brake of drilling winches. The basic principles of construction of designs with air and air-liquid cooling of disk-shoe brakes of drilling winches practically do not change, which limits the possibilities for improving the block for pressing and releasing the friction linings to the brake disc.

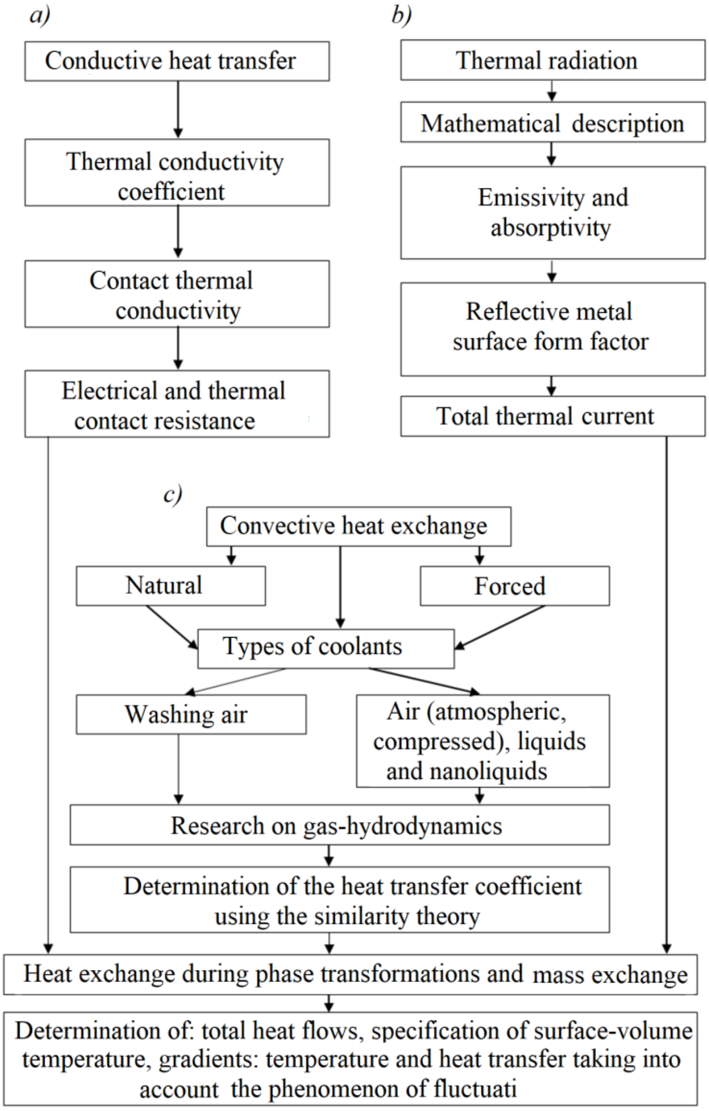

Figure 1 a, b, c – Determination of heat exchange thermodynamic parameters of friction pairs of braking devices based on conductive (a), convective (c) heat exchange and thermal radiation (b)

Table 1 – Modified list of boundary conditions (Dependencies)

I-st	The intensity of the heat flow from the outside into the body is given (q_v) $$-\lambda \frac{\partial t_n}{\partial x}\bigg|_{x=+0} = q_v \quad (2)$$
2-nd	The body is in contact with another body that has different thermophysical characteristics $$t_{n1}\big|_{x=+0} = t_{n2}\big|_{x=-0} \quad (3)$$
3-rd	The body surface temperature is known (t_p)
4-th	The heat flow coming from the washing environment is directly proportional to the difference in temperature between the body surface and the environment, multiplied by the heat transfer coefficient $$-\lambda \frac{\partial t_n}{\partial x}\bigg|_{x=+0} = \alpha(t_n - t_c) \quad (4)$$

