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Stress-Strain State of the Developed Single-Disc Shoe Brake of a Drilling Winch

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Abstract

Theoretical and experimental studies of forced air-nano-liquid cooling of a single-disk shoe brake of a drilling winch have made it possible to establish the following. Improvement of wear-friction properties of friction pairs is achieved due to operation in the temperature range below the permissible ones for friction lining materials and, as a consequence, braking qualities for the lifting shaft of a drilling rig. Application of low-melting metal nanopowders of various modifications diluted with water or acetone for the liquid, which allows to significantly increase the thermal conductivity coefficient of the nanoliquid and thereby improve the efficiency of forced cooling of the friction belts of the brake half-disks. The volumes of nanoliquid in the evaporation zones are much smaller than in the zones of its transport, which intensifies heat exchange in various aggregate states of the nanoliquid due to increased cycles of its circulation. The forced air heat exchange of matte and polished surfaces of the disk by convection and radiation, as well as thermal conductivity, spent on heating the friction belts of the disk, is taken into account, which allows determining a smaller part of the heat removed from their surfaces during braking. Accelerators of the motion of nanofluid in any aggregate state between the zones of evaporation and transport-condensation in their heated state are diffusers, and retarders are the nanostructure of the condensation and transport zone of the disk, which cause a change in the gradients of velocity, pressure and temperature in the layers of nanofluid. With a variable thickness of the friction belt of the disk and the specifics of cooling on the effect of a "heat pipe" using the method of finite element modeling, estimate the stress-strain state of the disk wall.

Keywords: drilling winch, disc-shoe brake, friction unit, brake disc, nanofluid, stress-strain state.

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Qazıma bucurqadının bir diskli kündəli əyləcinin gərginlik-deformasiya vəziyyəti

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Xülasə

Məqalədə qazıma bucurqadının bir diskli kündəli əyləcinin məcburi hava-nanomaye ilə soyudulmasının tədqiqinin nəticələri təqdim olunub. Sürtünmə cütlərinin yeyilmə-sürtünmə xassələrinin təkmilləşdirilməsi friksion kündə materialları üçün buraxıla bilən temperaturdan aşağı temperatur diapazonunda istismar nəticəsində əldə edilmiş və nəticədə, qazıma qurğusunun qaldırıcı valının əyləc keyfiyyətlərinə nail olunub. Mayelər üçün su və ya aseton ilə həll olunmuş müxtəlif modifikasiyalı asan əriyən metalların nanotozlarının istifadəsi nanomayenin istilik keçiricilik əmsalını əhəmiyyətli dərəcədə artırmağa imkan verir və bununla da əyləc yarımdisklərinin sürtünmə kəmərlərinin məcburi soyudulmasının səmərəliliyini yaxşılaşdırır (artırır). Diskin parlaq və cilalanmış səthlərinin konveksiya və radiasiya ilə məcburi hava istilik mübadiləsi, həmçinin diskin sürtünmə kəmərlərini qızdırmaq üçün istifadə olunan istilik keçiriciliyi nəzərə alınıb ki, bu da əyləc zamanı onların səthlərindən çıxarılan istiliyin daha kiçik bir hissəsini təyin etməyə imkan verir. İstənilən aqreqasiya vəziyyətində nanomayenin hərəkət sürətləndiriciləri buxarlanma və nəqliyyat-kondensasiya zonaları arasında onların qızdırıldığı zaman diffuzorlar, gecikdiriciləri isə - kondensasiya zonasının nanostrukturu və diskin nəqli sayılır. Diskin sürtünmə kəmərinin dəyişkən qalınlığı və "istilik borusu" effektinə əsaslanan soyutma xüsusiyyətləri ilə sonlu elementlərin modelləşdirilməsi metodu ilə disk divarının gərginlik-deformasiya vəziyyəti qiymətləndirilib.

Açar sözlər: qazıma bucurqadı, diskli-kündəli əyləc, friksion düyün, əyləc diski, nanomaye, gərginlik-deformasiya vəziyyəti.

