Sedimentation and Diffusion in Nanofluids in Rotating Systems of Metallic Friction Elements of Brake *(Part I)*

A.Kh. Janahmadov[1,3], N.A. Volchenko[2], M.Y. Javadov[3], V.V. Nischuk[4], Ye.Yu. Andreichikov[4], V.S. Skrypnyk[4], D.Yu. Zhuravlev[4]

[1] Azerbaijan National Academy of Aviation (Mardakan ave, 30, Baku, AZ1045, Azerbaijan)
[2] Kuban State Technological University (International Activities Support Department, Room A-523, Moskovskaya st., 2, Bld. A, Krasnodar, 350072, Russia)
[3] Azerbaijan Engineering Academy (Mardakan ave. 30, Baku, AZ1045, Azerbaijan)
[4]Ivano-Frankivsk National Technical University of Oil and Gas (Karpatska ave.15, Ivano-Frankivsk, 76019, Ukraine)

For correspondence:
Zhuravlev Dmitriy / e-mail: dmytro.2103@ukr.net

Abstract

According to the principles of nonequilibrium thermodynamics, it is necessary to study the processes of heat generation in friction pairs and the local nature of its removal from the inner surface of the brake pulley rim. Such means are briquettes made of nanoparticles and forming capillary structures resting in metal frames. The latter are installed in three rows in wide circular grooves on the inner surface of the pulley rim, to which the fluid chamber is attached. The interaction of the latter with the nanocapillary structure in briquettes is described. The connection between sedimentation and diffusion in a nanofluid was carried out by means of the intensity of the entropy source caused by the frictional interaction of metal-polymer friction pairs. To assess sedimentation, the gradient theory was applied to pressure, velocity, partial and specific volume, mass and molar concentration, as well as the determination of the sedimentation coefficient. The diffusion of nanoparticles was characterized by the coefficient and its mobility in the liquid. Selection by molecular weight of various materials of nanoparticles was made. The results of experimental studies on a model band-shoe brake are presented and the cooling efficiency is established.

Keywords: band-shoe brake, friction pairs, brake pulley rim, nanoparticles, liquid, diffusion-sedimentation processes, molecular weight.

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Əyləclərin metal friksion elementlərinin fırlanan sistemlərinin nanomayelərində çökmə və diffuziya *(I hissə)*

Ə.X. Canəhmədov[1,3], N.A. Volçenko[2], M.Y. Cavadov[3], V.V. Nişuk[4], Y.Y. Andreyçikov[4], V.S. Skrıpnık[4], D.Y. Juravlev[4]

[1] Azərbaycan Milli Aviasiya Akademiyası (Mərdəkan pr. 30, Bakı, AZ1045, Azərbaycan)
[2] Kuban Dövlət Texnologiya Universiteti (Moskovskaya küç. 2, Krasnodar, 350072, Rusiya)
[3] Azərbaycan Mühəndislik Akademiyası (Mərdəkan pr. 30, Bakı, AZ1045, Azərbaycan)
[4] İvano-Frankivsk Milli Texniki Neft və Qaz Universiteti (Karpatska küç.15, İvano-Frankivsk, 76019, Ukrayna)

Yazışma üçün: Juravlev Dmitriy / e-mail: dmytro.2103@ukr.net

Xülasə

Məqalədə nanohissəciklərdən hazırlanmış və metal karkaslarda dayanan kapilyar strukturlar əmələ gətirən briketlər nəzərdən keçirilib. Onlar maye kamerasının bağlandığı qasnağın halqasının daxili səthində geniş dairəvi yivlərdə üç cərgədə quraşdırılır. Bu mayenin briketlərdəki nanokapilyar strukturla qarşılıqlı təsiri təsvir edilib. Nanomayedə çökmə və diffuziya arasında əlaqə “metal-polimer” sürtünmə cütünün friksion qarşılıqlı təsiri nəticəsində yaranan entropiya mənbəyinin intensivliyi vasitəsilə həyata keçirilmişdir. Çöküntünün qiymətləndirilməsi üçün qradiyent nəzəriyyəsinin tətbiqi təzyiqin, sürətin, qismən və xüsusi həcmin, kütlə və molyar konsentrasiyanın, həmçinin çökmə əmsalı təyin edilmişdir. Nanohissəciklərin diffuziyası onun əmsalı və onun mayedə hərəkətliliyi ilə xarakterizə olunurdu. Nanohissəciklərin müxtəlif materiallarından molekulyar çəki üzrə seçimlər aparılmışdır.

