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UNIVERSITI
TEKNOLOGI
MARA

Professorial Lecture UiTM

My Story of TRIBOLOGY

SALMIAH KASOLANG

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PENERBIT PRESS
UNIVERSITI TEKNOLOGI MARA

UiTM Press is a member of
MALAYSIAN SCHOLARLY PUBLISHING COUNCIL

Perpustakaan Negara Malaysia Cataloguing-in-Publication Data

Salmiah Kasolang
Professorial Lecture UiTM : My Story of TRIBOLOGY / Salmiah Kasolang.
ISBN 978-967-363-707-2
1. Tribology.
2. Bearings (Machinery).
3. Lubrication and lubricants
4. Government publications--Malaysia.
I. Title.
621.89

Cover Design : Siti Suhaini Mazlan
Typesetter : Zairuddin Sukardi

Printed in Malaysia by: UiTM Printing Centre
Faculty of Art & Design
Universiti Teknologi MARA
40450, Shah Alam
Selangor

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PREFACE

Tribology is closely connected to humans. Our very own self is a proof of tribology. The blood that runs in our veins, the air that keeps us alive with oxygen, the joints that support our movements, the skin that gives the pleasant look and sensation are only a few examples of studies in tribology. Beyond, from the time we wake up till the time we reside again in the comfort of the bed, we must have encountered a long list of tribology related concerns. The toothbrush and the way we brush our teeth, the soap and the effect on the skin, the comb and way we comb our hair, the cloth and the comfort of the materials, the shoes and the grip on the skin and the road surface as we walk are all studied in tribology. Tribology related technology is all around us and we use them every day for our convenience and improved quality of life. Transmission systems in transportation, fuels and the enhancers, the lubricants and additives, selection of materials and the coating technology, and the ergonomic aspect of designs are also of concerns in tribology. Further, on biomimetics, we start looking at masterpiece designs found in nature that can be mimicked for greater benefits of mankind. Lotus, roses, bees, swamp, whale, dolphin, bats and birds have all inspired some modern technology we use today.

My Story of Tribology is the debut of my unique quest of tribology crafted in the **Story of Tribology Series** launched in

December 2020 during my Professorial Lecture. My intention is to write about tribology in a synergy of technical and non-technical content. This somewhat offbeat voice is to merge the artfulness to teaching and learning with meanings beyond the technical contents. With the philosophy of national education serving as the foundation for delivering knowledge, this venture is self-aligned.

In this debut series, the proportion of technical is higher but slowly to be reduced in the coming series so that the non-technical content becomes the focal of discussion in creating meanings beyond the obvious of the physical representation. The synergy of four (4) domains in teaching and learning (cognitive, affective, psychomotor and spiritual) is desired and this is to create mindfulness of the Creator as clearly stated in the National Education Philosophy. Let us consider tribology when dealing with our lives and see the greatness of the Creator. Indeed, Tribology is GREEN by design.

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ACKNOWLEDGMENT

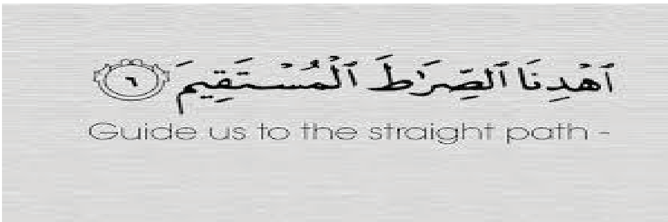
Alhamdulillah, *My Story of Tribology* has finally become a reality after a long pause since 2018. Thank you Allah for all the blessings coming in so many different forms; some through people and others through events, circumstances as well as unexpected means. May Your blessing and love shower our lives for eternity.

This book is a reminder of the journey I took earlier during my PhD work at the University of Sheffield supervised by Prof Dr Rob Dwyer-Joyce; the joy and pain intertwined partly shaping who I am today. This book also signifies my quest for new knowledge which I have extended through supervision of students via Final Year Projects and most importantly Research Work for Masters and PhD students. I thank you all very much.

To UiTM, this book symbolises the opportunity and help that I have received since my first recruitment on 16th of June, 1995. Thank you UiTM and the nation for investing in my development that enabled the journey to progress from a humble beginning as a young lecturer at Centre of Preparatory Studies UiTM (now INTEC International Education College) to what I am today, a Professor in Mechanical Engineering. I am humbled by all the blessings. I am so grateful to all my seniors and juniors who have helped me since my first day in UiTM.

To committee members of my professorial talk, and staff at Department of Mechanical Engineering UiTMCPP, thank you ever so much for making it a reality. Your determination and commitment have helped me complete this professorial book.

I am forever in debt to my late parents, Daeng Matutu and Daeng Matinno, my husband Ahmad Zamree Shaari, my sons and daughter, my siblings and all my friends who have supported me directly and indirectly throughout my journey this far. Thank you for the continuous prayers for me, given in open or silence. Finally, I would like to end with this prayer (we recite it 17 times daily in five prayers),



Chapter 1
Meanings of Tribology

INTRODUCTION

MOTION is key in mechanical engineering applications. Motion means ability to do useful work and most matters can be conditioned to be in a state of motion designed to suit the intended purposes and benefits set forth. In the study of Mechanical Engineering, students learn about rigid body and particle motion. They also learn about fluid mechanics to appreciate flows in pipes, open channels, rivers, dams and so forth. In thermodynamics, engineering students are exposed to the potential of heat transfer in creating useful work for systems in consideration. Therefore, in a state of motion and the creation of differences such as in kinetic and potential energy, engineering systems gain the ability to do useful work. But there is another side to motion. Motion is caused by the balance or imbalance of external forces acting on a body. When matters are in motion, there is a natural response of the system in the form of friction forces. In most instances, friction is undesirable and becomes a concern in engineering applications such as in machinery where interaction of machine components such as gears, journal bearing, and cams during motion is classified as *rubbing*. The study of rubbing in mechanical engineering is known as TRIBOLOGY.

IS TRIBOLOGY ABOUT TRIBES?

Because of the similarity in phonics, many people would associate tribology with the study of tribes when prompted with the word for the first time. In fact, this is a typical reaction received from even among those involved in engineering and science disciplines but new to Tribology. Similarly, there are many mechanical engineering students whom the author met have no idea of what tribology is about before taking tribology courses.

MAKING SENSE OF TRIBOLOGY

Let us see Tribology from the root of the word, -*TRIBOS* means rubbing in Greek while LOGY means study. Literally, Tribology means the Study of Rubbing. Now, how does that relate to mechanics? The subsequent discussion is to make sense why Tribology is considered under the mechanical engineering body of knowledge.

Rubbing is a form of motion that is very common in machine interactions. In mechanical engineering, machines and machinery constitute an important area of study. Responses to this so-called rubbing interaction between surfaces are friction, often unproductive and associated with losses in the form of wear and tear of the system. To combat friction and the subsequent wear problems, lubrication is then introduced to extend the life service of components, among others. Figure 1.1 shows the trilogy of tribology describing the main subsets important in of tribology study: Friction, Wear, and Lubrication.

In Jost's Report (1966), it is clearly stated that "Tribology is the science and technology of interacting surfaces in relative motion and of the practices related thereto."

Figure 1.1: Trilogy of tribology

It is simply unjust to talk about friction in tribology without referring to the work of Leonardo da Vinci (1452-1519). Bowden and Tabor (2019) included reference to the work of Leonardo in a book on friction and lubrication of solids published in 1950 where the work of Leonardo became more accessible by many. In a recent article entitled *Leonardo da Vinci's studies of friction* (Hutchings, 2016), Leonardo's work on friction has been extensively discussed and with tremendous amount of details (including drawings from Leonardo's notebook). Da Vinci once wrote that:

> *'friction produces double the amount of effort if the weight be doubled', and 'friction made by the same weight will be of equal resistance at the beginning of the movement though the contact may be of different breadths or lengths.' (Hutchings, 2016).*

Thanks to Hutchings for sharing much information on da Vinci's work on friction which many of those working in tribology have no access before. It is a fact that da Vinci was a man with many talents and his background is multi-disciplinary. The story of his life and achievements are described in a book, *The Flights of the Mind* a biography by Charles Nicholl published on 18 November 2004. His intriguing character and fascinating life have been made into a movie; The Da Vinci Code was a blockbuster in 2006. In short, da Vinci is one of the great minds of the world that is not to be missed. Anyone new to Tribology may start reading his early work and follow his thought process.

THE ECONOMIC IMPORTANT OF TRIBOLOGY

From the economic perspective, the impact of Tribology to the economy was first discussed in Jost's Report published in March 1966. The word Tribology was first coined and used in the report by a working group headed by Dr H. Peter Jost CBE (1921-2016). In 1964, the team was invited by the UK Department of Education and Science to investigate the state of lubrication education and research. In the report, the amount of potential saving by industry was estimated to be more than £500 million per year if an effective implementation of tribology solutions and practices are in place (Jost, 1966).

The losses (money, energy and materials) due to improper handling of tribology related issues in the relevant industries are tremendous. In an article published at the Tribology Laboratory Website of Lehigh University, it was reported that the estimated loss yearly due to ineffective tribological technique as well as wear and tear in automobiles were estimated to reach $800 billion and $10 billion respectively (Holmberg et al., 2012). To recognise the impact of Tribology on the US economy, the Bill (H. RES. 306) where resolutions on tribology matters have been passed in the House of Representative on May 2, 2017 during the 115th Congress (*GovTrack.us*., 2020). There are six resolutions passed to the House of Representative namely to:

1. recognise the impact of tribology on the United States economy and competitiveness;
2. recognise the important of tribology in providing solutions to critical technical problems in manufacturing, energy production and use, transportation vehicles and infrastructure, greenhouse gas emissions, defence and homeland security, health care, mining safety and reliability, and space exploration, among other sectors;
3. encourage federal agencies to develop and implement programs and projects related to tribology;
4. encourage the formation of public-private partnerships to advance fundamental research and accelerate the development of tribology-related products and technologies;
5. recognise the need for increased research and development investments in tribology and related fields; and
6. encourage the National Academy of Engineering to conduct a comprehensive survey of the status of research and development in academia and government laboratories and recommend a course of action to accelerate innovations in tribology.