Напряженно-деформируемое состояние разработанного однодискового колодочного тормоза буровой лебедки

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Аннотация

В статье приводятся результаты исследования принудительного воздушно-наножидкостного охлаждения однодискового колодочного тормоза буровой лебедки. Улучшение износо-фрикционных свойств пар трения достигается за счет эксплуатации в интервале температур ниже допустимых для материалов фрикционных накладок и, как следствие, тормозных качеств для подъемного вала буровой установки. Применение для жидкости нанопорошков легкоплавких металлов различных модификаций, разбавленных водой или ацетоном, позволяет значительно увеличить коэффициент теплопроводности наножидкости и тем самым улучшить эффективность принудительного охлаждения поясов трения полудисков тормоза. Учтен вынужденный воздушный теплообмен матовых и полированных поверхностей диска конвекцией и радиацией, а также теплопроводностью, идущей на нагревание поясов трения диска, что позволяет определить меньшую часть теплоты, отведенную от их поверхностей при торможениях. Ускорителями движения наножидкости в любом агрегатном состоянии между зонами испарений и транспорта-конденсации при их нагретом состоянии являются диффузоры, а замедлителями – наноструктура зоны конденсации и транспорта диска. При переменной толщине пояса трения диска и специфики охлаждения на эффекте «тепловой трубы» с помощью метода конечно-элементного моделирования оценено напряженно-деформированное состояние стенки диска.

Ключевые слова: буровая лебедка, дисково-колодочный тормоз, фрикционный узел, тормозной диск, наножидкость, напряженно-деформированное состояние.

Introduction

In the oil and gas industry, disc-shoe brakes are increasingly used. One of the reasons for the downtime of well drilling rigs is associated with the intensity of wear of friction pairs of the friction units of the brakes of drilling rigs. This occurs due to insufficient cooling of the disks. A particularly complex, urgent and important problem is the study and research of heat exchange in modern brake engineering for winches of drilling rigs. At high speeds of lowering the drill string into the well, the heat transfer conditions in the friction zone of the disc-shoe brake change significantly due to the insufficient efficiency of forced air cooling, depending on the speed of rotation of the brake disc washed by air flows. In this case, the issue of the need for forced air-nano-liquid (a mixture of the finest metal powder and liquid), located in the chamber of a new type of disc, is of significant importance. Therefore, studies devoted to the development of a method for reducing the thermal loads of friction pairs of disc-shoe brakes, as a result of which their operating parameters change, are relevant.

In the work [1] a comparison of foreign models of disc-shoe brakes with hydraulic drive PS440-9000 and PS40-900 of drilling rigs ZJ12 and ZJ15 was made. As a result, it was found that in order to increase the braking torque by 11 times, the diameter of the brake disc was increased by 1.7 times. The number of brake units was increased from 2 to 7, during sharp braking from 1 to 3, and the pressure in the hydraulic system increased from 7.0 to 8.0 MPa [2]. At the same time, the friction power arising from the frictional interaction of friction pairs was not considered, taking into account their heating and forced air-nano-liquid cooling, which makes the study no more complete. This approach is shown in the work [3], according to the results of which it was proved that the thickness of the brake disc has an uneven effect on the gradients of surface-volume temperatures and equivalent stresses [4] that occur during electro thermomechanical friction, washing microcracks on the friction belt of a serial disc. However, it was not noted that the main design parameter of the brake disc is its thickness, which affects the weight, and therefore, the target function during optimal design, and the control parameters are the thickness of the disc, which complicates subsequent studies. This could be reflected in the work [5], where, based on the systems approach, the possibility of forming equivalent series of friction pairs of a modular disc-shoe brake of mine hoisting machines with different lifting capacities was shown. According to their power parameters, brake friction pairs were used in them, which were tested and studied on vehicles as a dynamic model [6]. But the tests were carried out without taking into account the complex power factors of forced cooling and heat transfer, which are important parameters in the heat exchange of friction pairs. And in the work [7] the curves of formation of the total time costs under different operating modes of friction pairs of band-shoe brakes of a drilling winch without inclusion of an additional hydraulic brake are presented. In this case the energy loading of friction pairs of brakes during drilling at a depth of 2900 m was not taken into account. At such a drilling depth it is necessary to include a hydraulic brake [8]. But the factor was not taken into account that during drilling with disk-shoe brakes there is no need to use a hydraulic brake, since they have sufficient energy capacity and efficiency. In the work [9] a combination of mathematical models in tribonics with a physical experiment and operational experience was used. This made it possible to combine the calculation and theoretical studies with the experimental ones by developing the theory of thermal similarity and the method of generalizing the variable dimensionless parameters for friction pairs [10]. However, nothing was said about the generalization of the variable dimensional design and operational parameters of friction pairs.