Açar sözlər: lent-kündəli əyləc, sürtünmə cütü, əyləc qasnağı, nanohissəciklər, maye, diffuziya-çökmə prosesi, molekulyar çəki.

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Седиментация и диффузия в наножидкости во вращающихся системах металлических фрикционных элементов тормозов *(часть I)*

А.Х. Джанахмедов[1,3], Н.А. Вольченко[2], М.Я. Джавадов[3], В.В. Нищук[4], Е.Ю. Андрейчиков[4], В.С. Скрыпнык[4], Д.Ю. Журавлев[4]

[1] Азербайджанская Национальная академия авиации (Мардакянский пр. 30, Баку, AZ1010, Азербайджан)
[2] Кубанский государственный технологический университет (ул. Московская, 2, Краснодар, 350072, Россия)
[3] Азербайджанская Инженерная академия (Мардакянский пр. 30, Баку, AZ1045, Азербайджан)
[4] Ивано-Франковский национальный технический университет нефти и газа (ул. Карпатская, 15, Ивано-Франковск, 76019, Украина)

Для переписки: Журавлев Дмитрий / e-mail: dmytro.2103@ukr.net

Аннотация

В статье рассмотрены брикеты, изготовленные из наночастиц и образующие капиллярные структуры, покоящиеся в металлических каркасах. Они установлены в три ряда в широкие круговые пазы на внутренней поверхности обода шкива, к которому прикреплена камера с жидкостью. Описано взаимодействие этой жидкости с нанокапиллярной структурой в брикетах. Связь между седиментацией и диффузией в наножидкости осуществлялась посредством интенсивности источника энтропии, вызванного фрикционным взаимодействием пар трения «металл-полимер». Для оценки седиментации применялась градиентная теория к давлению, скорости, парциальному и удельному объему, массовой и мольной концентрации, а также определен коэффициент седиментации. Диффузия наночастиц характеризована коэффициентом и ее подвижностью в жидкости. Произведен подбор по молекулярному весу из различных материалов наночастиц.

Ключевые слова: ленточно-колодочный тормоз, пары трения, обод тормозного шкива, наночастицы, жидкость, диффузионно-седиментационные процессы, молекулярный вес.

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Janahmadov A.Kh et al.

Introduction

Suspensions based on solid phase nanoparticles are called nanofluids [1]. The thermal conductivity of suspensions with a low concentration of solid phase particles can be described by the Maxwell theory [2]. The theory is built on the basis of a number of assumptions: the concentration of particles of the solid phase is small (the distance between the particles significantly exceeds their size); particles are immobile in a liquid; particles have a spherical shape, the equations of conductive heat transfer are valid for describing the heat transfer process. When using particles of the nanometer range, shrouded in a polymer film, which are dipoles, during the movement of a nanofluid in cooling systems, a transformation of charges occurs, leading to the formation of electronic and ionic zones. The driving force in a nanofluid is jumps of various kinds of potentials. The large scatter of experimental data is associated with a number of objective reasons: the method of nanoparticle synthesis, the size distribution function of nanoparticles, the nanofluid manufacturing technology, as well as the method of measuring thermal conductivity and integrating results. In addition, depending on the mode of rotation of the metal friction element of the brakes, the effect of sedimentation of nanoparticles is observed. Sedimentation is the settling of small nanoparticles in a liquid or gas under the action of a gravitational field and centrifugal forces.

Analysis of literary sources and the state of the problem

In works [1-3] on the study of heat transfer in nanofluids, it was shown that the thermal conductivity of suspensions of ultrafine aluminum, silicon, and titanium oxides in water at a volume concentration of the order of several percent exceeds the thermal conductivity of a pure liquid by tens of percent.

The results of the experiment with nanoparticles of various sizes indicate that the thermal conductivity of a liquid based on larger particles is fairly well described using the Maxwell theory [2].

First of all, the data obtained with theoretical models built to describe the thermal conductivity of coarse suspensions. The first such model was created by Maxwell [2], who obtained the relation between the thermal conductivity of the suspension λ and the base fluid λ_0.

An analysis of the influence of the size of nanoparticles on the thermal conductivity coefficient (λ) of a nanofluid shows that the coefficient λ of nanofluids increases with an increase in the size of nanoparticles [4].

In [5], the simulation of the thermal conductivity coefficient of a nanofluid depending on the different masses of nanoparticles is presented. The authors found that λ of a nanofluid at a fixed size and concentration of nanoparticles increases with their mass. The dependence of the increase in the thermal conductivity of a nanofluid on the mass of nanoparticles means at the same time the same dependence on the density of particles with the same particle size.

