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# LUBRICANTS FOR FRICTIONAL PAIRS IN AUTOMOTIVE SYSTEMS: A REVIEW OF REQUIREMENTS AND CURRENT INVESTIGATIONS

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**ABSTACT**: It's well known that the performances of current technology oils are no longer sufficient to meet the increasing requirements of automotive lubricated systems. Innovative nanosized based additives could effectively act as friction modifier media in boundary and mixed lubrication regime through their unique behaviours at interfacial scale. Great expectations are also addressed towards the distinctive properties of the ionic liquids as lubricant media. They could likely replace some current technology additives such as detergents, anti-oxidants, anti-wear additives. The selection of appropriate lubricant additive is in an initial state, and more experimental research in physical and tribological properties are necessary.

**Keywords**: automobile lubricants, additives, friction losses, lubrication regimes, driveline fluids

## 1. INTRODUCTION

A set of mechanical subsystems properly coupled to transmit the power provided from engine to wheels is defined driveline, drivetrain, or simply transmission (Figure 1). The study of driveline in vehicle engineering has been receiving rising interest because of its great influence on vehicle dynamics, performance and fuel consumption [1].

A brief description about the role of each main subsystem is provided in this section.

- **Clutch** - The clutch main function, which is also the least demanding one, is interrupting torque flow between engine and gearbox during gear shifts. The heaviest operating condition, instead, is the vehicle launch. These functions have to satisfy three critical requirements: capacity of transmitting the maximum engine torque, engagement and disengagement smoothness characteristics, minimum torsional vibration.

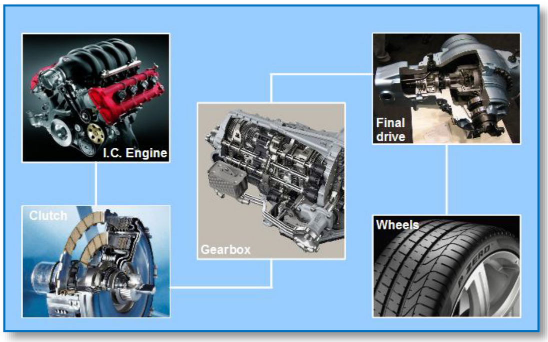

**Figure 1**. Main subsystems of a driveline.

- **Gearbox** - This subsystem allows adapting the torque provided by the engine and transmitted through the clutch according to the requirements of the traffic conditions, driving style, manoeuvres, etc.
- **Final drive** - When the vehicle runs along a curved path, inner wheels have to rotate with different angular speed respect to outer wheels to avoid tire sliding on the road. Differential and final drive accomplish such a requirement.
- **Wheels** - Vehicle wheels are supporting bodies through the tyres but also propulsion bodies. Vehicle drive wheels receive the power from final drive through driveshafts and allow vehicle motion.

For developing their functions each subsystem combine simple and complex kinematic pairs. So the drivetrain should be considered as a set of tribological systems [2]. Each tribological system involves wear phenomena, friction and lubrication request as well as mechanical efficiency. Nowadays several research groups are focusing their attention on driveline mechanical losses aiming at increasing the system mechanical efficiency and allowing beneficial effects on vehicle reliability.

## 2. DRIVELINE FRICTION LOSSES

Friction, the resistance to motion, has been a challenging phenomenon for mankind throughout history in all sectors. Nowadays a considerable amount of energy is still being dissipated by frictional losses in the transportation [3-6]. Considerable effort is being devoted to producing increasingly energy efficient vehicles, not only for economic reasons, but also to meet the requirements for reduced $CO_2$ emissions arising from the Kyoto Protocol on climate change.

A recent study [3] presents a method for evaluating the global energy consumption due to friction and potential savings from friction reduction in these vehicle types. Obviously, the authors also focus on driveline power losses by comparing them with the global vehicle friction losses. They take into account passenger cars as case study for two reasons. One is that passenger cars form the greatest consumer of energy and also generate a considerable part of the greenhouse emissions. The second one is that the energy use in passenger cars has been much studied from the system to component level. So, other types of vehicles are excluded from their analysis. The work is based on the current set of technical solutions for passenger cars.