All this gives grounds to assert that it is advisable to conduct research devoted to the development of new disc-shoe brakes for drilling winches.

The purpose and objectives of the work

The aim of the work is to develop a new disc-shoe brake for drilling winches. This will improve the braking qualities for the lifting shaft of the drilling rig.

To achieve the set goals, the following tasks were solved: create a new design of a disc-shoe brake for a drilling winch; to evaluate the stress-strain state of a variable disk wall thickness using a finite element modeling method.

Design and operation of the developed single-disc shoe brake for a drilling winch

Let us consider the design features and operation of a serial disc-shoe brake, forcedly cooled by air flows. Figure 1 *a*, *b* shows a serial drilling winch with disc-shoe brakes, cooled by air flows of the medium (*a*) and disc-shoe brakes with a hydraulic drive (*b*). The serial drilling winch 1 consists of a pair of disc-shoe brakes 2, having brake discs with friction belts 3, which cover supports 4 with friction linings 5 on a metal substrate and ring holders 6, installed by spring devices 7 and hydraulic drives 8. The disc-shoe brake with forced air cooling operates during lowering and lifting operations of the drill pipe column depending on its weight in aperiodic cyclic and long-term braking modes. Disc-shoe brakes 2 are installed on both sides of the drum 1 of the drilling winch.

a

b

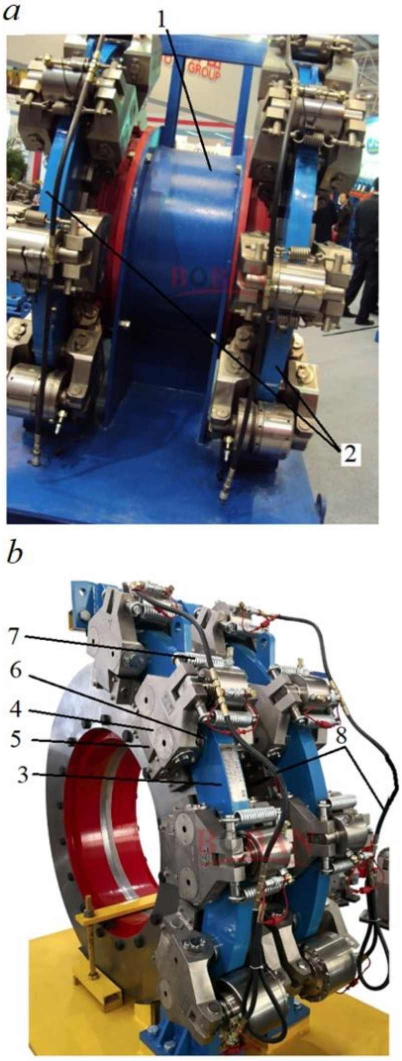

Figure 1 a, b – Serial drilling winch with disc-shoe brakes cooled by air flows of the medium (a) and disc-shoe brakes with hydraulic drive (b): 1 - drilling winch; 2, 3 - brakes with friction belts; 4, 5, 6 - supports with friction linings on a metal substrate and ring holders; 7, 8 - spring devices with hydraulic drives

Herald of the Azerbaijan Engineering Academy
2025, vol. 17 (3), pp. 15-24
A.Kh. Janahmadov et al.

They have solid metal disks 3, on the friction belts of which there are supports 4, having tong holders 5 of double action, which are friction linings 5 on metal substrates. Spring devices 7 for switching on and off the supports 4 are located on top. In this case, the supports 4 have individual hydraulic drives 8.

When braking, a large amount of heat is generated in the mating surfaces of the brake discs, which cannot be further removed into the environment from the matte and polished surfaces of the brake discs.