In Malaysia, there has not been a readily available report or data on the impact of Tribology on the economy. The awareness of the mass on this issue is still low and more work is needed to push this matter to the authority. Perhaps, a learned society such as Malaysian Tribology Society (MYTRIBO) could coordinate a working group (industry, government, higher institutions etc) for this purpose. Because this has been an established practice in many developed countries such as in the US, UK and Japan, the chance it will work in Malaysia is high. Since MYTRIBOS is currently one of the member societies in the International Tribology Council (ITC), getting international help and advice is plausible.

HOW TRIBOLOGY AFFECTS OUR LIVES

There are more to tribology than just economic concern and it actually affects our lives profoundly. Where there is motion, there is tribology. Where do we see motion? Beginning with how we manage ourselves: combing hair, brushing teeth, applying soap or cream onto the skins, the act of walking and the damage on the shoes soles and the human joints; tribology in food preparation and washing of clothes as well as tribology in the clothing to begin with. The more obvious of tribology is in machinery and machine components found in engineering.

To reach different areas of tribology including the emerging topics, a convenient yet clever starting point is to refer to established tribology conferences websites where the conference focus or theme is described. Examples of established conferences are World Tribology Conference WTC (4-year), Asia International Conference on Tribology AsiaTRIB (4-year), International Conference on BioTribologyICoBT, and Malaysia International Tribology Conference MITC (2-year). Based on the WTC2017 in Beijing China, areas of conference focus were classified into eight categories as shown in Table 1.1. Each category is divided into subcategories. Consider for example Biotribology and Biomimetics, there are six other subcategories included.

Table 1.1: Facets of Tribology in one perspective from a conference focus of WTC2017, Beijing

Science of Tribology	Biotribology and Biomimetics
(a) Friction fundamental (b) Lubrication fundamental (c) Wear fundamental (d) Tribochemistry (e) Tribophysics (f) Nano-tribology (g) Superlubricity (h) Contact mechanics	(a) Lubricants and lubrication in biotribology (b) Artificial joints (c) Tribology of mouth (d) Hair and skin (e) Tactile (f) Biomimetic

Wear and Surface Engineering (a) Wear (b) Coatings (c) Texturing (d) Heat treatment (e) Surface modification (f) Surface exploration (g) Tribo-corrosion (h) Tribo-materials	Tribology in Manufacturing (a) Machining (b) Metal forming (c) CMP and surface processing (d) Remanufacturing (e) Advanced processing
Lubrication and Lubricants (a) Chemistry of lubricants (b) Rheology of lubricants (c) Solid lubricants (d) Liquid lubricants (e) Additives	Engine and Transmission Tribology (a) Engine (b) Fluid-film bearings (c) Rolling bearings (d) Gas bearings (e) Sealing (f) Gears (g) Tribology materials
Industrial Tribo-systems (a) Automotive tribology (b) Railway (c) Space and aerospace (d) Energy equipment (e) Heavy machinery (f) Green tribology (g) Hard disk drives and micro systems	Tribotest and Monitoring (a) Tribotest (b) Condition monitoring (c) Sensors and instruments (d) Data analysis and fusion (e) Tribotest system development

Biotribology and Biomimetics are relatively new areas in tribology (perhaps the terminology) though the ideology and practice have its root at least in the time of Leonardo Da Vinci (1452-1519) as his famous quote goes,

> *"Human subtlety will never devise an invention more beautiful, more simple or more direct than does nature because in her inventions nothing is lacking, and nothing is superfluous."* (Leonardo da Vinci Quotes, n. d.).

Two more quotes by Leonardo Da Vinci that relate to nature are

> "*Nature is the source of all true knowledge. She has her own logic, her own laws, she has no effect without cause nor invention without necessity," and "Nature never breaks her own laws."* (Leonardo da Vinci Quotes, n. d.).

One of the prominent contributions of Da Vinci is in human anatomy and he was reported to have dissected more than 30 corpses in his quest to understand the human body.

On the other hand, International Conference on BioTribologyICoBT offers a platform to the tribology community working specifically on Biotribology. For example, in ICoBT 2018, focus areas including emerging ones were included. Details of the areas covered in ICoBT2018 are as follows:

- Medical and industrial applications of biotribology
- Biomimetics: bio-inspired tribology; materials; complex fluids
- Biotribology testing and modelling: developing test methods; correlation with perception and customer experience; numerical methods
- Prosthetic implants: materials and coatings; implant corrosion; synovial joint tribology; explant analysis
- Articular cartilage: mechanical and biochemical induced damage; modelling; lubrication mechanisms
- Soft contacts: contact lenses; stents; bio-probes; cells and tissue interaction
- Skin and personal care: creams and cosmetics; shaving products; hair conditioners; wounds and wound healing,

haptics, tactile perception, toothpaste
- Oral and dental tribology: tongue-palate interaction; ’mouth-feel’; food texture; multi-phase flow, tooth and implant wear; fretting
- Biomaterials for tribology: artificial cartilage; meniscus; bio-scaffolds
- Tribology in sports: equipment design and development; preparation, deterioration and testing of sport surfaces; grip; player interaction and gait analysis

The list in ICoBT is more extended and deeper compared to the one in WTC and are more suited to those looking for a deeper and intense discourse in Biotribology and Biomimetics.

At the national level, Malaysian Tribology Society MYTRIBOS provides a venue for local tribologists to share and network. Though relatively young, founded in 2007, compared to tribology societies in other countries, MYTRIBOS has reached such a remarkable progress as commented by Prof Ali Eldemir, at a meeting during WTC2017 in Beijing. Prof Eldemir preceded Prof Jost as President of ITC upon the demise of him. MYTRIBOS has become a member society of ITC and hence, the President of MYTRIBOS is automatically recognized as the Vice President of ITC. This is a meaningful recognition for MYTRIBOS and has helped in increasing the international visibility. Currently, MYTRIBOS is one of the 39-member societies listed in the ITC website.

LEARN FROM THE GURUS

Who are the Tribology gurus? Since the word tribology was first coined in the UK, then it makes more sense to start with great tribologists such as the founding figures namely Prof Peter Jost CBE (1921-2016) and Prof Duncon Dowson. The author had the privilege to meet both gurus, Prof Dowson and Prof Jost, in person during 2007 Leeds-Lyon Tribology Conference in Lyon, France and during 2009 World Tribology Conference in Kyoto, Japan respectively. This year 2020, a new award called Peter Jost Tribology Award has been established by ITC to recognise great contributions in Tribology. Other notable tribology gurus are Prof Ian Hutchings, Prof David Tabor, Prof Frank Philip Bowden, Prof Kenneth Holmberg, Prof Jean Michel Martin, Prof Mark Robbins, Prof Kenneth Holmberg, Prof Rob Dwyer-Joyce, Prof Ian Sherrington, Prof Prof Kaji Kato, Prof Jianbin Luo, Prof Mitjan Kalin, Prof Phillipe Kapsa, Prof Hugh Spikes, Prof Michel Khonsari, Prof Bharat Bushan, Prof Harish Hirani, Prof SSV Ramakumar, Prof Masjuki Hassan, and Prof Ali Erdemir (currently the President of ITC) to name a few. In the President's report published in Tribology & Lubrication Technology TLT August 2016, Prof Erdemir wrote an article entitled "The passing of a legend" to honour the contribution made by Prof Jost to the progress in modern Tribology. Indeed, tribology is very dear to Prof Jost till the very end of his life. Other GURUs can be spotted through different platforms such as Google Scholar and Scopus (recognized by the citation and h-index), publications in reputable journals (typically in Q1 and Q2 journals), Executive Committees of Tribology Societies recognized in ITC, Outstanding Tribology Labs around the globe, Universities offering tribology courses and research work, and Relevant Industries associated with Tribology.

Historically, Tribology related concerns have existed long before the invention of sophisticated machineries in locomotives and other modern transportation such as trains, ships and aeroplanes. For example, the use of lubricant from animals or plants to facilitate motion by reducing friction was recorded since the time of Mesopotamia. It was reported that the wheeled vehicle was invented around 3500 BC in Sumeria, now Egypt. Leonardo da Vinci, who is famous for painting Monalisa, is considered the renaissance of modern tribology based on his various works related partly to tribology.

Extensive historical background can be found in 'The History of Tribology' (Dowson, 1979) written by Prof Dowson, one of the prominent Tribology GURUs in the UK. Like Prof Jost, Prof

Dowson's contribution to promoting and pushing the frontier of knowledge in Tribology is tremendous. Their continuous support and energy are exceptional and have inspired many young tribologists around the globe. In Malaysia, a justified reference for some early tribology work is those by the immediate past president of Malaysian Tribology Society MYTRIBOS, Prof Masjuki Hassan of University Malaya who had the privilege to study at the University of Leeds UK and in fact attended tribology lectures by Prof Dowson. There are other early local tribologists at public universities such as the late Prof Muhamed Dahlan Muhamed Ramli and Prof Mohamad Nor Berhan. They worked on bearings and brakes at UniversitiTeknologi MARA (UiTM). Both completed their PhDs in the UK as well.