Defining an “average” passenger car in “average” operation is the first important task. For simplicity and clarity and with the main purpose of providing the reader only orders of magnitude about fuel energy dissipation as well as friction loss distribution, the typical four stage of the driving cycle (idle running, acceleration, constant speed, braking) are not separately analysed [4]. Instead, average values for friction losses during passenger car operation are used with the assumption of a global average passenger car. The main technical details of this fictitious vehicle and the main average operating features are given in the below table.

**Table 1**. Global average passenger car and global average operational conditions [3,4]

| Assumed global average passenger car, year 2000 | | Assumed global average operational conditions | |
|---|---|---|---|
| Feature | Value | Feature | Value and unit |
| Weight | 1500 kg | Annual mileage | 13000 km |
| Engine capacity | 1.7 $dm^3$ | Velocity | 60 km/h |
| Maximum engine power | 75 kW | Road conditions | Average-road, no inclination |
| Engine configuration | Four cylinders in line | Influence of wind | No contribution of wind |
| Type of fuel | 70% gasoline, 30% diesel | Average $CO_2$ emissions | 200 g/km |
| Drag coefficient, Cw | 0.345 | Average $CO_2$ emissions for fuel liter | 2.5 kg/liter fuel |
| Projected frontal area | 2.3 $m^2$ | Average fuel consumption | 8 l/100 km |
| Ideal rolling resistance of tires | 0.013 (new tires on paved road) | Average engine output power | 12 kW |
| Rolling resistance of tires | 0.02 (age 4 years, with average tire pressure on average-road) | Fuel efficiency at 12 kW power | 300 g/kWh |
| Engine oil grade | SAE 5W40 (age < 1 year) | Average braking power | 2.4 kW |
| Gearbox oil grade | SAE 75W-90 (age 10 years, usually never exchanged) | Engine oil temperature | 80 °C |
| Equipment | Hydro mechanical power steering, air condition with compressor in 25% of the car fleet, manual 5-speed gearbox, front wheel drive, driving brakes based on friction, standard summer tires 185/65R15 with an average of 4 year | Gearbox oil temperature | 60 °C |

The first result of this analysis based on collected available information was that the fuel potential energy is dissipated through the following mechanisms and percentage rates (Figure 2).

- 33% (30–37%) exhaust gases, mainly as thermal energy, and dissipated by convection (also includes gases of lower energy content that exit through the exhaust manifold/piping);
- 29% (25–33%) cooling, which is heat dissipated by conduction through the engine structure, the cooling radiator (and oil cooler), and occasionally the car heating system, and further dissipated to the environment;

- 38% (33–40%) converted into mechanical power to overcome air drag and friction losses [1]. This part can be split into:
  - 5% (3–12%) air drag, including both external and internal air flow resistance, as well as losses in the electrical and indoor cooling system.
  - 33% frictional losses (Figure 2).

The share of fuel energy lost in friction can be subdivided in different groups (Figure 3):

- 35% (12–45%) rolling friction in the tire–road contact;
- 35% (30–35%) friction in the engine system;
- 15% (7–18%) friction in the transmission system;
- 15% (10–18%) friction in the brake contact, even outside from braking operations.

