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THE STRIBECK CURVE AND LUBRICATION CONDITIONS OF METALLIC AND POLYMERIC MATERIALS

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ABSTRACT
The present work discusses the selection of metallic and polymeric materials to be used as bearings in water lubricated condition. The study depends on using Stribeck curve to compare the friction performance of metallic materials (aluminium, bronze and steel) as well as polymeric materials (polyamide, polyethylene terephthalate, polymethyl methacrylate and polytetrafluoroethylene) in boundary, mixed and hydrodynamic regimes. Experiments were carried out to investigate the friction coefficient of the tested materials under variable loads and sliding velocity in water lubricated medium.

It was found that, using Stribeck curve can provide specific information about friction coefficient of lubricating sliding in the boundary, mixed and hydrodynamic lubrication regimes. The lubricating conditions were controlled by controlling sliding velocity and load. Bronze and steel showed lower friction values than aluminum. Generally, values of friction coefficient were relatively high due the weak lubricating property of water. PTFE displayed the minimum friction coefficient (0.02). This result confirms the recommendation of PTFE as bearing material. The minimum friction values experienced by PA 6 and PETP were 0.083 and 0.07 respectively. Those polymers can be recommended to be used as bearing material in water lubricating medium. Usage of PMMA as bearing material should be avoided due to its high friction values.

KEYWORDS
Stribeck curve, boundary, mixed, hydrodynamic conditions, water, metallic, polymeric materials.

INTRODUCTION
Machines are operated by using sealed oil drive system which has disadvantages such as environment pollution caused by leakage of oil. It is necessary to use fresh water and sea water as working fluids to protect environment. Compared with metals and ceramics, polymers and polymer based composites have good corrosion-resistant property and the ability of burying foreign particles such as wear particles or sand particles, and often have excellent tribological property. So they are widely used to produce water lubricated bearings and gears. In hydrodynamic lubricated engineering surfaces and journal

bearings during start-up, shutdown and low velocity operation it is necessary to apply suitable materials to avoid the asperities interaction in boundary and mixed lubrication regimes.

The relationship between the friction coefficient and the product of sliding speed and viscosity divided by the normal load is well known as the Stribeck curve. Stribeck originally developed this theory in the early 1900s to study friction as it relates to both sliding and rolling bearings [1 - 4]. As this theory is dependent on viscosity, relative velocity and normal load, it was a reasonable place to start for the study of friction at the interface of steel and a heated, commingled glass–polypropylene woven fabric. The Hersey number, H, sometimes referred to as the Stribeck number is a function of viscosity, η, speed, U, and normal load, F. Boundary lubrication is lubrication by a liquid under conditions where the solid surfaces are so close together that appreciable contact between opposing asperities is possible, [5, 6]. The friction and wear in boundary lubrication are determined predominantly by interaction between the solids and between the solids and the liquid. The bulk flow properties of the liquid play little or no part in the friction and wear behavior.

The friction and wear of copper rubbed against a hardened steel in steady friction were studied, [7 – 14]. The effects of load and sliding velocity were interpreted by the Stribeck curve and the transitions from elasto-hydrodynamic lubrication (EHL) to boundary lubrication (BL) region were analyzed. Reliable prediction of friction and wear behavior upon different lubricant conditions remains a major challenge in mechanical engineering design and exploitation. The Stribeck curve is widely used for identification of friction and wear in different lubrication regions. Each lubrication region is characterized by definite values of friction, wear and structural state of surface layers.

It was observed that the engineering Stribeck curves were extracted and analyzed, [15]. In addition, the characteristic lubrication regimes were identified in these curves, by evaluating changes in the coefficient of friction of the tribosystem in accordance with the observed wear mechanisms and weight track evaluation. It should be noted that Stribeck curves provide vital information on the limitations of each lubricant, in order to understand under which wear parameters (applied load, sliding speed) a lubricant can minimize the friction phenomena in a tribosystem.

