Hindawi
International Journal of Rotating Machinery
Volume 2023, Article ID 9937708, 7 pages
https://doi.org/10.1155/2023/9937708

Review Article

Energy-Conserved Hydrodynamic Lubricated Components with Wall Slippage

Xiaoxu Huang[1] and Yongbin Zhang[2]

[1]*School of Mechanical Technology, Wuxi Institute of Technology, Wuxi, Jiangsu Province, China*
[2]*College of Mechanical Engineering, Changzhou University, Changzhou, Jiangsu Province, China*

Correspondence should be addressed to Yongbin Zhang; engmech1@sina.com

Received 4 January 2023; Revised 23 March 2023; Accepted 6 April 2023; Published 13 April 2023

Academic Editor: Abraham Engeda

The hydrodynamic thrust slider and journal bearings as well as hydrodynamic lubricated gears with the merit of energy conservation by the wall slippage are reviewed. The principle for designing these hydrodynamic contacts is to artificially set the wall slippage on the stationary surface in the hydrodynamic inlet zone. To design the wall slippage on the moving surface in the hydrodynamic outlet zone can also give additional benefits. The technical merits of these mechanical components are the improved load-carrying capacity and the lowed friction coefficient, i.e., the energy conservation due to the wall slippage. Owing to the designed wall slippage, the carried load of the hydrodynamic step bearing can be increased by 200%~400% while its friction coefficient can be reduced by 50%~85%, and the load-carrying capacity of the hydrodynamic journal bearing can be increased by nearly 100% while at the same time, its friction coefficient can be reduced by more than 60%. For hydrodynamic lubricated gear contacts, by covering ultrahydrophobic or oilphobic coatings on the slower moving surface, the friction coefficient can be approaching to vanishing and the contact load-carrying capacity can be increased very significantly for large slide-roll ratios under medium or heavy loads.

1. Introduction

Energy conservation is a big issue in modern industry. It is mostly related to the frictional power encountered in mechanical transmission. To realize it by reducing friction is of vital value to modern industrial development [1]. Bronshteyn and Kreiner showed that significant energy savings in machines can be obtained by using the energy-efficient lubricants; the performance of which is dependent on the viscosity shear thinning and the viscosity-pressure index [2]. They described that adding the friction modifier into the oils can reduce the friction. Tung and Gao also showed that by adding molybdenum dithiocarbamate (MoDTC) (friction modifier) into the engine oil, the friction and wear on the piston ring had been effectively reduced [3]. The reductions of friction were also realized by adding micrometer-scale or nanometer-scale particles into the lubricating oils [4–7]. These include the biolubricants containing boron nitride nanoparticles [4], the lubricating water containing titanium dioxide nanoparticles [5], the olive oil containing nanoparticles [6], and the avocado and canola oil containing boron nitride nanoparticles [7]. Surface texturing was also found to be an effective way for bettering the hydrodynamic lubrication and reducing the friction in mechanical contacts [8–13]. Surface coatings like diamond-like carbon, titanium nitride, graphite-like carbon, tantalum, and Mo-Se-C coatings have been found to effectively reduce friction in the boundary lubricated contacts [14–17]. The oils with low viscosities have also been used to reduce the friction in hydrodynamic lubrication [18–22]. All the above-mentioned methods are the classical popular dints to reduce frictional energy loss in lubricated contacts. In recent decades occurred the new hydrodynamic lubrication technology by using the boundary slippage to improve the load-carrying capacity but reduce the friction coefficient of the hydrodynamic lubricated contacts [23–27]. It revises the moving velocities of the fluid film adjacent to a solid surface and changes the fluid flow rate through the contact. By

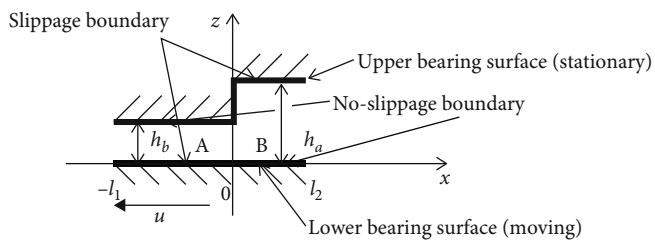

Figure 1: Hydrodynamic step bearing with designed wall slippage [42]. (A) Fluid outlet zone, (B) fluid inlet zone, and (u) moving speed.

designing the boundary slippage on specific surfaces such as on the stationary surface in the inlet zone or on the moving surface in the outlet zone or both of them, the performance of a hydrodynamic lubrication including the friction reduction can indeed be very effectively improved.