The present system is proposed to intensify forced air-nano-liquid cooling of friction pairs of the disc-shoe brake of a drilling winch. Figure 2 shows fragments of a single-disc shoe brake with a forced air-nano-liquid cooling system. The single-disc shoe brake of the drilling winch has design features and operates as follows.

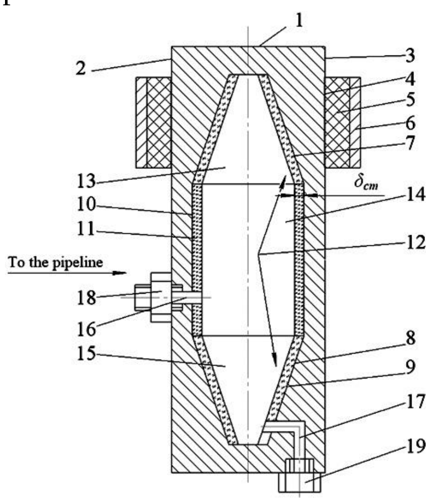

Figure 2 – Schematic representation of a single-chamber disc-shoe brake of a drilling winch with a system and method of forced air-nano-liquid cooling: 1, 2 and 3 brake disc with left and right halves; 4 - friction belt; 5, 6 - friction lining with a metal substrate; 7, 8 and 9 - upper and lower diffusers and their internal surfaces; 1 - modifications of capillary structures; 12 - common chamber; 13, 14 and 15 - zones: two evaporations, combined transport and condensation; 16, 17 - openings-channels; 18, 19 - inlet and outlet valves

The brake disk 1 consists of two half-disks 2 and 3 of variable thickness, the largest of which corresponds to the maximum radius of the location of the end of the lining 5 on the friction belt 4 of the half-disk 3, and the smallest of the thicknesses - to the minimum radius, and at the same time, with their internal shape, the half-disks 2 and 3 with a variable thickness according to a linear law form diffusers 7 and 8 in the upper and lower parts of the disk 1. Such a design solution allows two diffusers 7 and 8 to be accelerators of heat removal from the evaporation zones 13 to the combined transport zone 14 and condensation 15 at any aggregate state of the nanofluid. This occurs due to: firstly, an insignificant change in the gradient of the bulk temperature on the friction belt 4 of the right half-disk 3 and a decrease in the braking torque along the diameter of the disk 1; secondly, a significant difference in the heat exchange areas of the evaporation zones 13 and transport 14, as well as condensation 15; thirdly, a difference in the sizes of the particles of the capillary structure in the interaction zones. With extremely strong heat generation on the friction surface of the disc 1 in the brakes, the usual liquid in the chamber of its volume can almost instantly turn into steam, which will cause an explosion in it. A figurative example - as much heat is released as is needed to evaporate 6 gallons of water (27.0 *l*) per minute. Low-melting metals are used as heat carriers in the chamber 12 of the disc 1 in the cooling system *Na* (t_p = 97,79°C) и Li (t_p = 180,5°C) in the form of powders mixed with water, which are called nanofluids. The latter are used depending on the energy load of the friction pairs of the disc-shoe brakes of drilling winches. For disc 1 of the brake, lithium powder (Li) in nanofluid (50%

lithium powder and 50% water) is used, which is capable of removing significant heat flows (about 15.0 kW/ cm^2 at a surface-volume temperature of friction pairs of 800° C). The cooling system is filled through the opening of the channel 16 closed by the inlet valve 18 (Fig. 2) by ¾ of the volume of the chamber 12 of the disc 1. The outlet valve 19 serves to bleed the nanofluid. In addition, the nanofluid itself is not shown in the cooling system due to its state of aggregation.

The driving force in the processes of heating and cooling the friction belts of the brake disc are the temperature gradients of the layers of nanofluid, which take place in the zones of evaporation 13, condensation 15 and transport 14 (diffusers 7 and 8), located in the volume of chamber 12. When the disc 1 rotates, the centrifugal force drives the nanofluid to the inner walls of its chamber 12. The retarder of the stay of the nanofluid in the evaporation zone 13 is the modified capillary structure 11.