Experiments were carried out to investigate the surface parameters such as waviness and roughness as well as solid lubricants and contaminants on the friction of sliding surfaces, [16 – 22]. A test rig was designed and constructed to test the behaviour of journals with wavy surfaces, the circumferential undulations being varied both in amplitude and in number. Results showed that wavy journal surfaces may well enhance the load carrying capacity of a bearing. Moreover, surface undulations are shown to move the journal centre locus closer to the load line, ie cause a lower attitude angle. These effects are found to be more pronounced with larger wave amplitudes, and with higher numbers of waves around the journal circumference. In general, friction is found to be reduced with increase in surface wave amplitude. In the presence of sand particles, solid lubricants displayed significant friction decrease. solid lubricants such as molybdenum disulphide (MoS2), graphite (C), polytetrafluoroethylene (PTFE), calcium hydroxide Ca(OH)2, and

polar additive {copper quinolinolate (CuC18H1202N2)} were used as solid lubricants. Performance tests were carried out using two disc machine. A comparison performance was conducted using Air Cleaner Fine Test Dust (ACFTD) as an abrasive contaminant. Besides, the possibility of polymeric powders as solid lubricants was investigated. Four common types, low density polyethylene (LDPE), high density polyethylene (HDPE), polytetrafluoroethylene (PTFE), and polymethyl methacrylate (PMMA) of (0 - 50 μm) particle size were used at concentration of 10 wt. %. In the presence of sand particles, Ca(OH)2 displayed the lowest friction followed by CMOC, MoS2 and C, while CMOC displayed the lowestwear followed by Ca(OH)2, MoS2 and graphite for grease free of sand particles. Addition of Ca(OH)2 significantly decreased the abrasive action of sand particles. LDPE displayed the highest friction coefficient followed by HDPE, PTFE then PMMA. Friction increase observed for LDPE may be attributed to its adhesion into the sliding surfaces. The lowest friction was observed for PMMA, where its particles rolled on the contact surfaces.

The general form of the Stribeck curve was used to detect the friction coefficient for raw fluid and nano-fluid with copper nanoparticles focusing on the effect of copper nanoparticles on the tribological behavior of the nano-fluid, [23]. It was observed that nano-fluid with copper nanoparticles achieves reduction of friction. Besides, the nano-fluids with copper nanoparticles have a lower friction coefficient, compared with the raw fluid. It is found that the lubrication regime of the raw fluid is the mixed lubrication regime, whereas the nano-fluid with copper nanoparticles is in the full-film lubrication regime. A positive effect of the copper nanoparticles on the lower friction coefficient is observed in the full-film and mixed lubrication regimes. Moreover, the copper nanoparticles are more effective in the mixed lubrication regime than in the full-film lubrication regime. It can be inferred that the copper nanoparticles affect the friction mainly under the mixed lubrication regime when the friction in the tribotester appears between the surfaces of specimens.

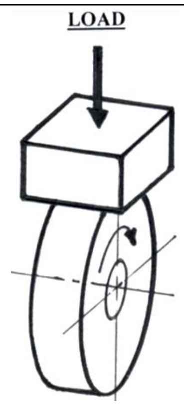
In the present work, the friction coefficient displayed by the sliding of metallic (aluminium, bronze and steel) as well as polymeric {polyamide (PA 6), polyethylene terephthalate (PETP), polymethyl methacrylate (PMMA) and polytetrafluoroethylene (PTFE)} test specimens against stainless steel lubricated by distilled water is investigated.

KEYWORDS
Stribeck curve, friction coefficient, metallic and polymeric materials, water.

EXPERIMENTAL

The friction experiments were performed under laboratory conditions (25° C temperature and 30 % humidity) using a block on ring rig, Fig. 1 assembled in Amsler testing machine. The details of the machine are shown in Fig. 2. The effects of sliding velocity and load on the friction coefficient of the tested material pairs were studied. Friction coefficient was determined by measuring the friction torque using a pendulum device, which is a part of Amsler machine. The sliding velocity was varied in the range of 0.4 – 1.2 m/s and the load was varied between 1.0 and 150 N. The fluid used in the experiments was distilled water of 0.894 mPa.s viscosity at 40°C. Water was supplied to