Hydrodynamic lubricated bearings are the important apparatus to support the load and reduce the friction coefficient in rotating machinery. Their energy conservation is a critical subject both in the research and in the production development. The classical method for reducing the friction coefficient and improving the energy efficiency of these bearings is to use the low-viscosity lubricant and the lubricant additives [4–7, 18–22, 28]. However, for the condition of heavy loads and high sliding speeds, the technical benefits of these methods seem very limited. In contrary, the boundary slippage technology is particularly suitable for these operating conditions because of its generated large lubricant film load-carrying capacity.

The wall slippage was found to occur in a hydrodynamic journal bearing long time ago [29, 30]. It was interpreted as the result of the shear stress exceeding the capacity of the adhering layer-fluid interface in a normal hydrodynamic journal bearing and found to pronouncedly reduce the load-carrying capacity of the bearing [29–31]. On the other hand, the friction coefficient of the bearing is significantly increased [31, 32]. Thus, the interfacial slippage in a normal hydrodynamic bearing made of steel, which is oilphilic, deteriorates the overall performance of the bearing.

The wall slippage was found to very easily occur in micro-/nanofluidics such as carbon nanotubes, which are hydrophobic [33–37]. With the reduction of the nanopore radius, the wall slippage more easily occurs [38]. By using the interfacial limiting shear strength model, Wang and Zhang satisfactorily explained this phenomenon [39]. The wall slippage can largely increase the water flow rate through carbon nanotubes [5–9]. In hydrophilic nanopores, the wall slippage was not detected, and the water flow rate through the nanopores is significantly reduced. These indicate that the wall surface property of a nanopore, which is hydrophobic or hydrophilic, can change the liquid flow rate in the nanopore. This indeed provides a strong indication for designing the hydrodynamic bearing by applying the wall slippage. Bronshteyn and Kreiner and Tung and Gao [2, 3] actually noticed the influence of the surface property on the carried load of a hydrodynamic journal bearing.

By using the slip length model, Salant and Fortier [40, 41] numerically showed that the wall slippage on the stationary surface in the bearing inlet zone can significantly increase the hydrodynamic pressure and carried load of a three-dimensional hydrodynamic journal bearing. The mechanism of this bearing performance improvement is that the flow rate into the bearing inlet zone is increased due to the occurring wall slippage, and for maintaining the flow continuity, the magnitudes of the pressure gradients as well as the pressures in the bearing must be increased. This also provides the indication that the wall slippage occurring on the moving surface in the bearing outlet zone can also pronouncedly increase the pressures and carried load of a hydrodynamic bearing, as it follows the same principle by reducing the flow rate out of the bearing outlet zone. The study by Zhang [42] on a hydrodynamic step bearing proves this wall slippage effect.

The wall slippage appears to be a promising technical dint for designing the energy-conserved hydrodynamic lubrication in the condition of heavy loads and high sliding speeds. The present paper reviews the impressive researches in recent years on hydrodynamic lubrication by applying the wall slippage to improve the bearing performance. This work can help to elucidate some critical points in the wall slippage, summarize the vital design principles for the bearings by applying the wall slippage, and give the direction in the future research in this area.

2. The Wall Slippage Model

In fluid mechanics, the flow velocity discontinuity on the solid surface indicates the occurrence of the wall slippage, and it shows the relative sliding between the adsorbed boundary layer and the solid surface. Consequently, the wall slippage is reasonably understood as the result of the shear stress exceeding the shear stress capacity of the adsorbed boundary layer-solid surface interface. The popularly used "slip length" is a fictitious concept and has no substantial physical meaning [43]. The slip length model was shown to be not reliable for evaluating the performance of a hydrodynamic bearing with interfacial slippage [44]. In contrast, the interfacial limiting shear strength model is physically reasonable for explaining the wall slippage, and it is expressed by

$$\begin{aligned} u &= u_{\text{solid}}, \text{ for } |\tau| < \tau_s, \\ u &\neq u_{\text{solid}}, \text{ for } |\tau| \geq \tau_s, \end{aligned} \tag{1}$$

where u is the velocity of the adjacent layer on the solid

surface, u_{solid} is the speed of the solid surface, τ is the shear stress, and τ_s is the maximum endurable shear stress, i.e., shear strength of the adsorbed boundary layer-solid surface interface.