Table 2 – Complex heat exchange between the body and the environment

No.	Dependencies and decoding of their parameters
1.	Heat exchange by conduction occurs according to Fourier's law: the heat flow density q is directly proportional to the temperature gradient, i.e. $$q = -\lambda grad t = -\lambda n_0 \frac{\partial t}{\partial n}, \quad (5)$$ where λ - coefficient of thermal conductivity of the material; n_0 - unit vector directed along the normal in the direction of increasing temperature; $\partial t / \partial n$ - derivative of temperature in the direction of the normal; $grad t = n_0 \partial t / \partial n$ - temperature gradient .
2.	Convective heat transfer between the surface A of a solid body and the surrounding liquid or gaseous medium obeys the Newton-Richmann law: $$q = \alpha_{ic}(t_i - t_c)A_i. \quad (6)$$ where q - heat flow from the surface of a solid to the environment; A_i - heat exchange surface area; α_{ic} - heat transfer coefficient between the surface of the body and the environment; t_i and t_c - temperatures of the body surface and the environment.
3.	Heat transfer by radiation is determined on the basis of the laws of thermal radiation and has the form [2] $$q = \varepsilon_{nij} C_0 \left[(T_i / 100)^4 - (T_j / 100)^4 \right] A_i \varphi_{ij}, \quad (7)$$ where ε_{nij} - the reduced degree of blackness of bodies i and j ; φ_{ij} - coefficient of irradiation of the i - th body by the j -th; T_i, T_j - values of absolute temperatures of bodies i and j ; C_0 - the emissivity of an absolutely black body, equal to 5.67W/($m^2 \cdot K^4$) . $$\frac{C_0}{C_1} = \frac{A_н}{A_{ox}}, \quad (8)$$ where C_1 - emissivity of polished body surface, W/(m2 ^{K4}) ; A_n, A_{ox} - heated and cooled body surface areas, m^2 .
4.	The total thermal resistance R or total thermal conductivity σ_0 is equal to [4] $$\left. \begin{aligned} \frac{1}{R_0} &= \frac{1}{R_T} + \frac{1}{R_K} + \frac{1}{R_p}; \\ \sigma_0 &= \sigma_T + \sigma_K + \sigma_p, \end{aligned} \right\}. \quad (9)$$ where R_T, R_K , R_P - thermal resistance of heat exchange by thermal conductivity, convection and radiation. Note that the addition of three parallel-connected conductivities is justified by the law of conservation of energy. If we were talking about thermal coefficients, then such an addition would be unjustified in the general case.