The method of forced air-nano-liquid cooling of friction pairs of a single-disk shoe brake of a drilling winch consists in the fact that the surfaces of diffusers 7 and 8 are covered with small particles of a capillary structure and are zones of evaporation 13, and zones of transport 14 and condensation 15 are large particles, and the external system of forced forced cooling of matte and polished surfaces of a rotating disk 1 is subject to convective and radiation heat exchange, washed by flows of the medium.

Finite element modeling of a single-disc shoe brake of a drilling winch

To study mechanical and thermal stresses, the finite element modeling method was used using the Ansys Workbench program, which considered the friction unit "disk-linings" with the following initial design and operational parameters: brake disc material - SCh 25, specific load on friction raceways p = 7,0 MPa, friction lining material FK-24A, permissible temperature of lining materials 390° C. In the thermal calculation, the surface-volume temperature was set at t_p=390° C, the ambient temperature was t_0=22° C. The coefficients of convection heat transfer from the outer surface to the washing environment were α_{in} = 27,0 W / (m^2 ·°C). As for the inner surface of the disk, the heat transfer coefficients from the inner surface of the disk and the surface of the diffuser into the washing nanofluid were α_{out} = 60,0 W/(m^2·°C) and α_d=90.0 W/(m^2·°C), respectively. Figure 3 *a*, *b*, *c* shows the finite element mesh of the disk model (*a*), the schemes of its thermal (*b*) and mechanical load (*c*).

In the simulation, a single-disk shoe brake of a drilling winch with the following disk thickness b was considered: 100.0 mm; 120.0 mm and 140.0 mm. The results of finite element simulation of equivalent stresses and their gradients are presented in Table.

Figure 4 *a*, *b*, *c* shows the results of modeling the temperature stresses of a single-disc shoe brake with different disc thicknesses: *a*–*b*=100,0 mm; *b*–*b* = 120,0 mm; *c*–*b* = 140,0 mm.

When analyzing the data in table 1 and (Fig. 4 *a*, *b*, *c*) we note the following: the greatest mechanical stresses were observed in zone II above the diffuser. They arise as a result of the action of pulsed specific loads on the friction belt of the disk, which lead to compression of the disk and deformation in the thinnest place - above the diffuser (see Fig. 4); there is also zone III with high mechanical stresses, also arising from the action of pulsed specific loads on the friction belt of the disk with a small thickness of its wall; with an increase in the disk thickness from 100,0 mm to 120,0 mm, with an increase in the thickness of its wall from 15,0 mm to 25,0 mm, the mechanical stresses in zone II decreased from 1154,2 MPa to 1029,6 MPa, i.e. by 10,8%. But with an increase in the disk thickness from 120,0 mm to 140,0 mm, an increase in mechanical stresses by 15,3% was observed in zone III; with an increase in the disk thickness by 1,4 times, the mechanical stress gradients decreased from 46,9 MPa/mm to 35,1 MPa, i.e. by 25,2%, which has a positive effect on resistance to crack formation in zone II.

When analyzing the data in table 1 and (Fig. 5 *a*, *b*, *c*) we indicate the following: the highest temperature stresses were observed in zone I at the minimum radius of the disk friction belt. They arise due to the action thermal load of the mating surface in places of the smallest thickness of the disk wall, which is deformed due to its intense heating and braking torque; with an increase in the thickness of the disk by 1,4 times, i.e. its wall by 2,14 times, the temperature stresses decreased from 246,2 MPa to 186,2 MPa, i.e. by 24,4%; with an increase in the disk thickness by 1.4 times, the temperature stress gradient decreased from 5,94 MPa/mm to 2,09 MPa/mm, i.e. by 64,8%, which has a positive effect on the resistance to crack formation in zone I of the wall.

When analyzing the data in table 1 and (Fig. 6 *a*, *b*, *c*) the following should be noted: the pattern of total equivalent stresses has clearly defined zones I and II, which are the result of the action of temperature and mechanical loads on the friction belt of the disk.