In designing the hydrodynamic bearing, the hydrophobic or oilphobic coating needs to be covered on the stationary surface in the bearing inlet zone so that the slippage can very easily occur on this coating. In this case, the slippage occurs on the adsorbed boundary layer-bearing surface interface, not on the adsorbed boundary layer-fluid interface. If the bearing surface separation is no less than one hundred times of the thickness of the adsorbed boundary layer, the adsorbed boundary layer can be ignored, and the wall slippage can be considered as occurring on the fluid-bearing surface interface [45]. This is usually the case for the hydrodynamic bearing with the designed artificial wall slippage.

In a thrust slider bearing or a journal bearing, the hydrodynamic pressures are not so high so that τ_s can be considered as independent on the pressure. This is also the case in the inlet zone of a hydrodynamic line contact. Thus in the theoretical research, it should be taken that τ_s = constant.

3. Hydrodynamic Bearings with the Designed Wall Slippage

3.1. Hydrodynamic Step Bearing. Figure 1 shows the hydrodynamic step bearing where the wall slippage is designed, respectively, on the stationary surface in the inlet zone and on the moving surface in the outlet zone. Principally, this step bearing is advantageous over the step bearing with the wall slippage only on the stationary surface in the inlet zone or only on the moving surface in the outlet zone. However, this mode of step bearing should satisfy the following conditions:

$$\lambda_\tau < 2U - \frac{1}{r_h^2}, \tag{2}$$

$$\lambda_\tau + G(\psi)(1+\psi) < 1, \tag{3}$$

$$\phi_\tau > 1 + \frac{G(\psi)}{r_h}\left(1 + \frac{1}{\psi}\right), \tag{4}$$

where $\lambda_\tau = \tau_{sa}/\tau_{sb}$, $U = u\eta/(\tau_{sb}h_a)$, $\psi = l_1/l_2$, $r_h = h_a/h_b$, $\phi_\tau = \tau_{sa,A}/\tau_{sb}$, and

$$G(\psi) = \frac{3(U - (\lambda_\tau/2))\psi r_h^3 - (3/2)r_h\psi}{(1+\psi r_h^3)(1+\psi)}. \tag{5}$$

Here, u is the sliding speed; η is the fluid bulk viscosity; τ_{sa} is the shear strength of the fluid-stationary surface interface in the inlet zone; $\tau_{sa,A}$ is the shear strength of the fluid-stationary surface interface in the outlet zone; τ_{sb} is the shear strength of the fluid-moving surface interface; h_a and h_b are the surface separations in the inlet and outlet zones, respectively; and l_1 and l_2 are the widths of the outlet and inlet zones, respectively. The results show that the increase of the load-carrying capacity of the step bearing by the designed wall slippage in Figure 1 can reach 200%~400%, while the reduction of the friction coefficient of the bearing by the wall slippage can be 50%~85% [42]. For the same load, by using the wall slippage, the frictional heating power in the bearing can also be reduced by 50%~85%. The energy conservation of the step bearing in Figure 1 is thus very obvious. Equations (2)–(5) show that the energy-conserved bearing in Figure 1 can be realized in the condition of high sliding speeds and heavy loads. For achieving the most pronounced technical effect of the wall slippage, the value of r_h may be as small as below 1.1 [42]. λ_τ must be less than unity. Both the reductions of λ_τ and τ_{sa} strengthen the beneficial effect of the wall slippage. The stationary surface in the inlet zone should at best be the most hydrophobic or oilphobic. It can be realized by covering the most hydrophobic or oilphobic coating on the stationary surface in the inlet zone. Developing the ultrahydrophobic or oilphobic materials is of great importance to the energy conservation in the bearing, and it should be put as an important research task in the following time. Both the stationary surface in the outlet zone and the whole moving surface should be hydrophilic or oilphilic.