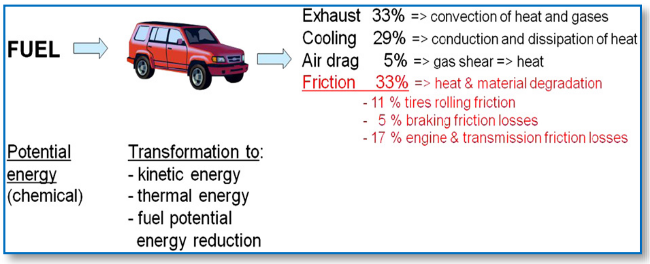

**Figure 2**. Fuel energy dissipation in passenger cars, as approximated for a speed of 60 km/h [1]

The fuel energy dissipated in the transmission system (the present analysis assumes a manual 5-speed gearbox with rolling bearings on all main shafts) can be classified as shown below:

- 20%, viscous losses (VL) in the oil tank, gear contacts, synchronizers, and bearings;
- 55%, friction in gears (EHDSR);
- 20%, friction in bearings (EHDR);
- 5%, friction in seals, forks, etc. (ML).

Based on extensive research on tribological contacts and lubrication mechanisms, especially during the last 40 years, nowdays there is a good understanding of how various contacts can be classified, and what level of frictional resistance they typically represent [2].

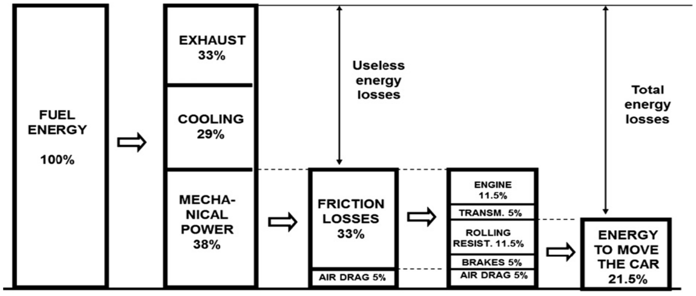

**Figure 3**. Breakdown of passenger car energy consumption [4].

Viscous losses (VL) in transmission systems are shear and churning of oil in the transmission case. The viscous losses are included in this study because, even if they are not directly friction losses, these losses can be reduced by tribological solutions resulting in lubricants with lower viscosity and thus also lower viscous losses.

Elastohydrodynamic lubrication [2] in sliding-rolling contacts (EHDSR) can occur in gearings. Elastohydrodynamic in rolling contacts (EHDR), instead, can occur in ball-and-roller bearings. Mixed lubrication [3] (ML) usually dominates in contacts with seals, forks, etc.

The Authors of the paper [3] also discuss in their study about possible future technical solutions for global friction reduction and they provide a graph shown below (Figure 4) based on available information and their own experience.

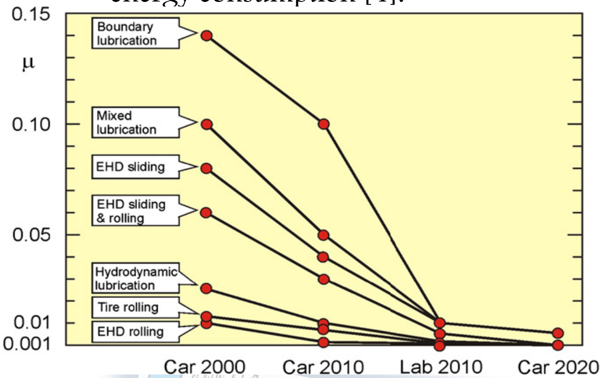

**Figure 4**. Trends in the reductions in coefficients of friction in four-passenger-car category for different lubrication mechanisms and for rolling friction. "Car 2000" is a typical 10-year-old car in use today according to [3].

The most positive trends about reduction in coefficients of friction are linked to the advances in different lubrication mechanisms which can occur in tribological systems of a transmission. It's true that EHD lubrication mechanism can occur in many drivetrain tribological systems, as shown above, but only under appropriate operating conditions. It is known that nearly all drivetrain components (engine, transmission, and axle components such as gears, bearings, pistons and rings, cams and followers, etc.) generally operate in the mixed lubrication regime. In a mixed lubrication interface, there are both hydrodynamic lubrication in the areas where the surfaces are separated, and boundary lubrication at locations of surface asperity contact. Typically, both are significant and, therefore, the total friction is the integration of both hydrodynamic friction and boundary friction over the entire domain. In engineering practice, there are three primary means of minimizing friction in this type of interface [5]:

- (1) in boundary lubrication, by reducing contact sliding friction through improved boundary film performance in the interfacial regions (use of low friction materials, coatings, and friction modifier additives);
- (2) in mixed lubrication, by reducing the percentage of solid to solid contact and optimization of operating conditions and surface topography (optimization of design and surface finish);
- (3) in hydrodynamic or elasto-hydrodynamic lubrication, reducing hydrodynamic friction by improving lubricant rheological properties and surface design (improved lubrication techniques, lubricants, and surface textures).

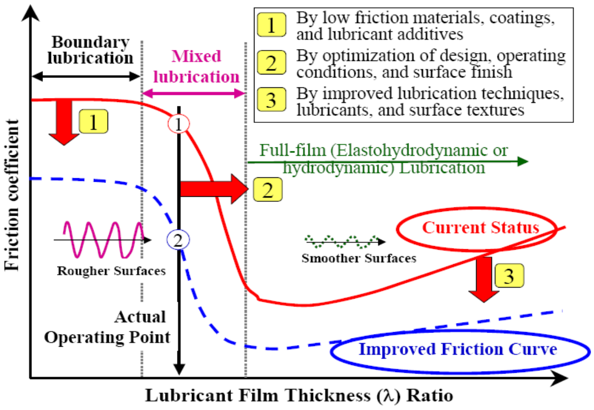

**Figure 5**. Stribeck curve (solid red line) and potential Stribeck curve (dashed blue line) benefiting by innovating technologies

The impact of these methods can be visualized by evaluating the effect of each on the Stribeck curve of friction as a function of the lubricant film thickness ratio, illustrated in Figure 5.

## 3. TRANSMISSION LUBRICANTS AND ADDITIVES

As described in the previous section, lubricating oil influences the gearbox efficiency through complex superposition of friction shares about the different lubrication regimes. Nevertheless increasing the efficiency is only one of transmission oil requirements. In general not only the oil viscosity has to be properly chosen but also other properties have to be accurately optimized to get high performance from the gearbox use over time. These properties are listed below, referring to mineral oils with proper additives which nowadays are widely used in vehicle transmissions. Since the performance of these mineral oils is no longer sufficient to meet the more demanding requirements of customers, for several years the research has focused on development of synthetic gear oils with higher performance characteristics compared to mineral oil-based products but they are still little used.

- Capability of reducing friction between moving parts.
- Capability of forming a lubricant film between the contacting surfaces that can withstand the toughest load conditions.

When the lubricant film is not strong enough to prevent contact between metal and metal, the result is heavy stress and excessive wear of the gear teeth.

- High cooling power.

Due to the rolling and sliding effect, the pressure between meshing teeth generates heating that can reach high temperatures.

- Sufficient tackiness.

To prevent the lubricant from being thrown outside by the centrifugal force.

- Capability to protect metal parts from corrosion.

This requirement is not very important in the case of gears enclosed in casings or in oil bath as in a vehicle gearbox. Nevertheless also in a gearbox, water may be present. Gear and lubricating oils should be used with a low water content because a high water content, especially free water, creates corrosion problems.

- Sufficient fluidity and handling features at minimum operating temperatures.

At low temperatures the fluidity of lubricants tends to decrease, therefore, at starting the teeth remain without lubrication until the oil regains the necessary fluidity due to the heat caused by friction. The lowest temperature at which an oil still flows is defined “pour point”.

- Adequate viscosity also at maximum operating temperatures.

The viscosity of lubricating oils varies with the changing temperature and must be suitable for the maximum operating temperatures in order to ensure constant lubrication.

- Appropriate resistance to load and shock stresses.

The lubricant must ensure protection of the surfaces also in the event of sudden overloads.

- Appropriate anti-foam power.