the contact area by gravity. The rings, of 40 mm diameter and 10 mm width, made from stainless steel {403S17(12 % Cr, o.5 Ni%, 1.0%, Mn, 0.8% Si)} slide against a block, in form of cube, of the metallic and polymeric tested materials (20 × 20 × 20 mm). The metallic materials were aluminium {BS 1490 LM 1 (Al 87 %, Cu 7%, Sn 3% and Zn 3%}, cast bronze {G – Bz 10 (90 % Cu and 10 % the rest, DIN 1705) of 600 N/mm2 hardness } and plain carbon steel {St. 34 (0.35 % C, DIN 1611) of 1500 N/mm2 hardness}. The polymeric were polyamide (PA 6), polyethylene terephthalate (PETP), polymethyl methacrylate (PMMA) and polytetrafluoroethylene (PTFE). The surface roughness of the test specimens that were finished by grinding was 0.7 µm Ra, while the roughness of the stainless steel ring was 0.17 µm Ra. The tested blocks were held in the stationary shaft, while stainless steel discs were assembled to the rotating shaft. Based on the analysis of the friction coefficient using fluid as well as water under different loads and sliding velocities, the Stribeck curves were presented for all tested materials.



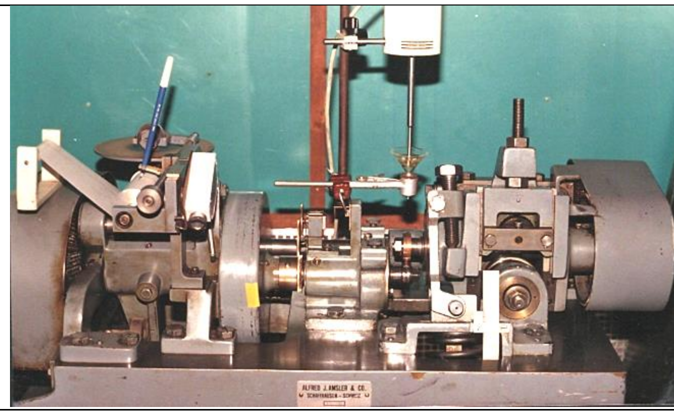


Fig. 1 Cube on ring test rig.	**Fig. 2 Amsler testing machine.**

RESULTS AND DISCUSSION

Based on friction experiments on fluid lubricated surfaces, Stribeck expressed the relationship between the friction coefficient, viscosity of the lubricating fluid [η], load [F], and velocity [U] in the Stribeck curve, Fig. 3. The curve illustrates the characteristics of various lubrication regions, including [I] boundary lubrication, [II] elastohydrodynamic lubrication (EHL), and mixed lubrication, [24, 25]. In hydrodynamic lubrication, the fluid completely isolates the friction surfaces, where the internal fluid friction alone determines tribological characteristics. In elastohydrodynamic lubrication, fluid viscosity and the elastic coefficient of the solid surface are the most dominant factors. In contrast, the boundary lubrication regime is mainly characterized by the facts that friction surfaces are in contact at microasperities, where hydrodynamic effects of lubricating fluid insignificantly influence tribological characteristics and the interactions in the contact between friction surfaces and between friction surfaces and the lubricant dominate tribological characteristics.

The results of friction coefficient displayed by metallic tested materials sliding against stainless steel are shown in Figs. 4 – 6. Friction coefficient displayed by aluminium sliding against stainless steel is illustrated in Fig. 4. It is clearly shown that at boundary lubrication, where the two surfaces mostly are in contact with each other even though a fluid is present friction coefficient values reached 0.5. The relative friction increase can

be attributed to the very low velocity therefore no pressure build up in the lubricant, where the load is carried by the asperities in the contact area. Characteristic for boundary lubrication is the absence of hydrodynamic pressure. As the sliding velocity and viscosity increase, or the load decreases, the surfaces will begin to separate, and a fluid film begins to form. The film is still very thin, but acts to support more of the load. The lubrication regime turns to mixed lubrication, where the load is carried by a combination of the hydrodynamic pressure and the contact pressure between the asperities of both surfaces. It is the intermediate region between boundary lubrication and hydrodynamic lubrication. friction coefficient decreases to its minimum value (0.12).