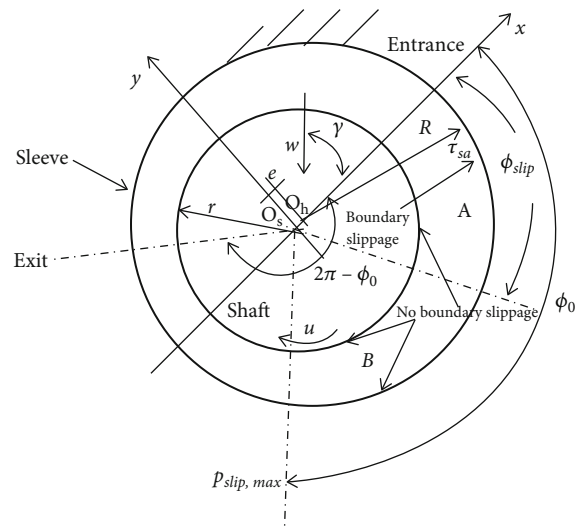

Figure 2: Energy-conserved hydrodynamic journal bearing with the wall slippage on the stationary sleeve surface in the inlet zone [26].

3.2. Hydrodynamic Journal Bearing. Figure 2 shows the energy-conserved hydrodynamic journal bearing where the wall slippage is designed on the stationary sleeve surface in the bearing inlet zone. The principle of the improvement of the performance of the hydrodynamic journal bearing by the wall slippage is the same with that of the thrust slider bearing. It should be satisfied that $\phi_{\text{slip}} \le \phi_0$, where ϕ_{slip} is the envelope angle of the wall slippage zone and ϕ_0 is the angular coordinate of the location where the maximum hydrodynamic pressure occurs as shown in Figure 2. It was found that this energy-conserved journal bearing is suitable for $\varepsilon \le 0.28$ [26]. As related to the eccentricity ratio, the optimum

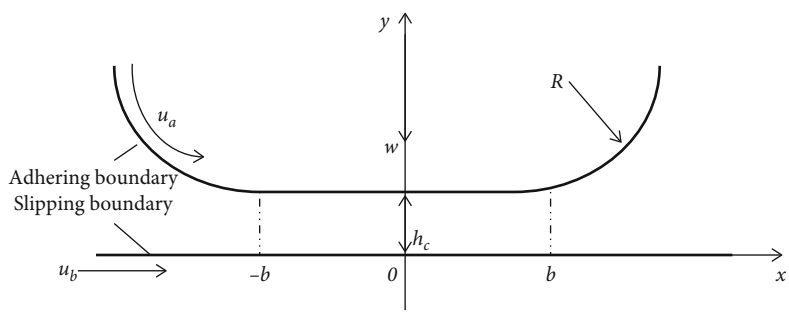

Figure 3: Energy-conserved hydrodynamic line contact, $u_a > u_b$ [27].

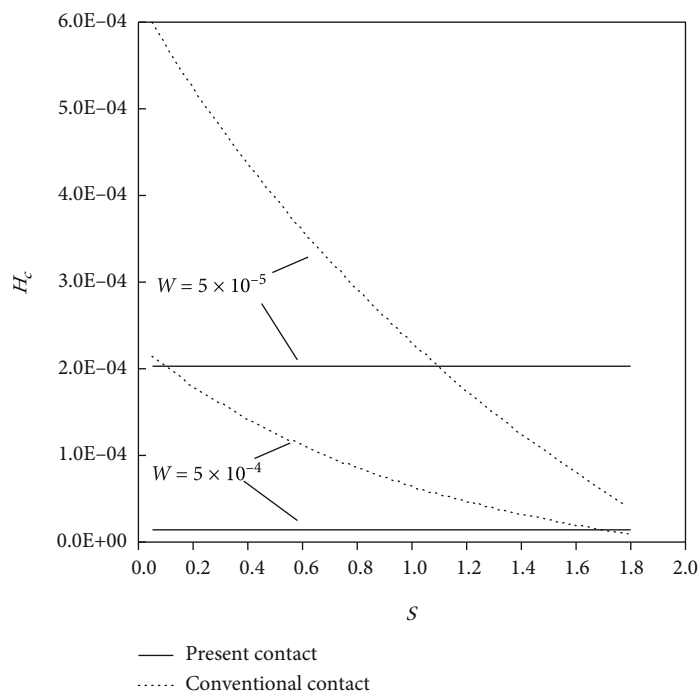

Figure 4: Comparison of the values of the dimensionless surface separations at the contact center, respectively, for the present line contact and the conventional line contact (without any wall slippage) for the same loads, $U_a = 1 \times 10^{-9}$ and $G = 4500$. Slide-roll ratio: $S = 2(u_a - u_b)/(u_a + u_b)$ [27].