The thermal conductivity coefficient of nanofluids is also affected by the shape of nanoparticles, which can be spherical, cylindrical, prismatic, flat, elliptical. Thus, in [2, 3], the thermal conductivity of a nanofluid with ZnO nanoparticles having prismatic and spherical shapes was experimentally studied at various volume concentrations of nanoparticles in the range from 0.05 to 5.0%. It was found that the coefficient λ of nanofluids with zinc oxide nanoparticles increased by 12% and

18%, respectively, for spherical and prismatic nanoparticles at φ = 5.0%, compared with the coefficient λ of the base liquid - water.

However, many of the experimental data obtained so far have a large scatter and often contradict each other. Some of the data indicate an anomalous increase in the thermal conductivity of nanofluids in comparison with the theory [1]. But in the course of joint studies conducted by organizations from different countries, an anomalous increase in thermal conductivity at low concentrations of nanoparticles was not found [6]. The classification of nanofluids and the analysis of theoretical approaches to modeling the transport coefficients are given in [7]. In particular, it was noted that a rigorous theory of transport processes in nanofluids has not yet been developed, and the use of molecular dynamics modeling of thermal conductivity still gives predictions that differ from the classical theory. In work [8] on a new type of composite brake pulley with a chamber of a band-shoe brake in bench conditions, liquid (water) cooling of its friction pairs was studied, the efficiency of which was 10 -14%. The modes of motion and changes in the parameters of nanofluid and vapor along the length of the inner wall of the pulley rim were studied in [9]. The presence of the following zones from the pinched edge of the rim to the free one was established).

The first one is a single-phase convective heat exchange of a nanofluid with macrosections of thermal and hydrodynamic stabilization; the second is the beginning of the nanofluid boiling; the third is the beginning of intense nanovapor content, after which the intensity of heat transfer increases significantly; the fourth - near-wall two-phase layers are formed; in this case, the mode of movement of the mixture, as a rule, is bubbly; fifth, superheated vapor and nanofluid move in the annular flow at saturation temperature; there is a sequential change in flow regimes - from bubble to dispersed-annular.The efficiency of air-nano-liquid cooling of friction pairs of a band-shoe brake in bench conditions of the material is 16 - 18%.

However, the considered systems of forced cooling of friction pairs of a band-shoe brake have the following disadvantages: - there was a sedimentation (falling) of nanoparticles under the action of the settling of the gravitational field and centrifugal forces on the bottom of the pulley chamber, which reduced the efficiency of forced cooling; - forced cooling contributes to uneven distribution of bulk temperatures from the pinched edge of the pulley rim to the free one due to the complex conductive heat exchange between the rim, its flanges and the mounting lug; - no substantiation was made for the choice of nanoparticles for capillary structures and liquids in rotating metal friction elements of brakes [10].

Formulation of the problem. It is necessary to solve the problem of using nanoparticles in the form of briquettes that make up the nanocapillary structure in the system of forced liquid cooling of the friction pairs of a band-shoe brake and evaluate the effectiveness of its operation.

The main issue of the article: the design and operation of a nanocapillary liquid cooling system for friction pairs of a band-shoe brake; the discussion of the results.

The purpose of the work is to substantiate the performance of nanoparticles in capillary structures and in liquid in rotating brake systems.

Design and operation of nanocapillary and nanofluid cooling systems for brake friction pairs. The principle of capillary-liquid cooling of friction pairs of a band-shoe brake is based on the following effects: convective, vortex, radiant, conductive, and evaporative-condensation in capillary structures located in briquettes. Let us dwell on a brief analysis of the types of cooling that were considered. The vortex effect is the movement of air or liquid layers, in which their small volumes not only move, but also rotate around the instantaneous axis, which are cooled due to the redistribution of energy over the flow layers, leading to a change in the specific density gradient.

Radiant heat transfer of a metal friction element from matte and polished surfaces occurs due to the conversion of its internal thermal energy into radiation energy carried out with the help of photons. The transfer of the specified thermal energy into space where it is absorbed by the ambient air or liquid in a different thermodynamic state. Conductive heat transfer is the transfer of thermal energy by microparticles (electrons, ions) from a more heated area, a metal friction element, to a less heated one. In this case, the microparticles in the considered body of the friction element not only move, but also interact. Let us proceed directly to the design features of the nanocapillary and nanofluid cooling system for the tribological couplings of the drawworks band-shoe brake. On fig. 1 *a*, *b*, *c*, *d* shows a band-shoe brake, longitudinal section (*a*); in fig. 1 *b* - section along A-A in fig. 1 *c*, *d* – longitudinal section of the cooling device (view B from fig. 1 *b*); *d* - diffusers and confusers.