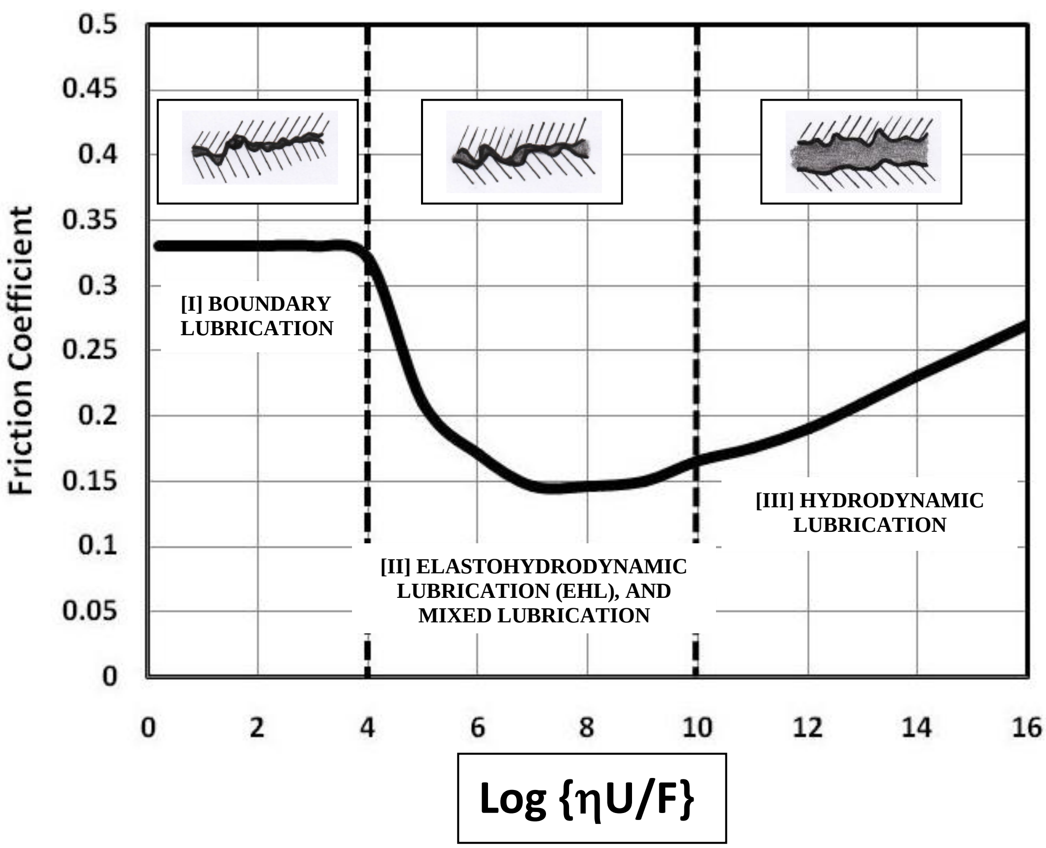


Fig. 3 The Stribeck curve showing the relationship between friction coefficient and Hersey number in log format.

The surfaces will continue to separate by a very thin water film, where elastohydrodynamic lubrication prevails and friction coefficient will reach its minimum. Further increase in velocity or decrease in load changes the sliding condition into hydrodynamic lubrication. At this point, the load on the interface is entirely supported by the fluid film. There is low friction and no wear in hydrodynamic lubrication since there is a full fluid film and no solid-solid contact. A significant friction increase in the hydrodynamic region is detected. This is due to fluid friction which increases with increasing the thickness of the fluid film. Higher sliding velocity may result in thicker fluid film, but it also increases the fluid friction on the sliding surfaces. It is observed that the values of friction coefficient are relatively high due the weak lubricating property of water.

Friction coefficient displayed by bronze sliding against stainless steel is shown in Fig. 5. At boundary condition the value of friction coefficient reached 0.43. Bronze displayed lower value for minimum friction coefficient (0.105) than aluminium. It seems that the good sliding property of bronze when sliding against stainless steel was responsible for that behaviour. The minimum value of friction depends on the asperities of the two sliding surfaces. The interaction of the contacting asperities leads to increased friction. In journal bearings during start-up, shutdown and low velocity operation it is necessary to apply suitable materials to avoid the asperities interaction.

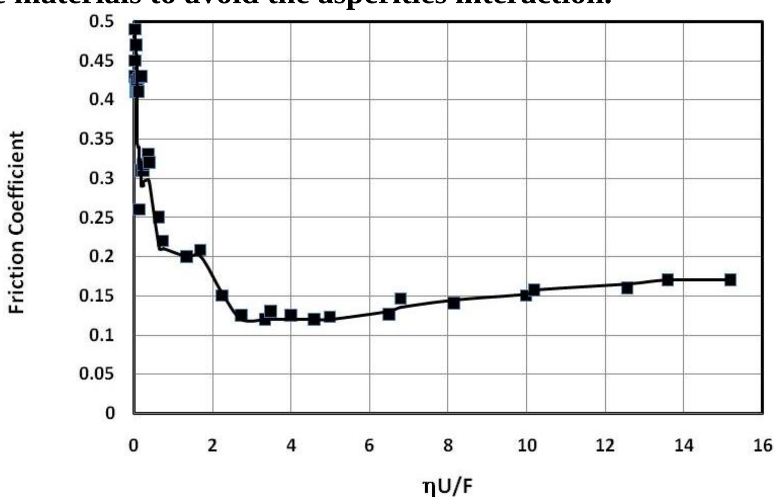


Fig. 4 Friction coefficient displayed by aluminium sliding against stainless steel.