value of ϕ_{slip} for the strongest wall slippage effect was given as [27]

$$\phi_{\text{slip,opt}} = -540\varepsilon^2 + 410\varepsilon + 46, \tag{6}$$

where $\phi_{\text{slip,opt}}$ is in degree. If $\phi_{\text{slip}} < \phi_{\text{slip,opt}}$, both the hydrodynamic pressure and carried load of the bearing are increased with the increase of ϕ_{slip}, while the value of the shear strength τ_{sa} of the fluid-sleeve surface interface in the inlet zone should be as lowest as possible. This relies on the application of the highly hydrophobic or oilphobic coating. The increase of the load-carrying capacity of the journal bearing in Figure 2 by the wall slippage can be nearly 100%, while at the same time, the reduction of the friction coefficient of the bearing by the wall slippage can be more than 60% [26]. The same amount is conserved for the frictional power in the bearing if the load is the same. This technical effect can be achieved when τ_{sa} is low. Although Zhang's analytical derivation [26] is for the two-dimensional hydrodynamic journal bearing as shown in Figure 2, these obtained results can also be implemented to the three-dimensional journal bearing by incorporating the side leakage effect. The detailed condition for the formation of the energy-conserved hydrodynamic journal bearing in Figure 2 can be found from Ref. 26. It was shown that this energy-conserved journal bearing is easily realizable for the condition of high sliding speeds and heavy loads [26].

3.3. Hydrodynamic Line Contact. Figure 3 shows the energy-conserved hydrodynamic line contact where on the faster moving surface, there is no wall slippage while on the whole slower moving surface, there is the wall slippage with the low fluid-contact surface interfacial shear strength τ_{sb}. This contact is subject to the condition $u_a > u_b$. If τ_{sb} approaches to zero, the dimensionless surface separation H_c at the contact

center is solved from the following equation [27]:

$$-0.2041\left(\lg \frac{W}{H_c}\right)^2 + 0.8876 \lg \frac{W}{H_c} + \lg\left(6.0954 G U_a\right) - 1.5 \lg W - 1.2725 = 0,$$

$$\text{for } 0.01 \le \frac{W}{H_c} \le 200, \tag{7}$$

where $H_c = h_c/R$, $W = w/(E'R)$, $U_a = u_a\eta_a/(E'R)$, and $G = \alpha E'$. Here, h_c is the dimensional surface separation at the contact center, R is the equivalent curvature radius of the two contact surfaces, w is the load per unit contact length, E' is the equivalent Young's elastic modulus of the two contact surfaces, u_a is the circumferential speed of the faster moving surface, η_a is the fluid bulk viscosity in the ambient condition, and α is the fluid viscosity-pressure index [27]. It was shown that when τ_{sb} approaches to zero, the friction coefficients on both the two contact surfaces approach to vanishing [27]. The wall slippage effect on the friction reduction and energy conservation in this line contact is thus very significant. By covering an ultrahydrophobic or oilphobic coating on the slower moving surface, it can be realized that τ_{sb} approaches to zero. Due to the wall slippage, the load-carrying capacity of this line contact is significantly increased for large slide-roll ratios and medium and heavy loads when τ_{sb} is very low. It is more pronounced when u_a is higher. Figure 4 shows the comparison of the dimensionless surface separations at the contact center, respectively, for the present line contact and the conventional line contact (without any wall slippage) for the same loads. This energy-conserved hydrodynamic line contact can occur in gear contacts such as planet gear systems, where $u_b = 0$.

4. Surface Coatings for Setting the Wall Slippage

Preventing or designing the wall slippage on specific surfaces in the hydrodynamic lubricated area relies on the use of the hydro-/oilphilic coatings or the hydro-/oilphobic coatings. The more hydro-/oilphobic the covered surface coating, the more pronounced the wall slippage, and the more significant the improvement of the performance of hydrodynamic lubrication. In contrary, the more hydro-/oilphilic the surface coating, the more reliable the prevention of the wall slippage, which is also required in the design of hydrodynamic lubrication with wall slippage. Besides the well-known hydrophobic materials such as polytetrafluoroethylene (PTFE), carbon, and grapheme, in recent decades, we noticed some impressive super hydro-/oilphobic coatings being used for enhancing the wall slippage such as octadecyltrichlorosilane [46], n-alkyl monolayers [46], silane [47], polydopamine coating [48], and fluoroalkylsilanes [49]. The hydro-/oilphilic materials like silica, silicon nitride, silicon carbonized, and γ alumina as well as steel can be used to prevent the wall slippage in a hydrodynamic lubrication. In the future, ultrahydro-/oilphobic coatings and ultrahydro-/oilphilic coatings should be the development directions for manufacturing reliable hydrodynamic lubricated contacts with a good performance improved by the wall slippage.