This is a particularly important requirement in the case of forced lubrication. The foaming behaviour depends on different factors, highlighting the base oil and its additivation. For an effective elimination of occluded air by mechanical energy of transmission trains, oil injection flows and other phenomena it is normally used anti-foam additives. Mineral oils have a very good solubility of additives (anti-wear and extreme-pressure mainly). Additives are chemical compounds which are added to base oils (or to base fluids in general) with the purpose of supplementing, improving or giving them some special characteristics. In most cases, a number of additives or additive packages are used to achieve the desired effect. Possible additives of a transmission oil are listed below (Figure 6).

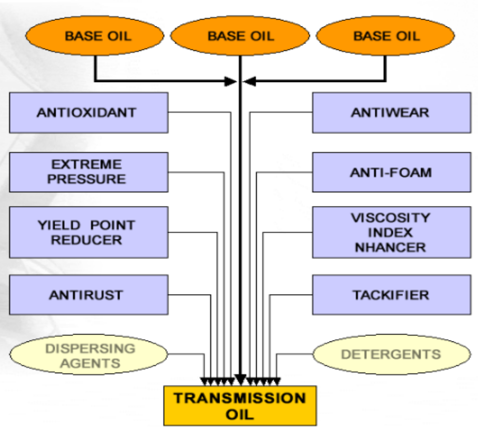

**Figure 6**. Transmission oil additives, current technology

» **Antioxidant**

To prevent the incorporation of oxygen in the oil. They react chemically with the oxygen, even before it touches the oil, forming harmless soluble compounds in the oil.

» **Antiwear**

To reduce mechanical wear. They melt at relatively low temperature filling and levelling, then solidifying the grooves on metal surfaces to improve the contact between moving parts.

» **Extreme pressure**

To prevent sticking and consequent jerking between surface roughness of moving parts. They chemically react at high temperature with the surface roughness of moving parts, locally forming substances with low friction coefficient and aiding the shearing of peaks rather than uneven and violent jerking.

» **Anti-foam**

To prevent the stable formation of foam in the oil owing to the inclusion of gas. They reduce the interfacial tension between the bubbles of gas and the oil, so that the gas bubbles formed in the oil group into larger bubbles and thus reach the free surface quicker and dissolve in the air.

» **Yield point reducer**

To lower the temperature at which the oil loses its fluidity. They act on the paraffin crystals, which form in the oil by cooling; surrounding them, they slow down the formation of the crystalline lattice, which prevents the oil from running.

» **Viscosity index enhancer**

To make the oil viscosity less sensitive to changes in temperature. The polymers inserted in an oil base, considerably increase hot viscosity without changing cold viscosity much. Therefore the oil to which a viscosity enhancer has been added has a less steep and a little higher viscosity-temperature curve than the base oil curve.

» **Antirust**

To prevent corrosion from attacking metal alloys. They prevent the development of acid substances or form protective layers on metal surfaces.

» **Tackifier**

To give the oil anti-drip and antispray features. They considerably improve the ability of the oil to adhere to the parts to be lubricated.

Several studies on synthetic gear oils performances have been made so far. A recent report [7] describes the advantages of modified polyalphaolefines for gearboxes, respect to the mineral oils. The most important advantages are about:

» Viscosity-Index and air release behaviour
» Low temperature behaviour
» Oxidation Stability
» Low residue formation and self-cleaning behaviour
» Foaming behaviour
» Optimised additive amount and solubility
» Bearing protection

## 4. NANOPARTICLE ADDITIVES AND IONIC LIQUIDS AS BREAKTHROUGH ADDITIVES

### 4.1 Solid nanoparticles

Nanoparticle additives could be blended with base oil as effective friction modifiers. The incessant literature dispute on the interfacial mechanism introduced by nanoparticles as friction reducer in boundary regime finds in the following list the more convincing physical explanations: rolling-sliding “rigid” motions together with flexibility properties [8], nanoadditive exfoliation and material transfer to metal surface to form the so called “tribofilm” or “tribolayer” [9-10], electronic effects in tribological interfaces [11], surface roughness improvement effect or "mending" [12]; along with the more classical hypothesis of surface sliding on lower shear stress layers due to weak interatomic forces, valid also for micro-scale additives used from decades.