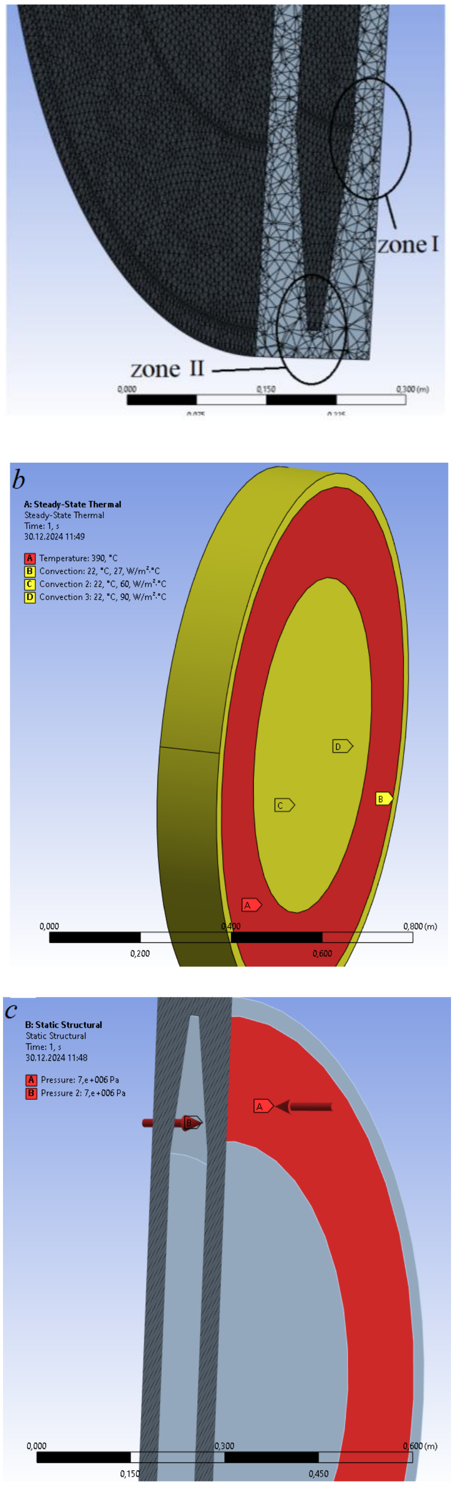

Figure 3 a, b, c – Finite element mesh of the disk model (a), thermal (b) and mechanical load (c) diagrams of a single-disk shoe brake of a drilling winch

Table – Results of finite element modeling of equivalent stresses and their gradients in a single-disc shoe brake of a drilling winch

D, mm	*b*, mm	δ_{st}, mm	m_d, kg	Maximum equivalent stresses in the disk, MPa				Stress gradients across the disk thickness, MPa/mm		
				temperature in zone I	mechanical in zone II	total in zone I	total in zone II	temperature in zone I	mechanical in zone II	total in zone I
1200	100,0	15,0	433,3	246,2	1154,2	278,0	1209,7	5,94	46,9	9,26
	120,0	25,0	596,1	208,3	1029,6	242,7	1074,4	2,98	38,5	4,22
	140,0	35,0	758,9	186,2	1215,4	221,4	1256,2	2,09	35,1	2,71