CONCLUDING REMARKS

In a nutshell, tribology looks into ways to reduce friction in engineering systems in its quest to prolong service life of components and reduce losses and costs of operation and making related processes more efficient, productive, and cost saving. If the amount of estimated losses (with values reaching billion dollars) can be prevented and used for other productive initiatives, the extended impact is tremendous on industry, economy, national productivity and eventually quality of human life as a whole. The horizon of tribology is wider, and it affects our daily lives in so many ways as evident by the range of different areas considered under tribology. So, next time you do things, think about tribology and do it the Tribology way because by design, it is Green.

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Chapter 2

Journals Bearing Potentials

INTRODUCTION

Most people use a form of transportation every day to get from one location to another. But perhaps many, especially non-technical people, are not aware of one essential component in the transmission system of any vehicles. That component is called bearings. This chapter introduces one type of bearings known as journal bearing that relies on hydrodynamic lubrication to function properly. In rotating machinery, bearings offer three main functions. First, bearings enable relative motion between interacting surfaces and in doing so, reduce friction to some extent. Second, bearings also constraint motion of the rotating elements to remain in the casing or sleeve as designed. Third, with the support of bearings, rotating elements can carry load and transmit power. Bearings are essential components in turbomachinery (turbines, gas compressors, pumps, and motors), automotive, airplanes, trains, power plant, and household appliances. One requirement common across different bearing types is the presence of lubrication.

BEARING BASICS

Bearings come in different geometry and dimensions, but in general, there are three main categories of bearings namely of (a)

Plain Bearings, (b) Rolling Elements Bearings, and (c) Magnetic Bearings. They can be differentiated by the geometry and application requirements including the dominant forces (radial, axial, or combination) and typical operating conditions such as load, speed, and temperature. Plain Bearings, namely journal bearings and thrust pad bearings, share a common ground in that both types require the presence of hydrodynamic lubrication to properly function and hence often called hydrodynamic bearings. There are different types of hydrodynamic bearings typically found in engineering systems such as plain cylindrical, axial groove, tilting pad, pressure dam, four-lobe, offset pivot, and lemon bore (Salamone, 1984). Specific types are deployed to address specific requirements of intended engineering systems and applications and hence give the best or optimum performance possible.

HYDRODYNAMIC JOURNAL BEARING

Hydrodynamic Journal Bearing is a subset of Plain Journal Bearing. The focus of this chapter is the simple form of hydrodynamic journal bearing as depicted in Figure 2.1.

The shaft in the middle is the journal and the part enveloping the shaft is the bearing, which is also known as the bush. The housing or the sleeve is to support the journal bearing structure. Plain hydrodynamic journal bearing is often considered as having two main components with the presence of hydrodynamic lubrication which offers, metaphorically, a soul in order for the bearing to come alive and properly function.

In many applications, bearing is deployed to facilitate motion as per design requirements and in doing so, friction is reduced to an acceptable level. In an engine transmission system, plain bearings are used to allow linear motion of a piston in the combustion chamber into rotational motion of tyres that enables a car to travel from one point to another. Journal bearing is established between the connecting rod and the crankshaft.

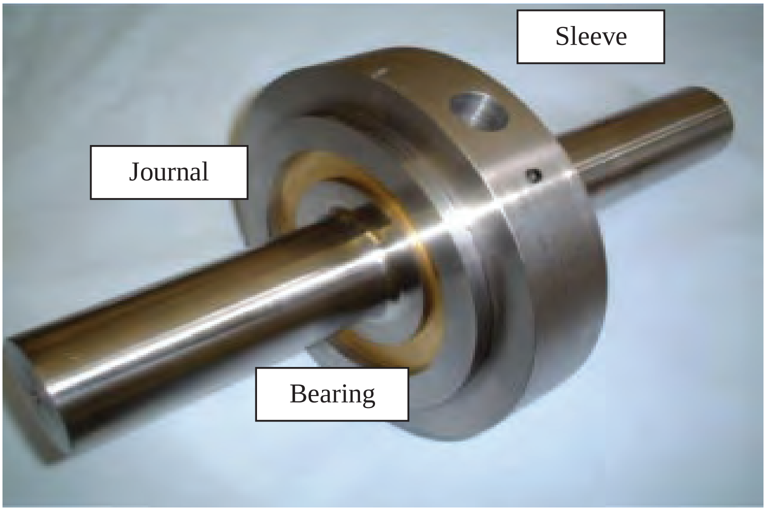


Figure 2.1: Assembly of hydrodynamic journal bearing

In Figure 2.2, the journal diameter (D), the bearing internal diameter (d) and length (L), and radial clearance (C) are important criteria. The values and relative proportions of these parameters play an important role in the capacity and performance of the journal bearing in actual applications (Khonsari & Booser, 2008).

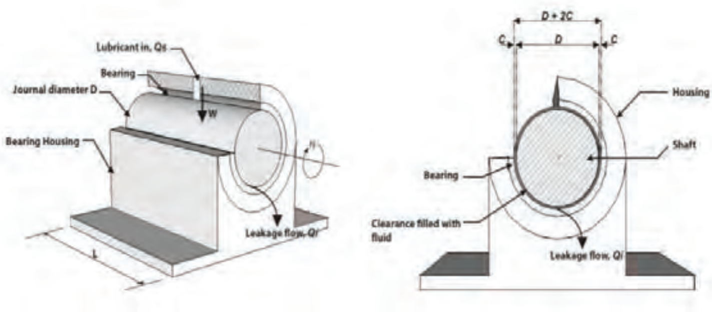


Figure 2.2: Journal bearing geometry and nomenclature

An important parameter in journal bearing operation is its eccentricity, *e*. It is the distance between the centre of the journal

(*Oj*) and the centre of the bearing (*OB*) as shown in Figure 2.3. The line passing through both *Oj* and *OB* is called the centre line. The positions of *Oj* relative to *OB* for three initial stages in a journal bearing operation are illustrated in Figure 2.3. An idle position is shown in Figure 2.3 (a) where the journal is in contact with the bearing with the line of contact opposing to the load and the distance between *Oj* and *OB* is equal to the radial clearance, *C*. At start up in Figure 2.3(b), mixed lubrication prevails, and the journal is displaced and slide in the interior of the bearing in the opposite rotational direction. As the fluid wedge becomes established and lift speed is attained, the journal starts to assume the position in Figure 2.3 (c).

The corresponding mathematical expression for film thickness around the journal bearing is given by equation (2.1):

$$h = C + e\cos\theta \quad (2.1)$$

where C is the radial clearance, e is the eccentricity and θ is the angular position. The eccentricity ratio, e is often determined from the operating conditions of a journal bearing (Khonsari & Booser, 2008).

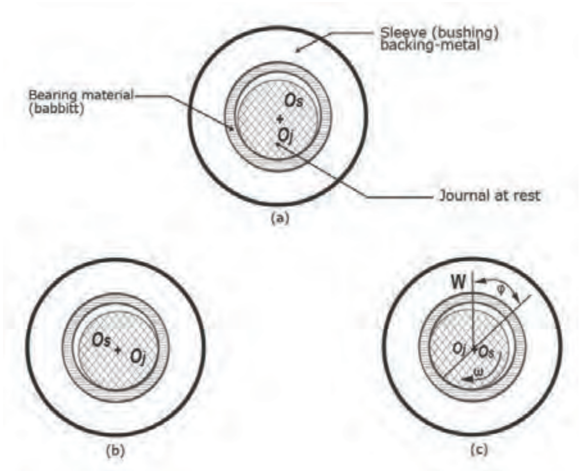


Figure 2.3: Schematic diagram of bearing positions at (a) start-up, (b) no load and (c) steady running conditions

JOURNAL BEARING TEST RIG

To further appreciate the design of a journal bearing, a bespoke Journal Bearing Test Rig (JBTR) is introduced in this section. JBTR is available at the Tribology Laboratory, Centre for Tribology (CenTRIB) Faculty of Mechanical Engineering UiTM. Figure 2.4 shows the schematic diagram of JBTR along with some angles of the actual pictures in Figure 2.5.