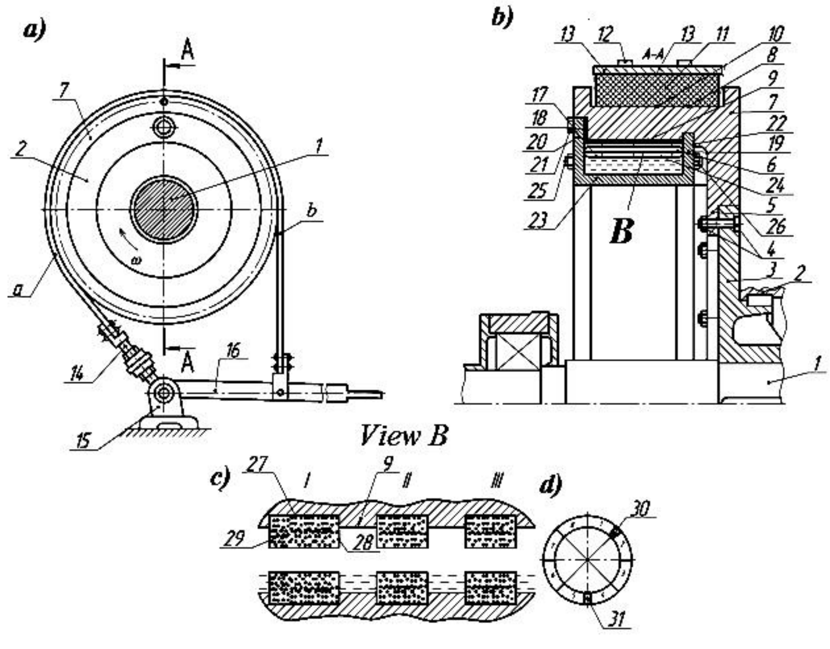

Figure 1 a, b, c, d – Band-shoe brake with a forced system of nanocapillary liquid cooling: a – general view; in fig. b - a section along A-A in fig. a; in fig. c - longitudinal section of the cooling devices (view B from fig. b) located in the upper and lower parts of the pulley rim; rice. 1 d - diffusers and confusers formed between the ends of fixed briquettes during the rotation of the pulley rim

A band-shoe brake with a nanocapillary system and nano-liquid cooling consists of a lifting shaft 1, a drum 2 with a flange 3, which is fastened with a bolted connection 4 to a heat-insulated protrusion 5 of the brake pulley 6. The latter has flanges 7, working 8 and non-working 9 surfaces. The working surface 8 of the pulley in the process of braking frictionally interacts with the working surfaces 10 of the polymer linings 11 attached with the help of antennae 12 to the brake band 13, which has an incoming (a) and running (b) branches. The running branch (*a*) of the tape 13 is attached to the support 15 by means of a threaded tie 14, and its running branch (*b*) is attached to the brake control lever 16.

Under the non-working surface 9 of the rim of the pulley 6 there is a chamber 17 occupying the volume from the first radial side wall 18, located on the side of the free edge of the rim of the pulley 6 and to the second radial side wall 19, located near the protrusion 5 of the pulley 6. From above, the first radial side wall 18 is located in groove 19 of the end of the flange 7 and through the sealing gasket 20 with the help of bolts 21 is attached along its perimeter to the rim of the pulley 6. The second radial side wall 19 is inserted with an interference fit into the circular groove 22. From the bottom, the walls 18 and 19 are interconnected cylindrical ring 23. Chamber 17 is filled with nanofluid 24 through inlet valve 25, and the resulting vapor in chamber 17 is vented into the atmosphere through outlet valve 26.

The chamber 17 is filled with liquid 24 for 2/3 of its volume and above it the non-working surface 9 of the rim of the pulley 6 is polished and circular grooves 27 of various widths are located in it (larger on the side of the free edge of the rim and smaller on the side of its pinched edge). Convex U-shaped briquettes are installed in circular grooves 27. The frame for the briquettes is made of sheet solid or perforated copper, in which there are sintered nanoparticles 29. The unclosed ends of the fixed briquettes form between themselves in the annular grooves 27 on top of the pulley rim into diffusers 30, and from below confusers 31.