Friction coefficient displayed by steel sliding against stainless steel, Fig. 6, showed relatively lower friction values than that observed for aluminium. The minimum friction value was the same for bronze. Based on that observation, it can be recommended to use those pairs in shaft and bearing for water lubricated.

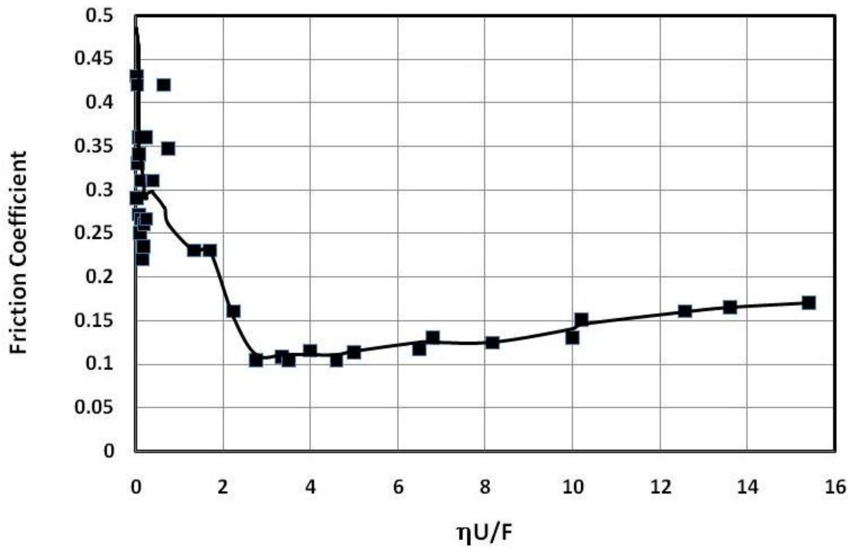


Fig. 5 Friction coefficient displayed by bronze sliding against stainless steel.

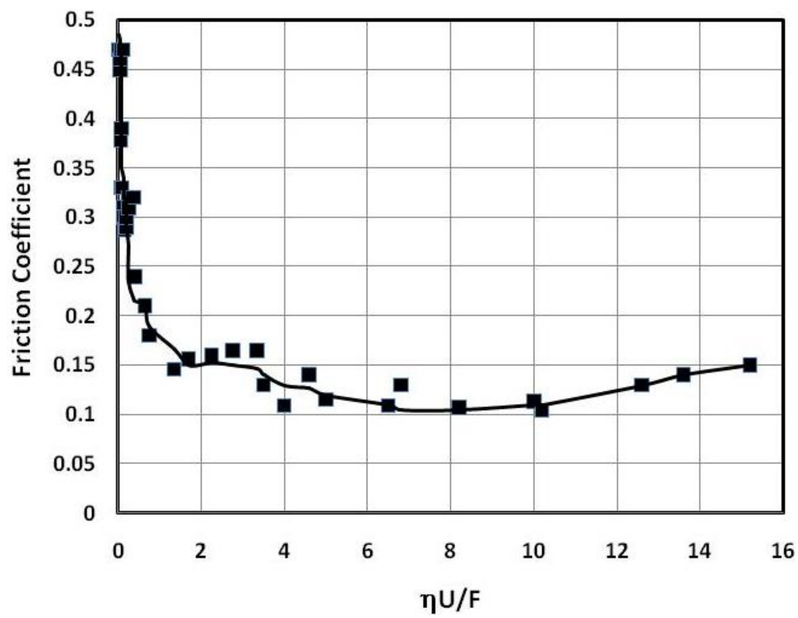


Fig. 6 Friction coefficient displayed by steel sliding against stainless steel.