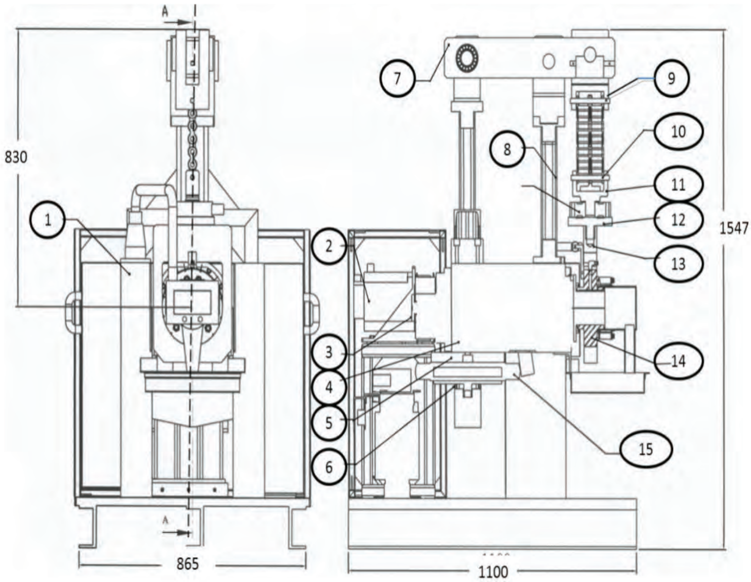


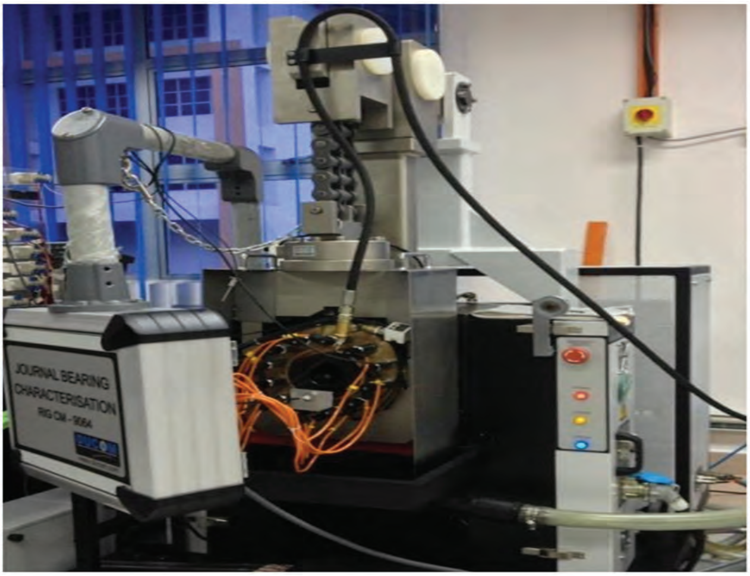
Figure 2.4: Diagram of journal bearing test rig 1. Frame, 2. Motor, 3. Motor bracket, 4. Spindle assy. 5. Bellow top plate, 6. Bellow guide plate, 7. Loading Lever, 8. Pivot assembly, 9. Chain, 10.Chain holder, 11. Load Cell holder, 12. Load Cell, 13. Loading plate, 14. Bearing unit and 15. Pneumatic bellows (Ahmad, 2014)

The frame of the bearing test rig consists of a course base plate and two firm angular beams with housings for the journal assembly. The width, length and height of the frame are about 0.9, 1.1 and 1.5 m, respectively. The frame was firm enough to resist disturbing yield and resonance phenomena in its nominal operating range. The journal is mounted horizontally on self-aligned bearings as shown in Figure 2.5. It is rotated by the servo motor with a timer belt of 2 over 1 pulley ratio. The journal or shaft is tightened to spindle by a draw bolt. The spindle is mounted to the inside housing rotating on taper roller bearings. A centrifugally casted flawless bearing made from brass materials was freely slid over journal with clearance of 104-micron meter. Hydrodynamic bearing was formed as it rotates. The loads were applied by pulling up the bearing upwards. This radial force was applied by a loading lever having 1 to 2 ratios of mechanical advantages. This loading lever was pulled down by a pneumatic bellow which fixed at the below of spindle housing.

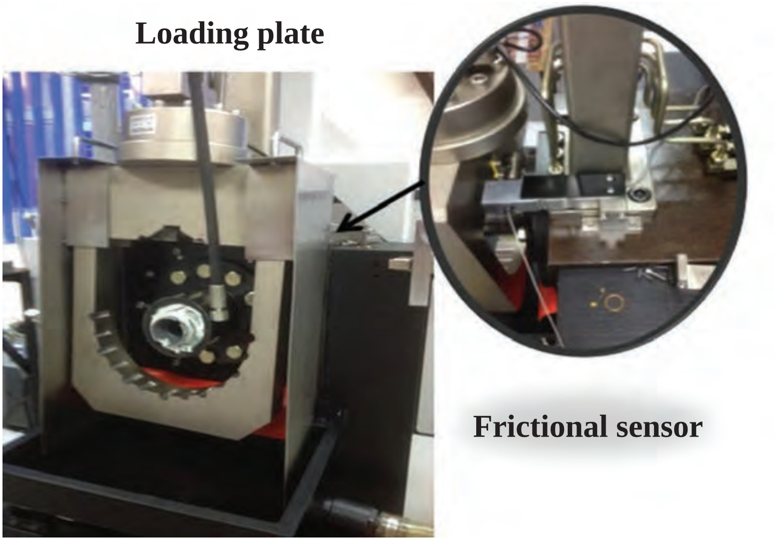
The bearing piece was modified to fix 12 thermocouples and 12 pressure transducers sensors around the face and bearing circumference (Figure 2.5). Temperature thermocouples terminal end was directly connected to the digital temperature controller monitor. Meanwhile the pressure transducer terminal end was connected to the junction box. The controller for operating the machine is fixed on the right of the pedestal. The electronic controller for receiving signal from the sensor was fixed on the left of the pedestal.

JBTR offers many advantages compared to other tribometers such as Four Ball Tester and Pin-On-Disc. Using JBTR, the behaviour and performance of lubricants can be tested in a context like real applications, making more realistic observations and results. The size of bearings in industry can be different but that is alright because the ratio of dimensions is often used in many representations of behaviour such as those found in Raimondi and Boyd Charts. Performance parameters are profiled based on L/D ratio for plain hydrodynamic journal bearings. Words of caution is that there are assumptions following the illustrated profiles and these must be considered when making conclusive remarks validations. There are many possible tests and benefits of JBTR and some are summarised in Figure 2.6. Generally, experimental work is needed to get preliminary results and for better anticipation of possibilities and challenges associated with actual applications. Preparedness for the worst is key to risk assessment management of many processes especially in industry where preventive approach is desired.

There are variations in test rig design as evident from the literature of previous work. Different designs have been used for different applications, for example testing of bearing designs or materials, testing of bearing lubricants or lubrication solutions, testing of durability or testing carried out during the development of measuring devices to be used in tribology research.



(a)



(b)

Figure 2.5: Journal bearing test rig (a) assembly and (b) components

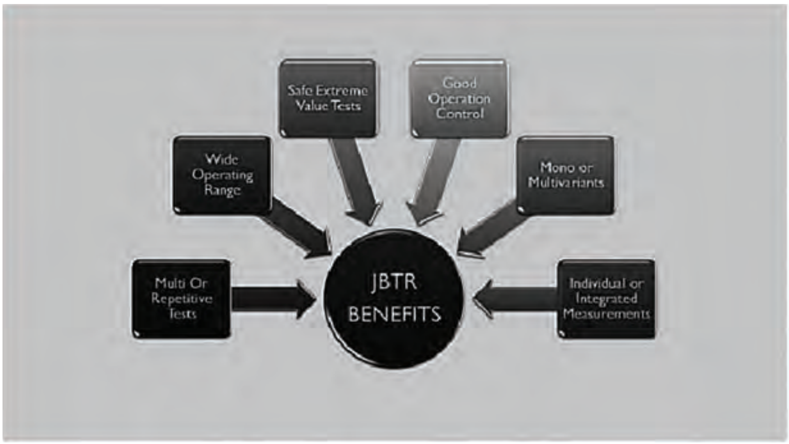


Figure 2.6: Benefits of deploying JBTR

Table 2.1: Dimensions of test bearing, lubricant properties, operating parameters and sensor specifications (Ahmad, 2014)

Parameter	Details
Journal Diameter, D Material	100 mm EN-8 hardened and ground to 1.6 R_a surface finish
Bearing Length, L Bearing Material Bearing Inner Diameter	50 mm Brass 100.104 mm
Radial Clearance, c	52 µm
Length over Diameter ratio	0.5
Applied Load, W	10 and 20 kN
Journal Speed,	300 – 800 rpm
Lubricant Type Lubricant Viscosity	Shell Tellus S2 M 68 cSt @ 40˚C 8.8 cSt @ 100˚C
Bearing Lubrication system Maker Tank capacity Maximum flow rate	 Cen-lube system 15 litre 4 litre per minute
Spindle Lubrication system Maker Tank Capacity Maximum flow rate	 Cen-lube system 40 litre 12 litre per minute
Temperature Sensor Model Range Accuracy	 PT 100 0 – 100 ˚C ± 1% measured temperature

Pressure Sensor Model	MEAS (M5156)
Range	10 MPa
Accuracy	0.001 ± 1% MPa
Frictional Torque Model Range Accuracy	Sensortronic beam type load cell 30 kg (0.01 ± 1% measured value) Nm
Room Temperature	23 - 26 ˚C

The operation of this test rig is controlled by an electrical and electronics controller. Both electrical and electronic controllers were mounted at the pillar of the test rig. The power electronics of the electrical components are housed inside the left side of the pillar and items for instrumentation are housed inside the other pillar. Details regarding the test bearing dimensions, lubricant properties and operating parameters are given in Table 2.1.

PERFORMANCE PARAMETERS IN HYDRODYNAMIC JOURNAL BEARING

Like any other engineering components, performance assessment is of utmost important which allows for monitoring, control, prevention, and CQI of related operations and processes. In plain hydrodynamic journal bearing, there are several parameters used to gauge its performance and these are summarized in Figure 2.7. Upon closer review, these parameters are all related to the behaviour of the lubrication system, the soul of the journal bearing.