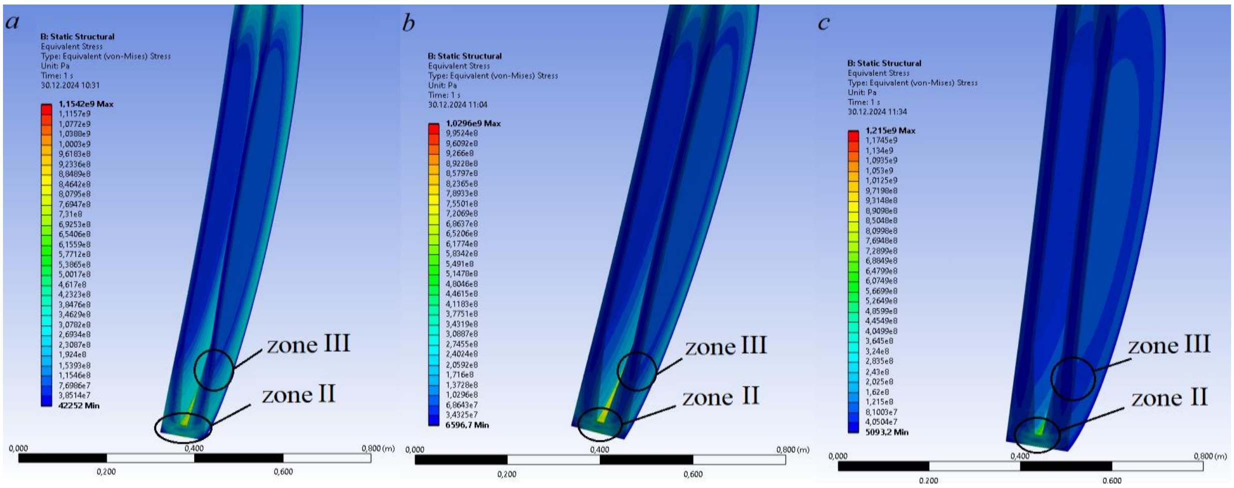

Figure 4 a, b, c – Results of modeling mechanical stresses in a single-disc shoe brake with different disc thicknesses: a – b=100,0 mm; b – b=120,0 mm; c – b=140,0 mm

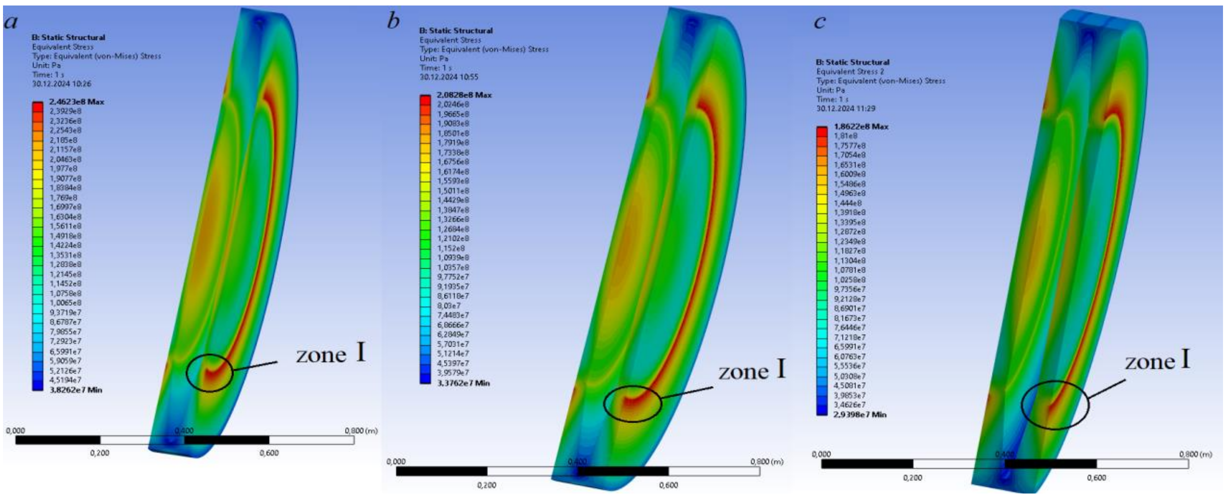

Figure 5 a, b, c – Results of modeling the temperature equivalent stresses in a single-disc shoe brake with different disc thicknesses: *a* – *b* = 100,0 mm; *b* – *b*=120,0 mm; *c* – *b* =140,0 mm