Band-shoe brake with nanocapillary and liquid cooling system works as follows. When the brake control lever 16 is pressed, the brake band 13 is tightened and the working surfaces 10 of the polymer linings 11 interact with the working surface 8 of the brake pulley 6, which contributes to the generation of heat on their surfaces. At the same time, a significant part of the heat is absorbed by the pulleys 6, which is an accumulator of thermal energy.

<u>The first case</u> is illustrated in Fig. 1*c*, when the liquid 24 does not wash the polished non-working surface 9 of the rim of the brake pulley 6 and its briquettes, and a gap has formed between their surfaces. From the polished non-working surface 9 of the rim of the brake pulley 6, radiant heat transfer is carried out: a radiant flux q_d is supplied from the polished working surface 8 of the rim of the brake pulley 6 and, in accordance with the Stefan-Boltzmann law, the flow of own radiation with a density of $C_d T^4_d$ is diverted directly to the surface of an absolute black body, i.e. liquid 24. In this case, there is also a weak convective heat transfer, since during the rotation of the pulley 6, due to centrifugal forces, liquid drops still fall on the polished non-working surface 9 of the rim of the pulley 6 and into the nanocapillary structure of the briquettes on which they immediately turn into steam. Thus, in this case, it has weak convective-conductive and strong radiant heat trans-

fers, which reduce the energy load of the brake pulley rim.

The second case is shown in Fig. 1 *c*, when the liquid 24 is on the polished non-working surface 9 of the rim of the brake pulley 6 and in its briquettes. In this case, the convective-conductive heat transfer is strong when the liquid layers 24 interact with the polished non-working surface 9 of the pulley rim 6 with their weak radiant heat transfer.

From fig. 1 *c* it follows that the thermal state of the parts of the brake pulley located at different poles in the vertical plane is not the same due to a change in the thermodynamic parameters of the liquid and surrounding air, which contributes to a change in their gradients, and as a result, the intensification of conductive, convective and radiative heat transfer in the proposed nanocapillary liquid cooling system.

When liquid gets between the rings of briquettes (I - II) on the non-working polished surface of the pulley rim, i.e., in the evaporation zone, it heats up and evaporates. Subsequently, due to the created pressure drop between the evaporation and condensation zones (between the rings of briquettes II - III), the liquid from the evaporation zone enters the condensation zone by centrifugal forces arising from the rotation of the pulley. In addition, part of the liquid heat carrier located in the left and right parts of the cooling chamber, respectively, under the free and pinched edges of the pulley rim, depending on its position, circulates in two phases - liquid and gaseous. The ratio of the design parameters of the cooling chamber provides the necessary amount of liquid in the condensation zone to wet the evaporation zone under the action of centrifugal forces. In addition, the separation of drops of condensate moving along the capillary structure of the briquettes under the action of centrifugal forces is prevented.

Thus, when operating in the modes of rotation of the brake pulley or frictional interaction of friction pairs of a band-shoe brake, the following types of heat transfer take place:

- in the first mode - convective air and liquid, conductive, as well as radiant with a working and non-working surface (polished) of the pulley rim; as well as evaporation-condensation heat exchange with nanocapillary structures of briquettes;

- in the second mode - convective, air and liquid, conductive, as well as radiant with a polished non-working surface of the brake pulley rim; in this case, the nanocapillary structure in the briquettes is saturated with liquid (Fig. 1 *d*).

The listed types of heat transfer to an unequal degree affect the energy load of the friction pairs of the drawworks band-shoe brake, and ultimately reduce their energy load, and as a result, the durability of working surfaces.

The discussion of the results

Theoretical and experimental studies of non-uniform nanocapillary and nanofluid cooling of friction pairs of a model tape-shoe brake of a drawworks made it possible to state the following: - at temperatures above 100 °C, an increase in the electrochemical potential and the formation of a system of electronic and ionic zones in the cavity, which contribute to potential jumps, are observed; in this case, the nanofluid acts as an electrolyte; - the use of nanofluid in the cooling system of the composite pulley made it possible to reduce its energy load by 21,8%, wear of friction linings by 19,9%, and increase the braking torque by 13,2%; - according to the principles of nonequilibrium thermodynamics, the processes of heat generation in friction pairs and the local nature of its removal from the inner surface of the brake pulley rim were studied.

Conclusion

Thus, due to the circulation of the coolant in briquettes with a nanocapillary structure and in the volume of the pulley rim chamber in different phases, its energy load is quasi-levelled, which contributes to the stabilization of the operational parameters of the friction pairs of the brakes, and as a result, a decrease in their wear.

Conflict of Interests

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

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