Sedimentation and Diffusion in Nanofluids in Rotating Systems of Metal Friction Elements of Brake *(Part III)*

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Abstract

To assess sedimentation, the gradient theory is 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 is characterized by the coefficient and its mobility in the liquid. Selection by molecular weight of various materials of nanoparticles is 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.

DOI 10.52171/2076-0515_2023_15_04_14_20

Received *14.01.2023*
Revised *14.12.2023*
Accepted *20.12.2023*

For citation:
Janahmadov A.Kh., Volchenko N.A., Javadov M.Y., Volchenko D.A., Fidrovskaya N.N., Zhuravlev D.Yu., Aleynikova O.M., Skrypnyk V.S., Slepuzhnikov Ye.D.
[Sedimentation and Diffusion in Nanofluids in Rotating Systems of Metallic Friction Elements of Brake *(Part III)]*
Herald of the Azerbaijan Engineering Academy, 2023, vol. 15, no. 4, pp. 14-20 *(in English)*

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

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Xülasə

Məqalədə, çöküntünün qiymətləndirilməsi üçün qradiyent nəzəriyyəsinin tətbiqi ilə təzyiq, sürət, qismən və xüsusi həcm, kütlə və molyar konsentrasiya, həmçinin çökmə əmsalı təyin edilib. Nanohissəciklərin diffuziyası onun mayedə hərəkətliliyi və əmsalı ilə xarakterizə olunur. Nanohissəciklərin müxtəlif materiallarından molekulyar çəkiyə görə seçimlər aparılmışdır. Lentli-kündəli əyləc modeli üzərində eksperimental tədqiqatların nəticələri təqdim olunub və soyutmanın səmərəliliyi müəyyən edilib.

Açar sözlər: lentli-kündəli əyləc, sürtünmə cütü, əyləc qasnağının dəndənəsi, nanohissəciklər, maye, diffuziya-çökmə prosesi, molekulyar çəki.

DOI 10.52171/2076-0515_2023_15_04_14_20

УДК 62.92.113; 621.2.082.18

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

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Аннотация

Для оценки седиментации в статье применялась градиентная теория к давлению, скорости, парциальному и удельному объему, массовой и мольной концентрации. Дано определение коэффициента седиментации. Диффузия наночастиц характеризовалась коэффициентом и ее подвижностью в жидкости. Произведен подбор по молекулярному весу из различных материалов наночастиц. Приведены результаты экспериментальных исследований на модельном ленточно-колодочном тормозе и установлена эффективность охлаждения.

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

Introduction

Diffusion characterizes the movement of nanoparticles together with liquid in the brake pulley rim chamber.

Sedimentation characterizes the movement of nanoparticles along with fluid in the brake pulley rim chamber. Sedimentation characterizes the movement of nanoparticles in the direction of their settling to the bottom of the chamber at a given time. In this case, thermal and dynamic forces act on nanoparticles in a liquid.

The analysis of literary sources and the state of the problem are disclosed in the first part of the article. The main questions of the article: the processes occurring in the brake pulley rim chamber; experimental studies; 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.

Processes occurring in the brake pulley rim chamber

If a nanofluid enters the inner surface of the wall of the lower part of the rim of a rotating pulley, which is subcooled to the saturation temperature T_s, then along its length it is possible to distinguish, then along its length it is possible to distinguish the following characteristic regions [1]. On fig. 1 shows an arrow → next to *z*, indicating that the folded pulley rim must be viewed from the pinched end of the pulley and towards the free end. Region I (Fig. 1) is the region of single-phase convective heat transfer, inside which, in turn, it is possible to single out areas of thermal and hydrodynamic stabilization.