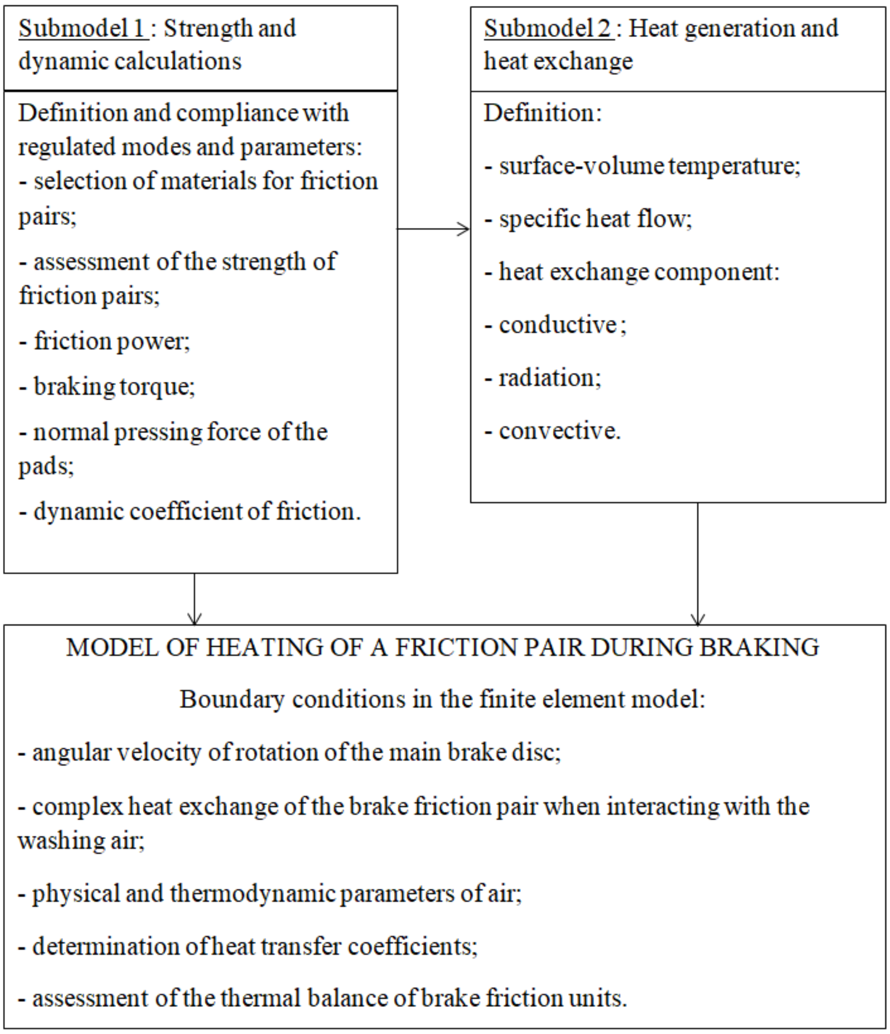

Figure 2 – Model of frictional interaction of the friction track of the main brake disc (new type) with friction linings on metal substrates during braking

The regularities of the change in the braking torque (M) developed by four friction pairs (calipers) of the disk-shoe (tubular type) brakes of drilling winches from: the weight G of the drill pipe column at different average radii R_c of the friction belt of the disk; the dynamic friction coefficient μ and R_c at pulse specific loads p = 3.2 MPa and the working area of the lining were established A = 0.07 m^2 ; b - p and μ at A = 0.07 m^2 and R_{cp}= 0.8 m; c - p and A at R_c = 0.8 m and μ = 0.35. The patterns of change in surface-volume temperatures in the conjugation of friction pairs from the weight G of the drill pipe column were determined at different average radii R_c of the friction belt and heat flow q penetrating the friction belt of the brake disc from the surface-volume temperature t and the thickness δ of the disc-shoe (tubular type) brakes of drilling winches. The studies were conducted with the following surface areas: polished main disk 0.126 m^2 and its matte 0.536 m^2, and the matte surfaces of the additional disk were 0.302 m^2. The total area of the matte surfaces was 0.838 m^2, and the confusers and diffusers were 0.000028 m^2. The volume of the chambers filled with nanofluid for the main and additional disks was 0.0094 m^3 and 0.0023 m^3, respectively. The main design parameters of models of disc-shoe brakes of foreign drilling winches were considered as analogues (Table 3).

Table 3 – Main design parameters of models of disc-shoe brakes for drilling rig winches

Model	PS440-9000	PS295-6700	PS240-4500	PS165-3150	PS60-1350	PS40-900
Drilling rig	ZJ120	ZJ90	ZJ70	ZJ50	ZJ20	ZJ15
Brake disc diameter	2100	1900	1600	1500	1400	1200
Number of main brake devices	7	5	4	4	3	2
Number of brake units during hard braking	3	3	2	2	1	1

Let us analyze the graphical dependencies shown in Fig. 3, concerning the change in braking torque by friction pairs of disc-shoe (tubular type) brakes with their forced air cooling: *a* – with an increase in the average radius R_c friction belt of the main disk and weight G of the drill pipe column lowered into the well, an increase in the value of the braking moment M is observed; *b* – with increasing R_c. and the dynamic friction coefficients μ received an increase of M [7]; *c* – with the growth of μ and pulse specific loads p, an increase in M was observed; *d* – with an increase in the area of the working surface of the pads A and p, there was an increase in M. Let us analyze the graphical dependencies shown in Fig. 4, related to the surface-volume temperatures of the friction pairs of the new brake and the specific heat flows q generated by them: *a* – with an increase in G and R_c, an increase in surface-volume temperatures t was observed in the conjugation of brake friction pairs; *b* – with a decrease in the wall thickness δ of the disk with an increase in t , q increases in the range of change from 15.0 to 45.0 $W/(m^2 \cdot °C)$ of heat transfer coefficients from polished and matte surfaces of the main and additional disks.