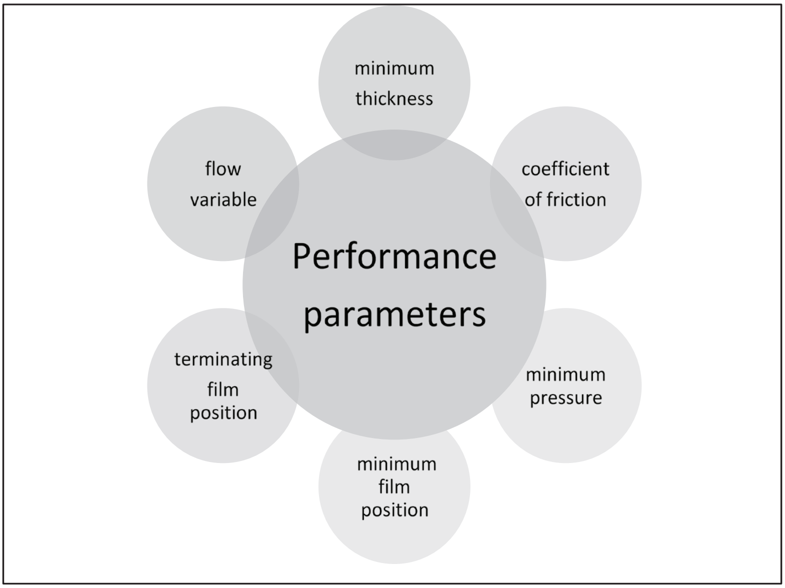


Figure 2.7: Performance parameters in Raimondi and Boyd Charts

Knowing the right performance parameters are important in the design process. It helps designers, engineers, and technicians focus on the right aspects of the journal bearing system to focus on to ensure optimum performance. There are still many misconceptions about the term 'optimum' and often, people tend to associate the term with the lowest or the highest values of specific parameters of interest. In practice, the term 'optimum' refers to the better or best set of parametric values for a given set of requirements or context defined by the owners. For example, it is desirable to have an increasing efficiency. Nevertheless, if the current efficiency is acceptable, it is not strategic to push further if the increment is small and yet the cost of the change is huge. Hence, optimization is very related to what is required by the system and how much the owner is willing to invest and sacrifice. In engineering, there are tools to help in quantifying optimisation processes. Some common tools are Taguchi Method and Response Surface Methodology. In the work of Ahmed et al. (2014), Box Behnken approach of RSM was deployed to study mixing of bio lubricants. Mohamad and Kasolang (2017) deployed RSM to study bio lubricant fortified with titanium oxide as additives. In another study on magnetic actuation in micropump, Mahat and Kasolang (2018) used the Box Behnken method as an optimisation tool of the design parameters.

For plain hydrodynamic journal bearings, graphical representations of performance parameters are depicted in Raimondi and Boyd Charts (Juvinall &Marshek, 2018). The charts are based on computerised solutions of the full Reynolds equation for two-dimensional flow and they provide solutions for plain bearings of all proportions with underlying assumptions shown in Figure 2.8. The charts have a normal scale for Y-axis and a logarithmic for X-axis. The choice of scales for the chart presentation affects the profiling final look and this is often chosen strategically by the designers with some purposes in mind. In this case, the Y-axis represents a specific performance parameter embedded in a dimensional ratio of values from which the desired performance parameter is determined given all the other known parameters. There are many stories to tell about these Raimondi and Boyd Charts which are to be addressed in other books planned by the author.

On a closer look at the X-axis, one would immediately notice a set of parameters, ($\mu n/P$) found in Stribeck Curve. X-axis represents a set of performance parameters, known as ***bearing characteristic number*** or simply ***Sommerfeld number*** as a dimensionless number. Representation in dimensionless values are preferred for some reasons including (i) the reported value is not bound to any system of units such as International System (SI) or British System and hence (ii) the chart can be used with any questions or designs regardless of the unit systems used. What is more critical to bear in mind prior to engaging these charts is the assumptions underlying the performance charts when they were first created. This gives the validity boundary of the values and thus an educated discussion, analysis and decision can be made with clear conscience of the limitations. For the case of Raimondi and Boyd Charts, the assumptions that follow are given in Figure 2.8.

Assumptions symbolise the limit of these performance charts, but they open up for new research opportunities and hence creations of new knowledge. Kasolang and Dwyer-Joyce (2008) deployed non-destructive techniques to study lubrication behaviour around a journal bearing. Kasolang et al. (2012) extended the study by looking at the pressure and temperature profiles. Other studies were also initiated including the influence of oil supply pressure and locations on the pressure profiles (Ahmad et al., 2013).

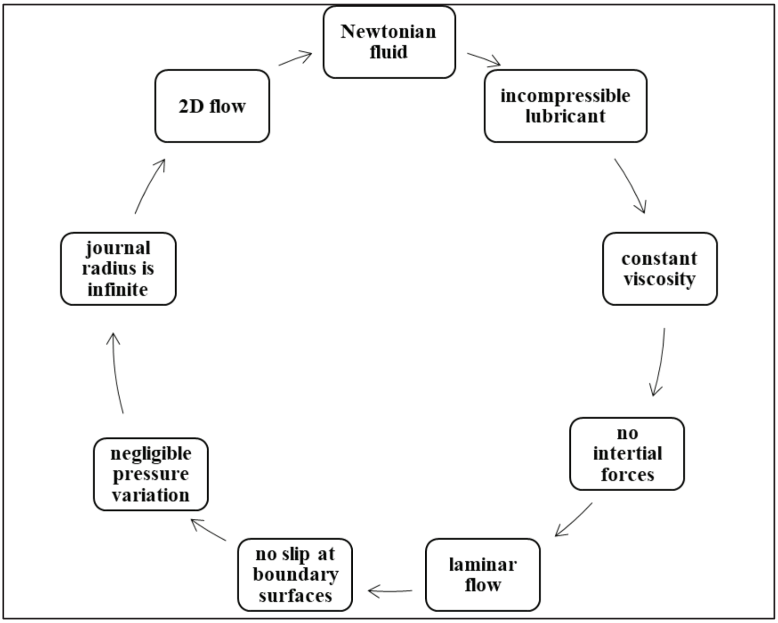


Figure 2.8: Assumptions in Raimondi and Boyd Charts

ACHIEVEMENT AND WAY FORWARD

In 2008, the author completed her PhD work entitled 'An Ultrasonic Investigation of Various Aspects of Hydrodynamic Lubrication in a Journal Bearing' at the University of Sheffield under the supervision of Prof Rob Dwyer-Joyce. There are many publications arising from her PhD work. Since 2005, some of her publications are Kasolang&

Dwyer-Joyce, 2005; Reddyhoff et al., 2005; Dwyer-Joyce & Kasolang, 2006; Kasolang & Dwyer-Joyce, 2007; Kasolang, 2008; Kasolang & Dwyer-Joyce, 2008a; Kasolang & Dwyer-Joyce, 2008b; Kasolang & Dwyer-Joyce, 2009; Kasolang & Dwyer-Joyce, 2010a; Kasolang & Dwyer-Joyce, 2010b; Kasolang et al., 2011; Kasolang et al., 2012a; Kasolang et al., 2012b; Kasolang et. al., 2013a; Kasolang et. al., 2013b.

This work was extended through supervisions of two PhD Students who had successfully graduated: Dr Mohd Ali Ahmad and Dr Diyar I. Ahmed . Some publications from supervision of the former student are Ahmad et al., 2013a; Ahmad et al., 2013b; Ahmad et al., 2013c; Ahmad et al., 2013d; and Ahmad et al., 2014a; Ahmad et al., 2014b; Ahmad et al., 2015; and Ahmad &Kasolang, 2019. From 2015 onward, Dr Ahmad has been working in a similar area and supervised a few postgraduate students with other collaborators. For the latter student, the publications are Ahmed et. al., 2013a; Ahmed et. al., 2013b; and Ahmed et. al., 2013c. There are other publications on lubricants by Dr Ahmed described in Chapter 3 which involved work on lubricants. There were also many Final Year Projects completed under the supervision of the author.

The next phase is to create benefits to the public through collaboration with industry and turn the findings into technology for commercialization. One potential support is through PRGS Grant.

CONCLUDING REMARKS

Plain journal bearings are essential in many engineering systems and come in different designs to best suit the intended applications. Many aspects of plain bearings including major categories and the purpose were discussed. A simple plain bearing consists of a journal housed in a bearing. Heart and soul to this plain bearing design is the hydrodynamic lubrication. The ability of the plain bearing to carry load is very much influenced by the lubrication condition. A bespoke journal bearing test rig developed at UiTM Tribology laboratory was also described in detail and the test rig has enabled an integrated measurement of bearing performance parameters. Finally, Raimondi and Boyd charts were discussed to introduce common bearing performance parameters used in many studies of journal bearings. Generally, Raimondi and Boyd charts offer design guidelines or measurement validations within the assumptions described.

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Chapter 3
Journals Bearing Soulmate

INTRODUCTION

In Chapter 2, it is learned that a plain journal bearing has two main solid components namely journal and bearing. For this journal bearing to function properly and become fully operational, the presence of a lubricant layer is needed to separate both solid surfaces. For the case of journal bearing, the lubricant layer provides hydrodynamic lubrication (HDL) and metaphorically, it can be considered as the soul of journal bearing. The soul that is hidden and unseen by the naked eye. The thickness of this 'soul' is very thin and often invisible to the naked eye and yet without it, the journal ceases to function. Without the 'soul', seizure of machine components is inevitable. Considering the important, key aspects of HDL are addressed in this chapter.

WORLD OF LUBRICANTS

There is a world of lubricant out there that marks the economy of many countries. Lubricant means business and the business scale associated with it is humongous, reaching billions of dollars every year. There is a spectrum of applications associated with lubricants and lubrication. In Figure 3.1, the application is defined into three main categories: ***Automotive, Marine,*** and ***Commercial & Industry*** as seen from the industry lenses. In automotive application, the business service covers passenger vehicles, car dealerships, quick lubes, and repair shops. As for the marine field, lubricant business scale includes marinas, tugs and barges, cruiser ships, container, tanker, car carrier and military field. For the commercial and industrial sectors, the business area involving lubricants are agriculture, construction, mining, food grade, and utilities.