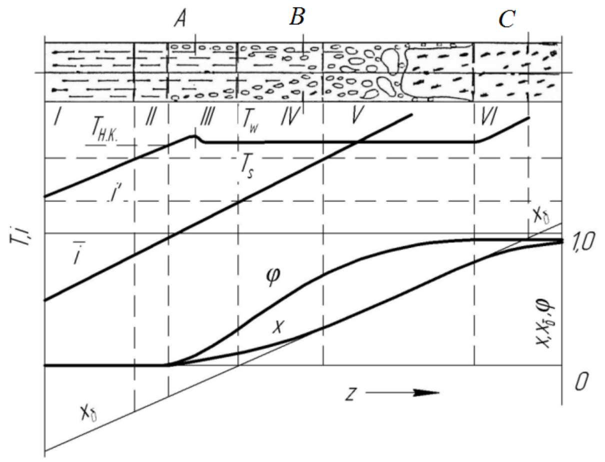

Figure 1 – Modes of motion and change of nanofluid and vapor parameters along the length of the inner wall of the pulley rim

The calculation of the nanofluid flow parameters in this area is carried out in accordance with the recommendations of known methods. At the end of region I, the temperature of the inner wall of the pulley rim reaches the value T_s, (which corresponds to the enthalpy of nanofluids on the saturation line *i*').

Region *II* covers the section of the inner surface of the pulley rim from the section, where the wall temperature T_w reached T_s, up to the section where the beginning of boiling was fixed by one method or another, that is, the actual nanovapor content in the flow became different from zero. The wall temperature at the end of region II is equal to the initial boiling point $T_{b.\ b.}$ and wherein $T_w = T_{b.\ b.}$, and the mass-average enthalpy of the flow *I* remains less than the enthalpy of saturation *i*', that is, the nanofluid, on average, as before, is undercooled to T_s. The flow parameters in region *II* can be calculated with sufficient accuracy (as in region *I*) using the formulas for single-phase heat transfer. Obviously, in regions *I* and *II*, the relative enthalpy $x_b < 0$.

Region *III* is located between the section of the beginning of boiling and the section where the mass-average enthalpy of the flow becomes equal to the enthalpy of saturation, i.e. $x_b = 0$. In region III, the flow is substantially unbalanced: the relative flow enthalpy x_b remains negative, while the mass nanovapor content x and the corresponding real volumetric nanovapor content $\varphi = V''/V_{mix}$, where V'' – nanopair volume; V_{mix} – the volume of the nanovapor-liquid mixture is different from zero and the presence of the nanovapor phase in the flow is determined experimentally. Inside this region, a section is sometimes distinguished (section *A* - Fig. 1), corresponding to the onset of intense nanovapor formation, after which the intensity of heat transfer noticeably increases, the hydraulic resistance increases, and the wall temperature either remains constant or even decreases. The boundary of regions *III* and *IV* does not reflect any physical changes that occur with the nanoflow.

Region *IV* begins in section $x_b = 0$ and ends with a section characterized by the fact that the average temperature of the nanofluid becomes equal to T_s, after which the flow becomes almost thermally balanced. Inside the area *IV* allocate section *B*, in which the near-wall two-phase layers converge. In this case, however, for the entire region IV, despite the fact that the mass-average enthalpy becomes greater than the enthalpy of saturation *i*' ($x_b > 0$). The flow remains unbalanced: the saturated nanovapor moves with the subcooled liquid. In region *IV*, the mode of motion of the mixture is, as a rule, bubbly.

Areas V – VI are areas of balanced flow of the mixture, starting from the section where the average temperature of the nanofluid is equal to T_s, and ends with a section where a new imbalance sets in: an overheated nanovapor and nanofluid move in the flow at saturation temperature. In this region, there is a successive change in flow regimes - from bubbly further to dispersed-annular. Values x and x_b in area *V* match up.

Region *VI* is the region of mixture movement, where the flow is usually unbalanced (nanofluid droplets in superheated steam), and this unbalance can be significant - large superheats of steam relative to T_s. At very high values of the heat flux on the wall, the so-called double imbalance is possible: an undercooled nanofluid in an overheated steam. Within area *VI* there can be a section *B*, wherein $x_b = 1$, although the actual value $x<1$ [2]. In practical cases, obviously, the set of regions along the length of the wall is far from necessarily complete, and the length of these regions depends on the parameters of the nanoflow and the heat flux density, which depend on the deceleration mode.