The inclusion of nanoparticles as viscosity modifier could be effective in the fully developed oil film regimes since they have higher viscosity and hence improve the load carrying capacity of fluid film bearings. Shenoy et al. [13] presented the effect of nanoparticle additive lubricants on the static performance characteristics of an externally adjustable fluid film bearing. Nair et al. [14] investigated the performance characteristics of hydrodynamic journal bearing with nanoparticle additive lubricants.

### 4.2 Ionic Liquids

On the others side, the discovery of ionic liquids (ILs) as high performance synthetic lubricants was initiated in 2001 and highlighted by Chemical & Engineering News [15,16]. In recent years, the publications on this topic have multiplied, either within academic journals or in the form of patents, implying widespread interest from both fundamental and industrial aspects. As research on tribological practices keeps growing, in the near future its mechanisms will be gradually illuminated and some technical bottlenecks will be tackled and overcome. This is dependent on the collective will of organic chemists to contribute to the area and more collaborative work between engineering scientists and chemists that can further improving their research for innovative engineering applications. The unique properties of room-temperature ionic liquids make them excellent lubricants [17]. Their pertinent physico-chemical characteristics include their negligible volatility, nonflammability, high thermal stability and high thermal conductivity, low melting point, and broad liquid range. In addition, ionic liquids are highly polar and miscible with water and with a number of organic solvents (aromatic, heterocyclic compounds, etc.). Their viscosity can be adjusted by selecting different lengths of the nonpolar alkyl side chain of the cation or different type of anion [18]. Indeed the intrinsic properties of ILs could likely avoid the use of some additives [19], such as: (1) detergents because ILs act as solvents, (2) anti-oxidants due to ILs' high thermal stability, (3) several anti-wear additives such as zinc butyl and octyl dithiophosphate (ZDDP) due to the formability of surface boundary films, although for several cases due to the corrosion, additives could be needed [20–22].

## 5. CONCLUSIONS

Nanoparticle additives could effectively act as friction reducer in boundary and mixed lubrication regime through several unique properties allowing rolling-sliding interfacial motions, nano-microscale flexibility, exfoliation and transfer to metal surface, surface roughness improvement effect. As novel additives for engineering lubricants the literature results clearly prove that nanoparticles in oil easily form protective deposited films to prevent the rubbing surfaces from coming into direct contact and, thereby, improve the efficiency of frictional automotive devices in wet regime.

Great expectations are also addressed toward the unique properties of the ionic liquids as excellent lubricants. Their intrinsic properties could likely avoid the use of some current technology additives such as detergents because ILs act as solvents, anti-oxidants due to ILs' high thermal stability, anti-wear additives such as zinc butyl and octyl dithiophosphate (ZDDP) due to the formability of surface boundary films. Of course, ionic liquids can be composed from a large number of cations and anions, with an enormous number of possible compounds. This means that searching for appropriate lubricants based on ILs is in an initial state, and more experimental research in physical and tribological properties are necessary.

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### References

[1.] Naunheimer H., Bertsche B., Ryborz J., Novak W., Automotive Transmissions, Fundamentals, Selection, Design and Application, Springer, 2011.

[2.] D'Agostino V., "Fondamenti di meccanica applicata alle macchine", Publ. Maggioli, 2013, in Italian.

[3.] Holmberg K., Andersson P., Erdemir A., Global Energy consumption due to friction in passenger cars, Tribology International, 2012, 47, 221-234.

[4.] Taylor, C.M., Automobile engine tribology – design considerations for efficiency and durability, Wear, 1998, 221, 1-8.