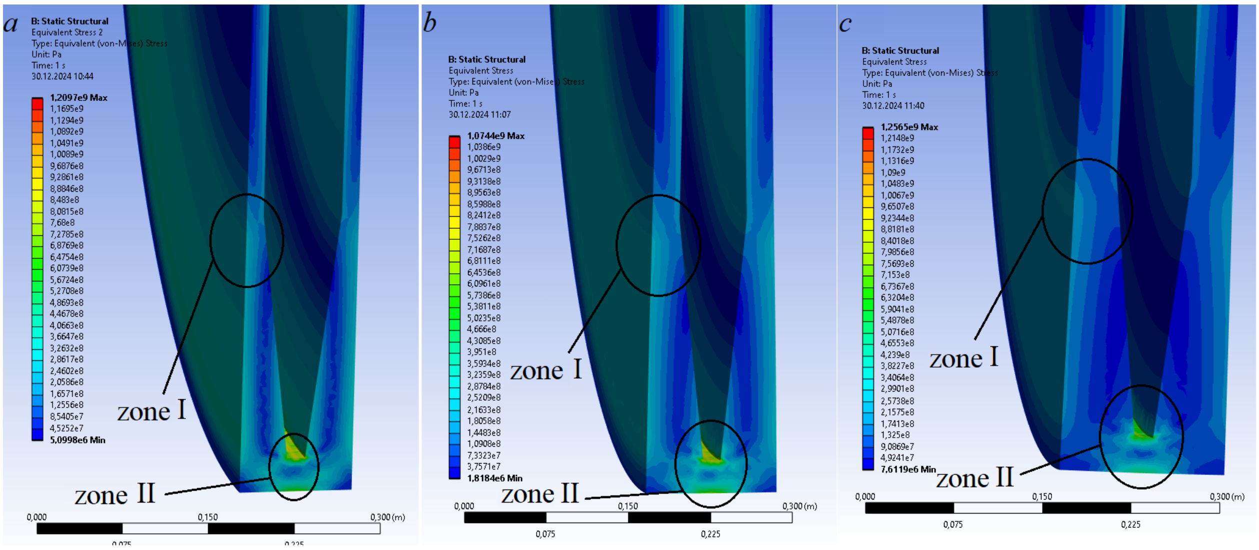

Figure 6 *a, b, c* – Results of modeling the total equivalent stresses in a single-disc shoe brake with different disc thicknesses: *a* – *b*=100,0 mm; *б* – *b* = 120,0 mm; *в* – *b*=140,0 mm

It has been established that with an increase in the thickness of the disk, the total equivalent stresses on the surface of its friction belt decrease, the surface and thickness gradients also decrease; with an increase in the disk thickness by 1,4 times and the thickness of its wall by 2,14 times, the total stress equivalents in zone I decreased from 278,0 MPa to 221,4 MPa, i.e. by 25,6%. In zone II of the disk, they first decreased from 1154,2 MPa to 1029,6 MPa, and then increased to 1215,4 MPa; temperature stress gradients decreased from 9,26 MPa/mm to 2,71 MPa/mm, i.e. by 241%, which contributes to resistance to cracking.

Thus, the intensification of heat removal cycles “evaporation zone – transport zone – condensation zone” of nanofluid in any aggregate state in the volume of the disk chamber allows to increase the braking efficiency of the disk-shoe brakes of the drilling winch when lowering the drill pipe column into the well.

Theoretical and experimental studies of forced air-nano-liquid cooling of a single-disk shoe brake of a drilling winch allowed us to establish the following: an improvement in the wear and friction properties of friction pairs is achieved due to operation in a temperature range below that permissible for friction lining materials and, as a consequence, the braking qualities for the lifting shaft of the drilling rig; an improvement in the wear and friction properties of friction pairs is achieved due to operation in a temperature range below that permissible for friction lining materials and, as a consequence, the braking qualities for the lifting shaft of the drilling rig; the use of low-melting metal nanopowders of various modifications diluted with water or acetone for the liquid, which allows for a significant increase in the thermal conductivity coefficient of the nanofluid and thereby improves the efficiency of forced cooling of the friction belts of the brake half-discs; the volumes of nanofluid in the evaporation zones are much smaller than in the zones of its transport, which intensifies heat exchange in different aggregate states of the nanofluid due to increased cycles of its circulation; forced air heat exchange of matte and polished surfaces of the disc by convection and radiation, as well as thermal conductivity used to heat the friction belts of the disc, is taken into account, which makes it possible to determine a smaller portion of the heat removed from their surfaces during braking; the accelerators of the movement of nanofluid in any aggregate state between the zones of evaporation and transport-condensation in their heated state are diffusers, and the retarders are the nanostructure of the condensation zone and transport of the disk, which cause a change in the gradients of velocity, pressure and temperature in the layers of nanofluid; with a variable thickness of the disk friction belt and the specifics of cooling based on the "heat pipe" effect, using the finite element modeling method, evaluate the stress-strain state of the disk wall.

Conclusion

A single-disk shoe brake for drilling winches has been developed and its stress-strain state has been studied, which has improved the braking qualities for the lifting shaft of a drilling rig.

Conflict of Interests

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

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