The friction behaviour of polymeric materials is illustrated in Figs. 7 – 10. Friction coefficient displayed by polyamide sliding against stainless steel lubricated by water is shown in Fig. 7. The minimum friction coefficient value is 0.083 which is lower than that observed for the tested metallic materials. Besides, the friction values in the hydrodynamic zone are lower too. This behaviour indicates that friction drag between polyamide and water is lower than that experienced for metallic surfaces.

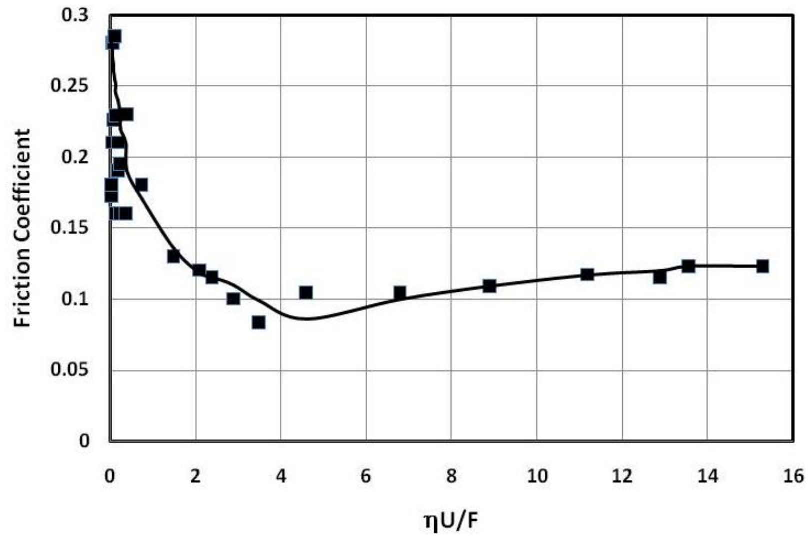


Fig. 7 Friction coefficient displayed by polyamide sliding against stainless steel.

Further friction decrease was observed for the sliding of polyethylene terephthalate sliding against stainless steel, where minimum friction coefficient value was 0.07, Fig. 8. The hydrodynamic performance of that polymer showed lower values than that observed for polyamide. This observation suggests the use of PETP to be used as bearing material in water lubricated application. PMMA showed relatively higher friction coefficient than PA 6 and PETP, Fig. 9. The friction behaviour of PMMA is similar to that displayed by aluminium. It seems that glassy polymers are not suitable to be used as water lubricated bearing materials.

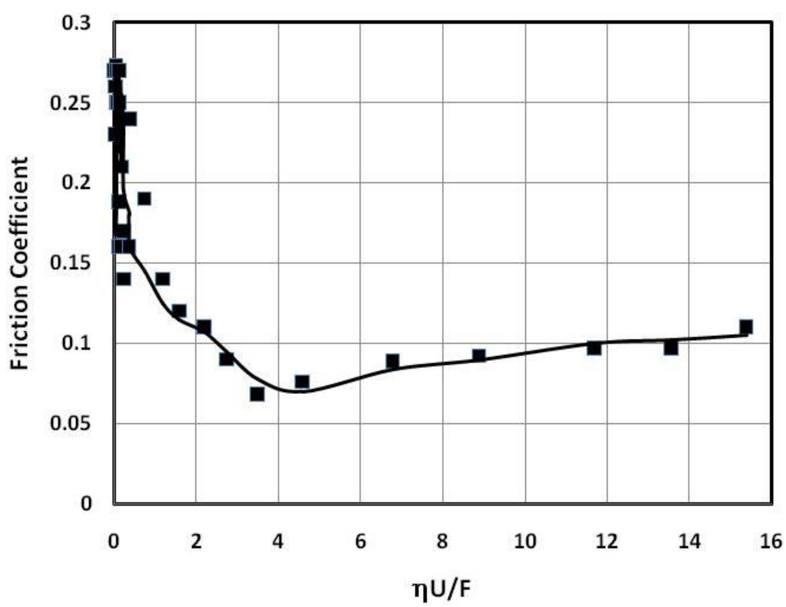


Fig. 8 Friction coefficient displayed by polyethylene terephthalate sliding against stainless steel.