5. Conclusions

Energy-conserved hydrodynamic thrust slider and journal bearings as well as energy-conserved hydrodynamic lubricated gears by applying the wall slippage are reviewed. Typically, the wall slippage is designed on the stationary or slower moving surface in the hydrodynamic inlet zone. The wall slippage on the moving surface in the hydrodynamic outlet zone can give additional beneficial effects. By the inlet wall slippage, the flow rate into the hydrodynamic contact is increased, or by the outlet wall slippage, the flow rate out of the hydrodynamic contact is reduced. For maintaining the flow continuity, the magnitudes of the pressure gradients as well as the hydrodynamic pressures must be increased in the whole hydrodynamic contact. Thus, the carried loads of the bearing or the gear contact are correspondingly increased. On the other hand, the wall slippage effect reduces the friction coefficient of the hydrodynamic contact. The designed bearing or gear contact with the wall slippage is therefore energy-conserved. Different from the classical energy conservation method such as using low-viscosity lubricants or lubricant additives, which are not very suitable for high speeds and heavy loads, the present mentioned energy-conserved bearings or gear contacts are realizable particularly for high sliding speeds and heavy loads.

The main technical issue and the future research task are to develop highly or ultrahydrophobic or oilphobic coatings which can be covered on the steel bearing or gear surfaces. In recent years, a few of such coatings have been developed, but their applications are still not seen. Besides these, the design principles of these bearings or gear contacts need to be further complemented by considering more realistic factors such as the thermal and surface roughness effects.

Data Availability

The data reported in this paper will be available from the corresponding author with reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest with this research.

References

[1] O. Pinkus and D. F. Wilcock, *Strategy for Energy Conservation through Tribology*, Technical report, TID-28175 USA, 1977.

[2] L. A. Bronshteyn and J. H. Kreiner, "Energy efficiency of industrial oils," *Tribology Transactions*, vol. 42, no. 4, pp. 771–776, 1999.

[3] S. C. Tung and H. Gao, "Tribological characteristics and surface interaction between piston ring coatings and a blend of energy-conserving oils and ethanol fuels," *Wear*, vol. 255, no. 7-12, pp. 1276–1285, 2003.

[4] C. J. Reeves, P. L. Menezes, M. R. Lovell, and T. C. Jen, "The size effect of boron nitride particles on the tribological performance of biolubricants for energy conservation and sustainability," *Tribology Letters*, vol. 51, no. 3, pp. 437–452, 2013.

[5] Y. Gu, X. Zhao, Y. Liu, and Y. Lv, "Preparation and tribological properties of dual-coated TiO_2 nanoparticles as water-based lubricant additives," *Journal of Nanomaterials*, vol. 2014, Article ID 785680, 8 pages, 2014.

[6] L. Kerni, A. Raina, and M. I. Ul Haq, "Friction and wear performance of olive oil containing nanoparticles in boundary and mixed lubrication regimes," *Wear*, vol. 426, pp. 819–827, 2019.

[7] C. J. Reeves and P. L. Menezes, "Evaluation of boron nitride particles on the tribological performance of avocado and canola oil for energy conservation and sustainability," *International Journal of Advanced Manufacturing Technology*, vol. 89, no. 9-12, pp. 3475–3486, 2017.

[8] K. Yamaguchi, Y. Takada, Y. Tsukuda, M. Ota, K. Egashira, and T. Morita, "Friction characteristics of textured surface created by electrical discharge machining under lubrication," *Procedia CIRP*, vol. 42, pp. 662–667, 2016.

[9] C. Y. Chen, C. J. Chung, B. H. Wu et al., "Microstructure and lubricating property of ultra-fast laser pulse textured silicon carbide seals," *Applied Physics A*, vol. 107, no. 2, pp. 345–350, 2012.

[10] D. Z. Segu, S. G. Choi, J. H. Choi, and S. S. Kim, "The effect of multi-scale laser textured surface on lubrication regime," *Applied Surface Science*, vol. 270, pp. 58–63, 2013.

[11] V. Kumar, S. C. Sharma, and K. Narwat, "Influence of microgroove attributes on frictional power loss and load-carrying capacity of hybrid thrust bearing," *Industrial Lubrication and Tribology*, vol. 72, pp. 589–598, 2020.