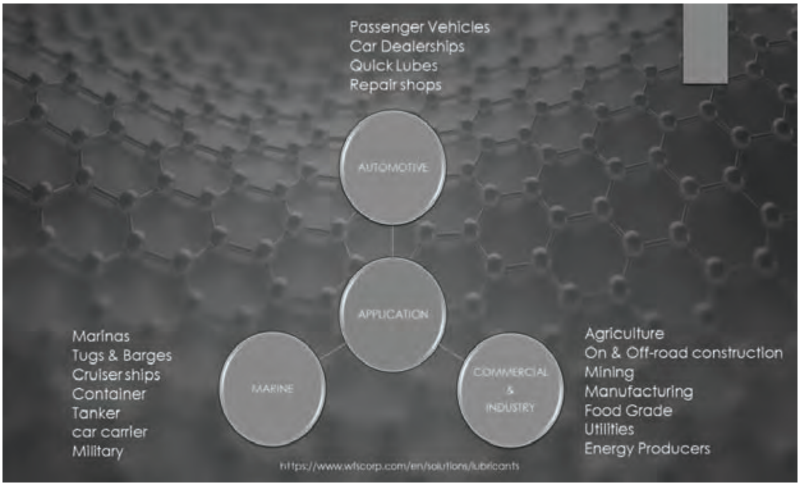

Figure 3.1: Lubrication applications in various industries

Applications and advancements in lubricants can be best learned from what the industry has to offer other than the research findings published by the university. A good start is to figure out the leading lubricant companies. Figure 3.2 shows ranking of main lubricant companies in the world based on reports by The Daily Records (Jegede, 2019). In Figure 3.2, PETRONAS, a Malaysian based company is top in the list. These companies may offer the same segment of products, such as for engine oils, but they promote their specific brand with defined advantages over those of their competitors. Each company offers different formulations often backed up by long years of study. Learning from these leading companies is strategic as they have established brands with sound quality.

1. Petronas
2. Indian Oil Corporation
3. Valvoline
4. British Petroleum
5. Royal Dutch Shell
6. Castrol
7. Kuwait Petroleum Corporation
8. Pemex
9. PetroChina
10. ConocoPhillips

Figure 3.2: World leading lubricant companies

The demand for lubricants is expected to continue for many more years to come so long machine components in relative motion requiring a thin layer of lubricant are still deployed by the industry. There are different types of lubricants used in the market and they can be grouped in three categories: liquid (oil or gas), semi solid (grease), and solid (graphene, molybdenum disulphide, and PTFP or Teflon). In hydrodynamic lubrication, lubricant in the form of oil is typically used to create a thin layer separating the mating surfaces. This is the focus of Chapter 3, to introduce oil lubricant and other related topics such as lubricant properties and lubrication regimes.

ENGINE OILS

Engine oils are typical lubricants which most people, especially car owners can relate to as they must change the engine oil when the time is due as indicated by the mileage of the car (Schrader & Weissler, 2020). There are different types of engine oils used in industry as shown in Figure 3.3.

A full synthetic oil is chemically engineered and with different types of additives for high properties and better performance. If compared to a semi synthetic oil, there is a mixture of synthetic and mineral oils in semi synthetic oil, which provides better oxidation resistance and excellent low temperature properties. The mineral oil is used for moderate engine requirements, or simpler engine design which has moderate performance requirements. A high mileage oil is a special formulated oil for older or high mileage vehicles, which purpose to reduce burn off effect of engine and oil leaks.

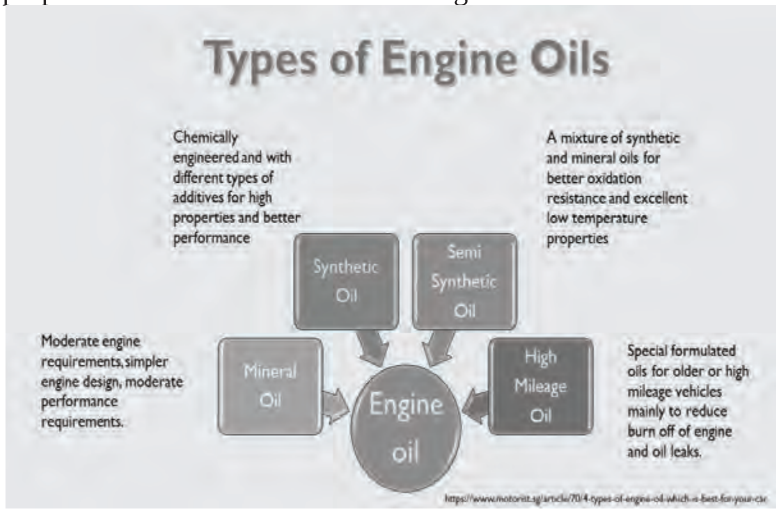

Figure 3.3: Different types of engine oils

Engine oil has its own formulation, and the basic ingredients are made of two parts namely base oil and additives. Base oils can be natural, mineral, or synthetic but the most common choice for base oils are mineral oils for three reasons (1) price, (2) availability, and (3) compatibility. Additives are added to base oils to improve the performance and capability of specific lubricants as required by the intended applications. Some common additives for engine oils include antioxidants to keep the oil from oxidizing, corrosion inhibitors to prevent parts from corroding, and detergents to keep deposits from forming just to name a few.

There are different ways of classifying oil lubricant by its viscosity and one established method is the SAE (Society of Automotive Engineers) Index (SAE Standard, 2015) where oils are graded based on single (e.g. SAE 30; SAE 20W) or multi grades (SAE 5W30; 10W40) (*Engine Oil Viscosity Classification J300_201501*, 2015). Multi-grade engine oil is often more superior compared to single grade oil in the ability to be adaptive to lower and higher temperature requirements. Hence, they are better at start-up (such as during winter) as well as during operating temperature. When choosing the right lubricant for a specific car, the advice is that always refer to the manufacturer recommendation as they have done extensive testing before the car is released into the market for consumers.

LUBRICATION REGIME

Solutions to lubrication problems are often defined by the effective regime over the machine operation. Lubrication regime is often introduced using Stribeck Curve in Figure 3.4 (Wang & Wang, 2013). The main function of oil lubricant is to facilitate motion between interacting surfaces in relative motion. Facilitation comes in the form of friction reduction and in the case of hydrodynamic lubrication, there is a complete layer of fluid separating the surfaces and hence, there is no solid-to-solid contact. There are other functions of oil lubricants and these functions are defined by the design intention.

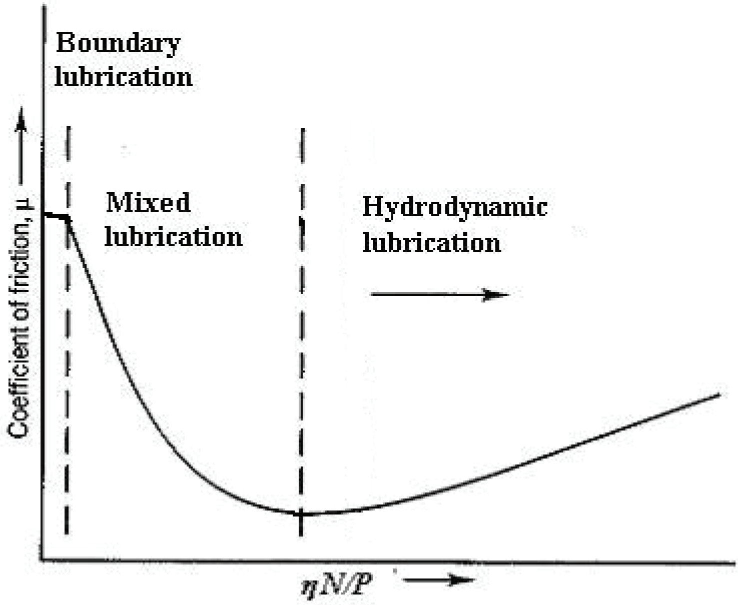

Figure 3.4: Stribeck curve showing coefficient of friction plotted against the product of the absolute viscosity (*η*) and the rotational speed in revolutions per second (*N*) divided by the projected load (*P*)(Wang & Wang, 2013)

There are important stories about Stribeck Curve in Figure 3.4. It describes the correlation between friction coefficient and the synergy of properties. Friction coefficient is a dimensionless number representing the ratio of frictional force over a normal force acting on a body. The synergy of properties ratio for the Y axis represent three key factors: (1) lubricant viscosity, (2) operating conditions (speed and load), and (3) bearing geometry (L & D). The synergy indicates the opportunity for the designer (engineer) to manipulate the factors to the advantage of reducing the friction coefficient to optimum value. This could be systematically achieved via an optimum technique such as Response Surface Methodology (RSM) using Box-Behnken Model (Mahat&Kasolang, 2018).

Friction is the main concern in most machinery and engineering applications and in the context of TRIBOLOGY, it is basically the focal of interest followed by WEAR as the consequence of friction and LUBRICATION as the solution to reduce the effect of friction. Friction is a system response not a system property and hence becomes effective when motion, including impending motion, takes place. Friction coefficient can be measured experimentally using a specific sensor and it is commonly recorded as a value for two defined interacting surfaces. Friction coefficient is reported for a material combination and a specific surface condition. For example, the friction coefficient for Brass-Steel interaction at clean and dry condition is 0.57 whereas the value reduces to 0.19 when lubrication is introduced. The used of lubricants in the metal can reduce the value of friction coefficient to about 3 to 52% (Trzepiecinski&Lemu, 2020).