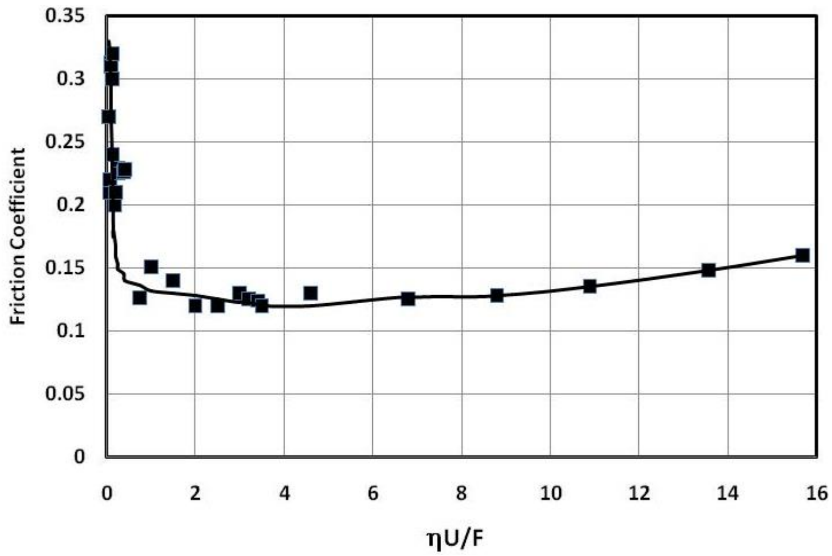


Fig. 9 Friction coefficient displayed by polymethyl methacrylate sliding against stainless steel.

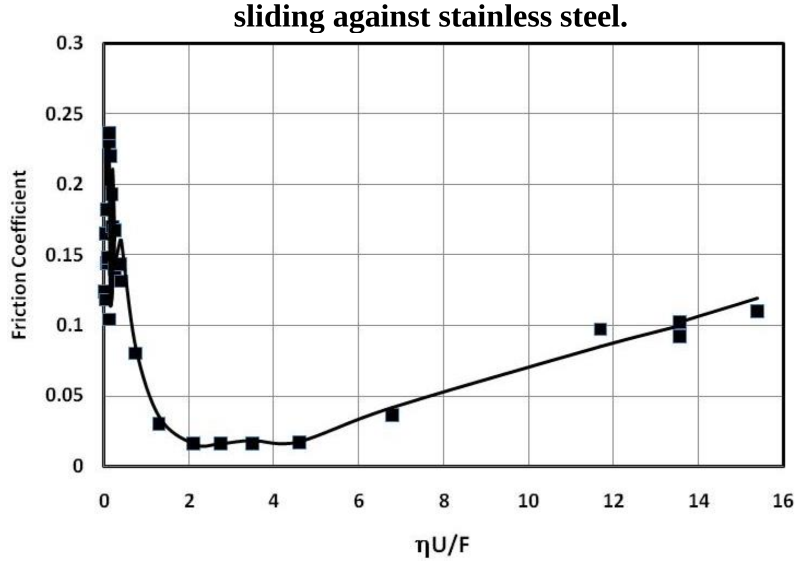


Fig. 10 Friction coefficient displayed by polytetrafluoroethylene sliding against stainless steel.

The best friction performance was displayed by PTFE, Fig. 10. The minimum friction value was 0.02. This result confirms the recommendation of PTFE as bearing material. It was believed that PTFE chips form and can be smeared onto the wear track, thus acting as solid lubricant. However, they are gradually removed from the contact interface, [26]. PTFE is an excellent self-lubricating material, [27 – 30]. It has very low friction coefficient and water absorption, excellent chemical stability in various corrosive environments. So it is considered as a potential friction material used in water, sea water and other aqueous environment.

CONCLUSIONS

1. Stribeck curve can give specific information about friction coefficient of lubricating sliding in the boundary, mixed and hydrodynamic lubrication regimes.

2. Among the metallic materials tested, bronze and steel showed the lowest friction values.

3. Values of friction coefficient are relatively high due the weak lubricating property of water.

4. The minimum friction (0.02) was displayed by PTFE. This result confirms the recommendation of PTFE as bearing material. The minimum friction values experienced by PA 6 and PETP were 0.083 and 0.07 respectively. Those polymers can be recommended to be used as bearing material in water lubricating medium.

5. PMMA showed relatively higher friction coefficient (0.12). Usage of PMMA as bearing material should be avoided.

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