[12] A. Usman and C. W. Park, "Modeling and simulation of frictional energy loss in mixed lubrication of a textured piston compression ring during warm-up of spark ignition engine," *International Journal of Engine Research*, vol. 18, no. 4, pp. 293–307, 2017.

[13] C. Y. Chen, B. H. Wu, C. J. Chung et al., "Low-friction characteristics of nanostructured surfaces on silicon carbide for water-lubricated seals," *Tribology Letters*, vol. 51, no. 1, pp. 127–133, 2013.

[14] H. A. Ching, D. Choudhury, M. J. Nine, and N. A. Osman, "Effects of surface coating on reducing friction and wear of orthopaedic implants," *Science and Technology of Advanced Materials*, vol. 15, no. 1, article 014402, 2014.

[15] C. Donnet and A. Grill, "Friction control of diamond-like carbon coatings," *Surface and Coatings Technology*, vol. 94, pp. 456–462, 1997.

[16] S. Yazawa, I. Minami, and B. Prakash, "Reducing friction and wear of tribological systems through hybrid tribofilm consisting of coating and lubricants," *Lubricants*, vol. 2, no. 2, pp. 90–112, 2014.

[17] J. Caessa, T. Vuchkov, T. B. Yaqub, and A. Cavaleiro, "On the microstructural, mechanical and tribological properties of Mo-Se-C coatings and their potential for friction reduction against rubber," *Materials*, vol. 14, no. 6, p. 1336, 2021.

[18] D. E. Sander, C. Knauder, H. Allmaier, S. D. Baleur, and P. Mallet, "Friction reduction tested for a downsized diesel engine with low-viscosity lubricants including a novel polyalkylene glycol," *Lubricants*, vol. 5, no. 2, p. 9, 2017.

[19] P. Carden, C. Pisani, J. Andersson et al., "The effect of low viscosity oil on the wear, friction and fuel consumption of a heavy duty truck engine," *SAE International Journal of Fuels and Lubricants*, vol. 6, no. 2, pp. 311–319, 2013.

[20] S. Park, Y. Cho, K. Sung, and N. Han, "The effect of viscosity and friction modifier on fuel economy and the relationship between fuel economy and friction," *SAE International Journal of Fuels and Lubricants*, vol. 2, pp. 72–80, 2010.

[21] J. Sorab, S. Korcek, C. Brower, and W. Hamm, *Friction reducing potential of low viscosity engine oils in bearings*, SAE Technical Paper 962033, 1996.

[22] R. Fein, "Water-based phosphonate lubricants," 1980, US Patent 4215002.

[23] M. Tauviqirrahman, A. Pratama, J. Jamari, and M. Muchammad, "Hydrodynamic lubrication of textured journal bearing considering slippage: two-dimensional CFD analysis using multiphase cavitation model," *Tribology in Industry*, vol. 41, no. 3, pp. 401–415, 2019.

[24] E. Alinovi and A. Bottaro, "Apparent slip and drag reduction for the flow over superhydrophobic and lubricant-impregnated surfaces," *Physical Review Fluids*, vol. 3, no. 12, article 124002, 2018.

[25] S. Ismail and M. Sarangi, "Effects of texture shape and fluid–solid interfacial slip on the hydrodynamic lubrication performance of parallel sliding contacts," *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 228, no. 4, pp. 382–396, 2014.

[26] Y. B. Zhang, "An improved hydrodynamic journal bearing with the boundary slippage," *Meccanica*, vol. 50, no. 1, pp. 25–38, 2015.

[27] Y. B. Zhang, "Hydrodynamic lubrication in line contacts improved by the boundary slippage," *Meccanica*, vol. 49, no. 3, pp. 503–519, 2014.

[28] S. Kennedy and L. D. Moore, "Additive effects on lubricant fuel economy," *SAE Transactions*, vol. 96, pp. 681–691, 1987.

[29] L. Rozeanu and L. Snarsky, "The unusual behaviour of a lubricant boundary layer," *Wear*, vol. 43, no. 1, pp. 117–126, 1977.

[30] L. Rozeanu and N. Tipei, "Slippage phenomena at the interface between the adsorbed layer and the bulk of the lubricant: theory and experiment," *Wear*, vol. 64, no. 2, pp. 245–257, 1980.

[31] Z. L. Xie, N. Ta, and Z. S. Rao, "The lubrication performance of water lubricated bearing with consideration of wall slip and inertial force," *Journal of Hydrodynamics*, vol. 29, no. 1, pp. 52–60, 2017.