Discussion of results

Experimental design developments and theoretical studies of disk-shoe (tubular type) brakes of drilling winches with forced air cooling of their friction pairs allowed us to establish the following: an improvement in the wear and friction properties of friction pairs has been achieved by reducing the metal content of the main disk and increasing the area of matte surfaces by using an additional disk; forced air heat exchange with the environment of the matte and polished surfaces of the main and additional discs was taken into account by thermal conductivity, convection and radiation, which made it possible to estimate the variable value of the brake thermal balance; the surface-volume temperature gradient of the friction belts during braking with the main disc of the tubular design is insignificant, and the depth gradient is small in magnitude, which led to uniform wear of the brake friction pairs; the influence of the design parameters of the main and additional brake discs on the weight of the drill pipe column lowered into the well and its operating parameters, from which the braking torque is extracted.

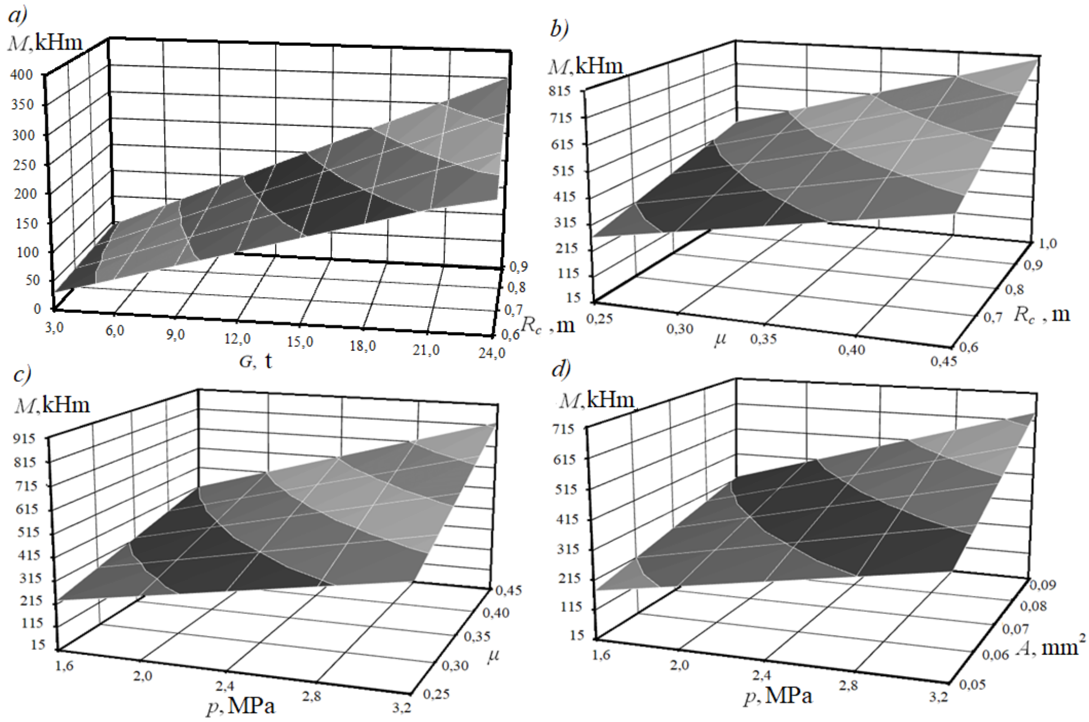

Figure 3 ***a*** **,** ***b*** **,** ***c*** **,** ***d*** **–** Patterns of change in the braking torque M , developed by four friction pairs of disc-shoe (tubular type) brakes of drilling winches from: from a – weights of the pipe column G for different average radii of the friction belt R_c of the disk; b – dynamic coefficient of friction μ and R_c for pulse specific loads p = 3.2 MPa and the working area of the lining A = 0.07 m^2 ; c - p and μ at A = 0.07 m^2 and R_c = 0.8 m; d - p and A at R_c = 0.8 m and μ = 0.35