The calculation of two-phase flow parameters, especially in regions *III*, *IV*, *VI*, is characterized by significant imbalance, is very complex and is currently carried out according to empirical or semi-empirical methods.

Experimental studies

The heat transfer coefficient in the nanocapillary structure system can be increased by varying the particle size, i.e., their area of interaction with the liquid or by its transformation into vapor. At the same time, an increase in the particle size contributes to a decrease in the heat transfer coefficients.

In addition, during heat transfer in systems with a nanocapillary structure, the main influence is exerted by the volume concentration of nanoparticles in briquettes and their thermal conductivity coefficient.

The liquid in the cooling chamber in a rotating pulley comes into motion under the action of centrifugal and gravitational forces, as well as volumetric and surface forces [3-5].

The penultimate ones arise as a result of the fluid density gradient. The latter arise as a result of the liquid density gradient and are caused by a local change in the surface tension of the liquid, which is mainly associated with the occurrence of an uneven distribution of the bulk temperature or the concentration of nanoparticles in the briquettes on the inner surface of the pulley rim, which is, as a rule, a consequence of a change in their thermodynamic state in volume of liquid in briquettes with nanoparticles.

Conductive-capillary convection contains several new hydrodynamic effects due to the concentration inhomogeneity of nanoheat carriers near the surfaces of the pulley rim and the cooling chamber. This contributes to the appearance of bubbles and drops near microroughnesses of their surfaces.

The structure of fluid movement in the cavity of the cooling chamber depends on its shape, as well as on the location of the heated pulley rim in space. In this case, the surface forces prevail over the bulk forces arising in briquettes with nanoparticles. Such a condition is characteristic of thin horizontal layers and films of a liquid, near the surface of drops and air bubbles in a liquid. Two main factors must be taken into account. The first factor is that the characteristic time of heat diffusion is hundreds and even thousands of times shorter than the time of existence of concentration inhomogeneities. As a result, the latter exist in liquids much longer than thermal ones, and their duration and intensity of action of capillary forces at the phase boundary increases many times. This contributes to the intensification of heat removal from nanoparticles in briquettes to the liquid washing them. The second factor is the adsorption of liquid on the surfaces of nanoparticles in briquettes, which contributes to the concentration-capillary drift of air bubbles. The action of Marangoni forces on the free surface of a liquid causes it to move in the direction of increasing surface tension. The surface drags the layers of fluid adjacent to it. As a result, if the free surface belongs to a bubble, then it begins to be displaced in the direction opposite to the liquid flow in the capillaries of the briquette nanoparticles. This ability of air bubbles to spontaneously move in a liquid in the direction of decreasing surface tension causes their capillary drift.

In order to control the heat fluxes generated on the working surfaces of friction pairs of drawworks band-shoe brakes, it is necessary to have reliable data on the thermal conductivity coefficients that are in sintered form, forming capillary structures that are limited by a metal frame, i.e., they are a briquette. In table 1, nanoparticles were selected for the inner surface of the pulley rim. In this case, the number of nanoparticles was determined in the cross-sectional area of the briquette. Based on the table 1 we write a relation of the form

$$\frac{\lambda_1}{\lambda_2} = \frac{A_1}{A_2}; \tag{1}$$

$$\frac{\lambda_2}{\lambda_3} = \frac{A_2}{A_3}; \tag{2}$$

$$\frac{\lambda_1}{\lambda_3} = \frac{A_1}{A_3}; \tag{3}$$

Table 1 – Selection of nanoparticle materials for sector briquettes according to thermal conductivity coefficients and their cross-sectional area

Options for selecting nanoparticles	Coefficient of thermal conductivity λ, W/(m·°C): I – Al; II – Cu; III – SiC	Number of segment briquettes		
		I	II	III
		Relations between thermal conductivity coefficients, λ, W/(м·°C)		
		I – II	II - III	I - III
		$\lambda_1/\lambda_2 = 1{,}7$	$\lambda_2/\lambda_3 = 2{,}0$	$\lambda_1/\lambda_3 = 3{,}3$
		Relations between the cross-sectional areas of briquettes, cm^2		
		$A_1/A_2 = 1{,}9$	$A_2/A_3 = 2{,}1$	$A_1/A_3 = 3{,}5…4{,}1$