[32] J. Yan, X. Jiang, Y. Zhu, and Y. B. Zhang, "An analysis for a limiting shear stress effect in a hydrodynamic step bearing. Part I. First mode of boundary slippage for film breakdown," *Journal of the Balkan Tribological Association*, vol. 20, pp. 259–270, 2014.

[33] M. Majumder, N. Chopra, R. Andrews, and B. J. Hinds, "Enhanced flow in carbon nanotubes," *Nature*, vol. 438, no. 7064, p. 44, 2005.

[34] J. K. Holt, H. G. Park, Y. Wang et al., "Fast mass transport through sub–2-nanometer carbon nanotubes," *Science*, vol. 312, no. 5776, pp. 1034–1037, 2006.

[35] X. C. Qin, Q. Yuan, Y. Zhao, S. Xie, and Z. Liu, "Measurement of the rate of water translocation through carbon nanotubes," *Nano Letter*, vol. 11, no. 5, pp. 2173–2177, 2011.

[36] R. R. Nair, H. A. Wu, P. N. Jayaram, I. V. Grigorieva, and A. K. Geim, "Unimpeded permeation of water through helium-leak-

tight graphene based membranes," *Science*, vol. 335, no. 6067, pp. 442–444, 2012.

[37] L. Wang, R. Dumont, and J. M. Dickson, "Nonequilibrium molecular dynamics simulation of water transport through carbon nanotube membranes at low pressure," *Journal of Chemical Physics*, vol. 137, no. 4, article 044102, 2012.

[38] E. Secchi, S. Marbach, A. Niguès, D. Stein, A. Siria, and L. Bocquet, "Massive radius-dependent flow slippage in carbon nanotubes," *Nature*, vol. 537, no. 7619, pp. 210–213, 2016.

[39] M. Wang and Y. B. Zhang, "Water transport through hydrophobic micro/nanoporous filtration membranes on different scales," *Membrane and Water Treatment*, vol. 13, pp. 313–320, 2022.

[40] R. F. Salant and A. E. Fortier, "Numerical analysis of a slider bearing with a heterogeneous slip/no-slip surface," *Tribology Transactions*, vol. 47, no. 3, pp. 328–334, 2004.

[41] A. E. Fortier and R. F. Salant, "Numerical analysis of a journal bearing with a heterogeneous slip/no-slip surface," *ASME Journal of Tribology*, vol. 127, no. 4, pp. 820–825, 2005.

[42] Y. B. Zhang, "Boundary slippage for improving the load and friction performance of a step bearing," *Transactions of Canadian Society for Mechanical Engineers*, vol. 34, no. 3-4, pp. 373–387, 2010.

[43] P. G. de Gennes, "On fluid/wall slippage," *Langmuir*, vol. 18, no. 9, pp. 3413-3414, 2002.

[44] Y. B. Zhang, "Review of hydrodynamic lubrication with interfacial slippage," *Journal of the Balkan Tribological Association*, vol. 20, pp. 522–538, 2014.

[45] W. Lin, J. Li, and Y. B. Zhang, "Mass transfer in the filtration membrane covering from macroscale, multiscale to nanoscale," *Membrane and Water Treatment*, vol. 13, pp. 167–172, 2022.

[46] M. Chinappi, F. Gala, G. Zollo, and C. M. Casciola, "Tilting angle and water slippage over hydrophobic coatings," *Philosophy Transactions of Royal Society A.*, vol. 369, no. 1945, pp. 2537–2545, 2011.

[47] D. Gentili, G. Bolognesi, A. Giacomello, M. Chinappi, and C. M. Casciola, "Pressure effects on water slippage over silane-coated rough surfaces: pillars and holes," *Microfluidics and Nanofluidics*, vol. 16, no. 6, pp. 1009–1018, 2014.

[48] J. Chen, Z. Luo, P. Dong et al., "Slippage on porous spherical superhydrophobic surface revolutionizes heat transfer of non-Newtonian fluid," *Advanced Materials*, vol. 9, no. 34, article 2201224, 2022.

[49] S. Suzuki, A. Nakajima, M. Sakai et al., "Rolling and slipping motion of a water droplet sandwiched between two parallel plates coated with fluoroalkylsilanes," *Applied Surface Science*, vol. 255, no. 5, pp. 3414–3420, 2008.