[5.] Plank R., New measures for reducing friction in the drive train, Schaeffler Symposium, 2010, 336-367.
[6.] Martini A., Zhu D., Wang Q., Friction Reduction in Mixed Lubrication, Tribology Letters, 2007, 28, 139-147.
[7.] Cabello E. C., Advantages of modified polyalphaolefines for gearboxes in wind power industry, LUBMAT Conference, June 2012.
[8.] Tevet, O., Von-Huth, P., Popovitz-Biro, R., Rosentsveig, R., Wagner, H.D., Tenne, R., Friction mechanism of individual multilayered nanoparticles, Proceedings of the National Academy of Sciences, 2011, 108, 19901–19906.
[9.] Sarno, M., Senatore, A., Cirillo, C., Petrone, V., Ciambelli, P., Oil lubricant tribological behaviour improvement through dispersion of Few Layer Graphene Oxide, Journal of Nanoscience and Nanotechnology, 2014, 14(7), 4960-4968.
[10.] Yadgarov, L., Petrone, V., Rosentsveig, R., Feldman, Y., Tenne, R., Senatore, A. Tribological studies of rhenium doped fullerene-like MoS2 nanoparticles in boundary, mixed and elasto-hydrodynamic lubrication conditions, Wear, 2013, 297, 1103–1110.
[11.] Altavilla, C., Sarno, M., Ciambelli, P., Senatore, A., Petrone, V. New 'chimie douce' approach to the synthesis of hybrid nanosheets of MoS2 on CNT and their anti-friction and anti-wear properties, Nanotechnology, 2013, 24, 125601.
[12.] Liu, G., Li, X., Qin, B., Xing, D., Guo, Y., Fan, R. Investigation of the mending effect and mechanism of copper nano-particles on a tribologically stressed surface, Tribology Letters, 2004, 17, 961-966.
[13.] Shenoy, B.S., Binu, K.G., Pai, R., Rao, D.S., Pai, R.S. Effect of nanoparticles additives on the performance of an externally adjustable fluid film bearing, Tribology International 2012, 45, 38-42.
[14.] Nair, K.P., Ahmed, M.S., Al-qahtani, S.T. Static and dynamic analysis of hydrodynamic journal bearing operating under nanolubricants, International Journal of Nanoparticles, 2009, 2, 251-262.
[15.] C. F. Ye, W. M. Liu, Y. X. Chen and L. G. Yu, Chem. Commun., 2001, 2244, Highlighted by C&Eng News, 2001.
[16.] Zhou, F., Liang, Y., Liu, W., Ionic liquid lubricants: designed chemistry for engineering applications, Chemical Society Reviews, 2009, 38, 2590–2599.
[17.] Pensado, A.S., Comunas, M.J.P., Fernandez, J., The Pressure–Viscosity Coefficient of Several Ionic Liquids, Tribology Letters, 2008, 31, 107–118.
[18.] Canongia-Lopes, J.N., Pàdua, A.A.H., Nanostructural organization in ionic liquids. J. Phys. Chem. B 110, 2006, 3330–3335.
[19.] Qu, J., Truhan, J.J., Dai, S., Luo, H., Blau, P.J.: Ionic liquids with ammonium cations as lubricants or additives. Tribology Letters, 2006, 22, 207–214.
[20.] Minami, I., Watanabe, N., Nanao, H., Mori, S., Fukumoto, K., Ohno, H., Improvement in the tribological properties of imidazolium-derived ionic liquids by additive technology. J. Synth. Lubr. 2008, 25, 45–55.
[21.] Uerdingen, M., Hilgers, C.: Ionic Liquids as New Lubricating Base Oils. Presented in 16th International Colloquium Tribology, Lubricants, Materials and Lubrication Engineering, Stuttgart, Ostfildern, Germany, 15–17 January 2008.
[22.] Uerdingen, M., Treber, C., Balser, M., Schmitt, G., Werner, C., Corrosion behaviour of ionic liquids. Green Chem., 2005, 7, 321–325.

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