Table 2 – Experimental data on the energy load of the serial pulley rim (in the numerator) and with its nanocapillary liquid cooling

Number of segment briquettes		I	II	III
Specific loads, MPa		$\frac{0{,}75^*}{0{,}7}$	$\frac{0{,}85}{0{,}75}$	$\frac{0{,}95}{0{,}8}$
Temperatures, °C	Forces: superficial	$\frac{320{,}0^*}{300{,}0}$	$\frac{340{,}0}{320{,}0}$	$\frac{360{,}0}{340{,}0}$
	voluminous	$\frac{100{,}0^*}{20{,}0}$	$\frac{110{,}0^*}{85{,}0}$	$\frac{120{,}0^*}{90{,}0}$

***Note:** the patterns of changes in the parameters of energy loading obey a linear law (from the pinched edge of the rim to the free one, III - I)

The discrepancy between the values in relation (1) is 13.0%, in (2) only 5.0% and in (3) 6.0%, and averages 8.0%. This indicates that the materials for nanoparticles in briquettes are chosen correctly. This is evidenced by the ratios for nanoparticles from powder for: aluminum (Al) - $\frac{0{,}748}{0{,}9}$; меди (Cu) $\frac{0{,}8}{0{,}95}$; карбида кремния (SiC) - $\frac{0{,}63}{0{,}7}$ thermal conductivity coefficients, W/(m·°C) [in the numerator there are nanoparticles in the liquid, and in the denominator in the sector briquettes washed by the liqui].

Experimental studies of friction pairs "steel 35KhNL - FK-24A" of a model band-shoe brake, the pulley rim of which was equipped with a liquid chamber with a volume of 200 dm^3). The weight of each type of briquette was: I - 80 g; II - 50 g; III - 25 g. At the same time, the weight of the sheet copper frame was: I - 55,4 g; II – 28,7 g; III – 13,4 g. While the weight of the perforated frame was twice as light. In table 2 shows the results of experimental studies.

Theoretical and experi-mental studies of non-uniform nanocapillary and nanofluid coolin An analysis of uneven forced cooling by local heat exchangers (sector briquettes) of the brake pulley rim made it possible to establish the following: increase in thermal conductivity coefficients λ_1, λ_2, λ_3, respectively, from 0,748; 0,8 and 0,63 W/(m·°C) up to 0,9; 0,95 and 0,7, W/(m·°C), i.e. by 60,0%; a change in the parameters of the nanofluid in sector briquettes was achieved at a heat flux density q = $2 \cdot 10^2 \ldots 2 \cdot 10^4$ W/m^2, an average bulk temperature to = 85 ºC of the pulley rim at an average linear speed of 2,0 to 6,0 m/s of its rotation; - while the heat transfer coefficient was 100…350 W/(m^2·ºC) from the polished inner surface of the pulley rim, the heat transfer coefficient was 75…300 W/(m^2·ºC) through the multilayer structure [6, 7]; comparison of operational parameters during cooling of the pulley rim with liquid and with the help of sector briquettes with nanoparticles washed by liquid, made it possible to stabilize the values of specific loads in friction pairs, surface and volume temperatures of the rim pulley, as well as by reducing their fluctuations, the efficiency of the system was 25%. 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: nanoparticles due to their thermal conductivity change the mode of motion and thermodynamic parameters of nanofluid and vapor along the length of the inner wall of the pulley rim; experimental studies of the forced local cooling system showed that in briquettes with nanoparticles from various materials and capillary structures realized in them, an increase in the thermal conductivity coefficient by an average of 60% was achieved; for a given brake loading mode, fluctuations in specific loads across the width of its rim amounted to 0,7-0,8 MPa, approximately 35% less on average than in a serial water-cooled rim.

Conclusion

Nanofluidic and nanocapillary forced cooling will allow the friction pairs of a band-shoe brake to operate in the temperature range below that acceptable for friction lining materials.

Conflict of Interests

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

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