HYDRODYNAMIC LUBRICATION (HDL)

A typical example of hydrodynamic lubrication in journal bearing is found in the engine system. Stribeck Curve in Figure 3.4 shows three main lubrication regimes namely (1) Boundary Lubrication, (2) Mixed Lubrication, and (3) Hydrodynamic Lubrication. In the context of journal bearing, the effective regime during the operating condition is Hydrodynamics. However, during start up and stop, the main regimes are Boundary and Mixed Lubrication. Another crucial regime is Elasto-Hydrodynamic Lubrication (EHL) which is a variation of HDL. In EHL, the softer surface experiences elastic deformation due to a very high pressure experienced by the mating system. This is commonly observed in gears at the contact between gear teeth.

Coming back to HDL, during a journal bearing operation, a floating condition is achieved when bearing surfaces are separated completely by a thin layer of lubricant. A wedging is established when a minimum thickness is achieved at a point around the journal bearing and this location is given by the attitude angle. At the converging section, a wedging action causes the pressure of the lubricant layer to rise until right before the minimum film thickness. This wedging action is responsible for the load carrying capacity of the journal bearing operation. The established wedge is extremely thin and often in the range of micron in journal bearing applications and hence, not visible to the naked eye. In other words, this level of thickness is like a strand of hair being split into 10 pieces. This, seemingly weak thin layer of lubricant, creates the ability of a bearing to carry load. Imagine a layer of fluid with thickness 10 times smaller than a strand of hair could carry a load of 20 or more average people.

Recall that HDL is characterized by the presence of a thin layer of lubricant, completely separating two mating surfaces. There is no contact between asperities of both surfaces. For this regime, the typical lubricant thickness ranges from 1 to 100 micron and the coefficient of friction is between 0.001 to 0.01. The behaviour of the HDL is very much determined by the properties of the lubricant chosen. Some properties of the lubricants are discussed subsequently.

PROPERTIES OF LUBRICANTS

The choice of lubricant plays important roles in providing the desired support for the lubrication system. The main purpose of lubrication introduction is to reduce friction, but other benefits can be realized with proper designs.

Some common properties of oil lubricants include density, viscosity, viscosity index, pour point, flash point, cloud point, and fatty acid contents. The quality of oil lubricants are also evaluated based on factors such as having the ability to offer boundary lubrication, thermal stability, chemical stability, corrosiveness, thermal and heat conductivity, toxicity, low friction, cooling, and ability to remain in the machine components. In many considerations of lubricant properties, top in the list is viscosity and this is often used in Stribeck Curve, Raimondi and Boyd Charts, Newton's Law of Viscosity and many more (Patil et al., 2017). Viscosity of a lubricant is a measure of its internal resistance to flow (Ville, 2013). Scientifically, fluid viscosity is described in terms of shear stress and shear strain at a given temperature. When shear stress is applied, fluid layers will slide relative to the other at a rate determined largely by its viscosity. The flow will subside only when the shear stress is removed or balanced. This resistance to flow or simply viscosity is quantifiable by a resistance law in equation (2.1), which was first postulated in 1687 by Isaac Newton (Bai & Bai, 2019).

$$\eta = \frac{\tau}{\frac{du}{dy}} \qquad (3.1)$$

Where η is the dynamic viscosity, τ is the shear stress (i.e shearing force over parallel area), $\frac{du}{dy}$ and is the velocity gradient or shear rate.

The higher the viscosity value, the more resistance there is and hence a ball drops faster in water then in ketchup. It is not quite right to say that less viscous fluid is better than more viscous. There is an optimum value for every application, and this can be predicted using available means such as equations, table of data, or charts. For hydrodynamic lubrication in journal bearing, the use of Raimondi and Boyd charts provide guidelines for choosing the optimum region with the assumptions in mind.

How do people express viscosity? Generally, two types of viscosity are used namely kinematic viscosity (KV) and absolute or dynamic viscosity (DV). DV is often expressed as cSt (centiStoke) or mm^2/s and DV as cP (centiPoise). Water (distilled) has a KV of 1 cSt or 1 mm^2/s, milk has 4 cSt, SAE 10 has 110 cSt. In other words, the resistance by SAE 10 Oil is 110 times more compared to that of water and this can be readily felt and appreciated. Kinematic viscosity of any fluid is related to dynamic viscosity by its density (Rapp, 2017). Mathematically,

$$\nu = \eta / \rho \qquad (3.2)$$

Where ν is kinematic viscosity, η is the absolute viscosity, and ρ is the density.

VISCOSITY AND TEMPERATURE RELATION

Viscosity is the most important property of lubricant and its behaviour is readily affected by temperature and less affected by pressure. The viscosity of liquids decreases as the temperature increases. Conversely, the viscosity of gases increases as the temperature increases. The change in viscosity due to a temperature variation for different fluids can be obtained experimentally. For industrial fluids like oil lubricants, data on viscosity-temperature relations are often available for users.

For higher pressure conditions (such as in journal bearing lubrication), the relationship can be quantified by the Walther equation (Khonsari&Booser, 2008),

$$loglog\,(\nu + 0.7) = A - B\log T \qquad (3.3)$$

The constants *A* and *B* can be determined given the values of kinematic viscosity at two temperatures (typically 40 and 100 °C). Another model is Vogel equation (Khonsari&Booser, 2008) which offers a better approximation of viscosity over an extended temperature range.

$$\eta = \eta_{ref}\, e^{-\beta(T-T_{ref})} \qquad (3.4)$$

Similarly, the constant is approximated from the viscosities at two different temperatures by,

$$\beta = \frac{\ln\left(\frac{n_2}{n_1}\right)}{T_2 - T_1} \qquad (3.5)$$

The first rule in selecting a suitable engine oil for your car or other components is to follow what is recommended in the manual that comes with a car or components. Most companies made it available at the official website important information on matters related to the vehicles they manufactured including the types of engine oils. This can be accessed anywhere and anytime as long as internet connectivity is available. Many times, the manufacturers of the oil engine, such as MOBIL1, would list out the recommended engine oil for specific types of car.

ACHIEVEMENTS AND WAY FORWARD

The work on journal bearing by the author requires a form of lubricant to function and that explains the title of this chapter, ‘Journal Bearing SOULMATE’. During operation, the main regime is hydrodynamic lubrication. One of the key factors affecting the performance of journal bearing is the choice of lubricants. This work has produced one PhD (Dr Diyar I. Ahmed), one Masters (Nor Syahirah Mohamad), and many Final Year Projects students. Some of the publications through the supervision of PGs and UGs are Ahmed et al., 2014a; Ahmed et al., 2014b; Kasolang et al., 2015; Kasolang et al., 2015; Mohamad &Kasolang, 2017; Mohamad et al., 2018; Roselina et al., 2020. Through collaboration with other tribologists, successful work was carried out as described in Shaari et al., 2015; Bakar et al., 2018; Fuad et al, 2018; and Razak et al., 2018.

There is a long way to go in this research field on Lubricant and Lubrication. The interest in biolubricants is rising as people are more aware of the need to be green. There is also future work on the potential of additives which help enhance the ability of lubricants and extend the functionality as required by the intended applications. It is intriguing to design lubricants that fulfil multiple functions comparable to existing commercial products yet very green to the environment.

CONCLUDING REMARKS

The heart to journal bearing is the hydrodynamic lubrication, one of the distinct regimes of lubrication in Stribeck Curve. In real applications, there is a transition from Boundary Lubrication to Mixed Lubrication before HDL can be established. Lubricants can be defined by different properties but the most important property is viscosity, a measure of internal resistance to flow. It is not about how low or high a viscosity to be desired. Rather, the right question should be what is the optimum viscosity value for the intended application. This can be determined by a specific equation, data table, established charts like Raimondi and Boyd and so forth. Raimondi and Boyd charts show bearing performance parameters and specify the region of optimum design in the first chart. Viscosity may be expressed as kinematic or dynamic values. Both values are connected via the oil density. Viscosity is readily affected by temperature and less by pressure. Specific equations can be deployed to get the right values of viscosity for a given condition.

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Chapter 4
Unfolding Nature

INTRODUCTION: THE END IN MIND

Humans have been looking into nature for solutions for many years. In medicine specifically, voluminous literature points out the use of different plants and roots as sources for alternative medicine across cultures around the world. In engineering studies particularly, researchers have turned to nature for solutions in complex applications. A relatively new term, BIOMIMETICS or BIOMIMICRY was coined to describe this and becomes the centre of discussion in this chapter.

The interest of the author is to pursue research work in the area of Biomimetics as this was not readily established in Malaysia. It was hard to find literature on Biomimetics especially those related to plants indigenous to Malaysia. The challenge was to link the current research to biomimetics. There are different themes and one of the earliest one is on lubrication specifically hydrodynamic lubrication. There is existing work on Lotus Effect and Rose Effect widely reported with focus on Hydrophobicity and Hydrophilicity.

With lubricant and lubrication background, the author is more interested in creating plant inspired surfaces to promote Oleophilicity as well as Oleophobicity. With that in mind, a study to look at Pistia

Stratiotes (Pokok Kiambang) was initiated. Pistia was selected as it has some similarity to Lotus. The first phase involved investigating the actual Pistia Leaf and producing inspired surfaces based on the natural leaf characteristics. This was successfully completed with indexed publications. The second phase is to push the pistia inspired surfaces into a pilot application. The idea is to have surfaces that promote the spread of the oil during application and to remain in the oil with certain minimum film thickness without the help of any circulation system or additional system so that the design can be simple, easy to fit, less maintenance and less costly. The third phase is to get this technology fully developed into real applications through a collaborative work with interested strategic partners from industry. This work is also linked to another theme on Self-Healing Materials via oil impregnated material foams which are also in progress. Subsequently, this chapter presents selected topics such as Biomimetics in Tribology, Plant Surface Structures, Surface Wetting and Contact Angle to name a few.