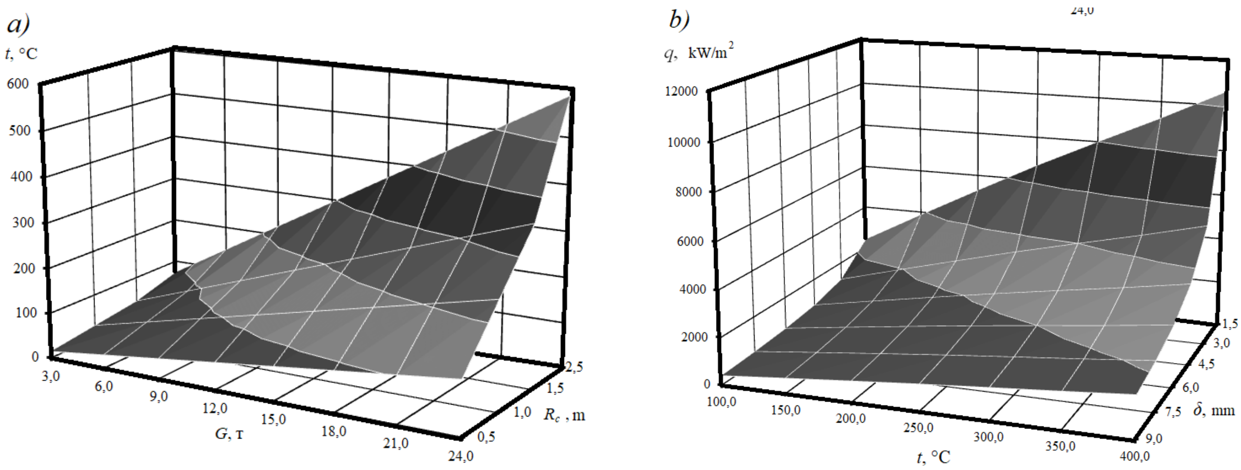

Figure 4 a, b – Patterns of change in surface-volume temperatures (a) in the conjugation of friction pairs from the weight of the drill pipe column G at different average radii of the friction belt R_c and heat flow q (b) penetrating the friction belt of the brake disc from the surface-volume temperature t and thickness δ of the disc-shoe (tubular type) brakes of drilling winches

Conclusion

Thus, the intensification of heat removal cycles from the matte and polished surfaces of the main and additional disks will improve the braking efficiency of the disk-shoe brakes of the drilling winch when lowering the drill pipe column into the well.

Conflict of interests

The authors declare there is no conflict of interests related to the publication of this article.

REFERENCES

1. **Janahmadov A.Kh., Volchenko D.A., M.Ya. Javadov, Volchenko N.A., Skripnik V.S., Vozny A.V.** Forced air-nano-liquid cooling of friction pairs of disc-shoe brake devices. Herald of the Azerbaijan Engineering Academy, 2024, vol.16 (4), pp. 8-16.
2. **Titarev D.V.** Justification and development of a rational design of a brake disc for a passenger car (abstract of a candidate of technical sciences). Bryansk, 2008. – 20 p.
3. **Janahmadov A.Kh., Volchenko A.I., Perverdiev E.S. [et al.].** Forced cooling of the tribosystem of the band-shoe brake of the drilling winch. Herald of the Azerbaijan Engineering Academy, 2018, vol.10 (2), pp. 7-19.
4. **Janahmadov A.Kh., Volchenko D.A., Javadov M.Ya.** [et al.] Forced Air-nano-fluid Cooling of Friction Pairs of Disc-pad Brake Devices. Herald of the Azerbaijan Engineering Academy, vol.16 (4), 2024. – Pp. 8-16.
5. Handbook of tribotechnics: In 3 volumes // Under the general editorship of M. Hebta, A.V. Chichinadze. – Vol. 1. Theoretical foundations. – Moscow: Mechanical Engineering, 1989. – 400 p.
6. **Evtushenko O.O.** Methods for monitoring the contact interaction of thermospring bodies for local rubbing due to frictional heating and wear: dis. doc. Physics and Mathematics Sciences: 01.02.04. – Lviv, 2000. – 342 p.
7. **Janahmadov A.Kh., Volchenko D.A., Volchenko N.A. [et al.]** Disc and disc-shoe brakes in mechanical engineering. Vol. 2. - Baku: Apostrof-A, 2021. - 392 p.