BIOMIMETICS

In principle, Biomimetic or biomimicry can be defined as a process of imitation in which the idea, models, system, concepts or principles developed by nature are mimicked to provide new solutions to complex problems; new perspectives on design; and better ways of making things (Koch et. al, 2009). Specifically, it is an artistic form of technology that uses to emulate nature to solve human problems. According to Julian et al. (Vincent et al., 2006), the word made its first public appearance in Webster's Dictionary in 1974, accompanied by the following definition:

> '*the study of formation structure or function of biological produced substance and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones*' *(Harkness, 2011)*

In the 15th century, the Renaissance man Leonardo da Vinci invented the most famous flying machine known ‘ornithopter’, inspired from bats. He is one of the first who used a biomimetic approach to technology. Figure 1 shows the area of biomimetic applications. Even though this concept is not really new, it has recently become very much popular especially in the tribology field (Guo et al., 2017; Lu, 2018; Maksimkin et al., 2017).

Biomimetic field, where flora and fauna or in nature ecosystems are emulated as a basis for design, has fascinated global interest in the fields of engineering or even in architecture. Nowadays, a large area of biomimetic research deals with functional micro and nanostructures and the transmission of biological principles and functional structures. This is due to the fact that it is an inspiring source of potential for new inventions and the possibility of supporting a more sustainable built environment. Major fields in Biomimetics are shown in Figure 4.1.

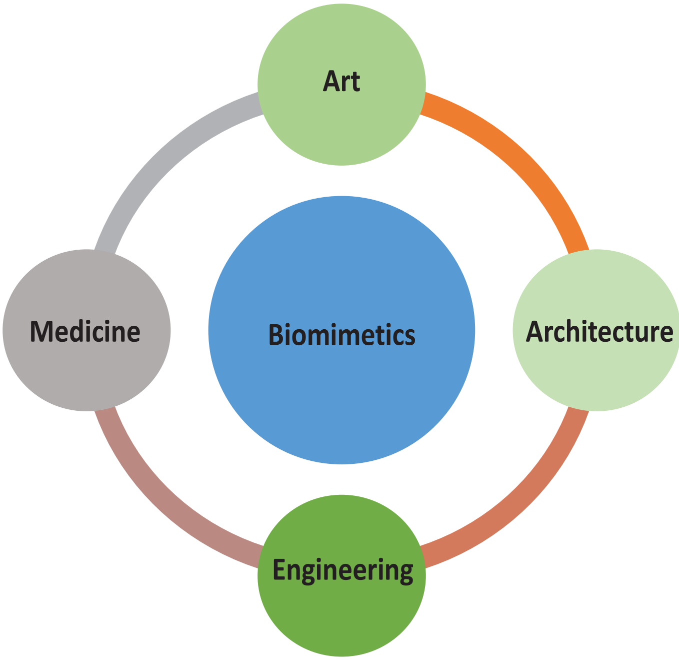


Figure 4.1: Major fields in biomimetics

BIOMIMETICS IN TRIBOLOGY

Tribology can be described as a scientific discipline concerned with the study of solid surfaces in relative motion covering friction, wear, lubrication, and adhesion. Since the tribology word was introduced almost 50 years ago, new scientific disciplines and various aspects of interacting surfaces in relative motion have developed including nanotribology, biotribology, microelectromechanical and nanoelectromechanical systems and adhesive contact (MEMS) (Nosonovsky& Bhushan, 2016).

Recently, the new theory of green tribology has been defined as the science and technology of the tribological features of ecological balance and of environmental as well as biological impacts. This comprises tribology technology that mimics living nature (biomimetic surfaces) and thus is likely to be environment friendly (Nosonovsky& Bhushan, 2016).

The area of biomimetic tribology has been evolving very rapidly due to new prospects to synthesize micro/nanostructured surfaces. Materials, processes and systems in nature are analyzed. Hence the underlying principles are extracted and subsequently applied to science and technology.

Following the ‘lotus effect’ successful study, new areas of biomimetic such as in surface applications have been investigated. These novel areas include antifouling and underwater oleophobicity, water-oil separation, icephobicity, oleophobicity, corrosion-resistance and omniphobicity (Nazanin et al., 2015).

Advancement in related technology could be pursued. For example, in the study of Lotus leaves, findings on lotus effect has made it possible for the invention of smart paints with self-cleaning properties and coatings of surfaces with superhydrophobicity. This lotus inspired technology is one of the many solution-based approaches described in literature (El-zeiny, 2012). Table 4.1 shows some of the biomimetic success stories with the corresponding nature inspired technology (Goddard, n. d.).

Table 4.1: Nature inspired technology

Source of nature	Inspired technology
Lotus	Super hydrophobicity coating; Paint;
Bees	Honeycomb structure; swarm logic in energy grids;
Gecko skin	Setae silicone for gripping; gizmo for climbers; grippers for aerospace and robot arms;
Whale	Tubercle effect on Turbine blades to reduce drags and noise;
Shark skin	Coating on boat to reduce drag;
Burdock burrs	Velcro.

PLANT SURFACE STRUCTURES

Surfaces define the boundaries of exterior and upper of solids (Barthlott et al., 2017). They play vital roles in ecological connections. Plant surfaces provide a large variety of functions. This is of particular important for sessile organisms with large functional plants. According to other researchers, green plants cover the terrestrial biomes of our planet and not surprisingly show a striking diversity of hierarchical surface structures which has been discovered with the help of scanning electron microscopes (SEM) (Koch et al., 2009) as shown in Figure 4.2.

Some surface-like lotus leaves are extremely water repellent (super hydrophobicity). However, others such as the air roots of epiphytic orchids and some lichens and mosses show opposite behaviour; these are created for the most efficient water absorption (super hydrophilicity) through their surface.

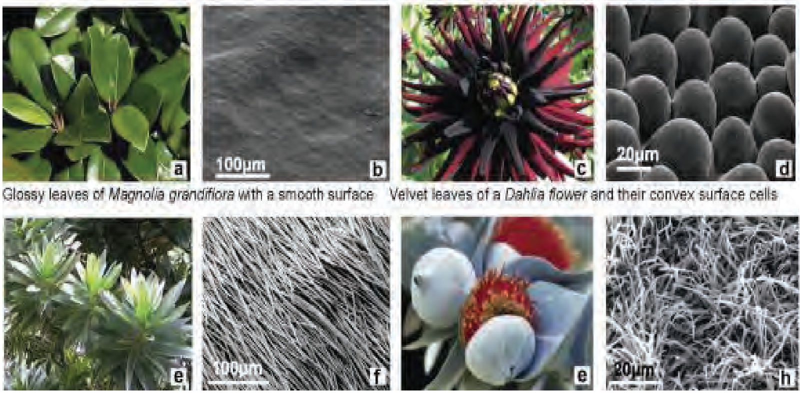


Figure 4.2: Macroscopically appearance and microstructures of plant surfaces (Koch et al., 2009)

The boundaries for the well-structured world of solids called surfaces. Basically, every interaction of biological organisms with the surrounding are subjected by their surface (Ashton and Martin, 1967). These surfaces got optimized to either improve this interaction or to defend the organism from unsafe environmental conditions. Studying the natural surfaces and understanding their functionalities does not just expand our knowledge of the biological developments but also reveals exciting chances to transfer and apply such functionalities in engineering and technical applications (Mayser, 2014). Many researchers are interested in biological micro and nanostructured as well as hierarchical structured surfaces because these surfaces exhibit attractive properties. Many researchers claimed that surfaces of living organisms can be very elaborated and complex on many hierarchical levels such as superhydrophobic plants that cover millions of square kilometres of our planet (Barthlott et al., 2016). They are living models of biomimetics.

In the plant surface, micro and nanostructure surfaces play a special character, and a huge miscellany of surface structures exists at different size levels. According to researchers, biological materials are highly organized from the molecular to nanoscale, microscale, and macroscale often in a hierarchical manner with complex nanoarchitecture that ultimately makes up a countless of different functional elements. Basically, a primary epidermis cell usually visible at low magnification by digital microscopy or SEM. (Koch et al., 2009) reported that anticlines or anticlinal walls are called for two perpendicular cell walls boundaries. Meanwhile, the outer area of the cell surface is called the periclinal wall. The primary sculpture involves the outline of epidermal cells including the shape and curvature of the outer periclinal wall. Figure 4.3 shows the outcome of SEM analysis for the pistia stratiotes leaf conducted at the Centre for Tribology lab, Faculty of Mechanical Engineering UiTM.

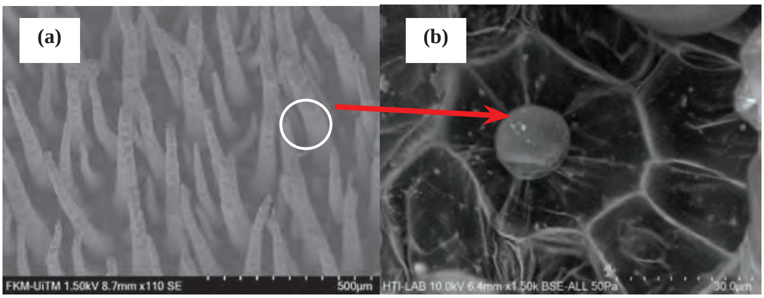


Figure 4.3: SEM micrograph of hierarchical and multicellular surface structure of pistia stratiotes leaf (a) hairy structure for primary surface of pistia stratiotes leaf and (b) secondary structure of pistia stratiotes leaf

FUNCTIONAL ADAPTATIONS OF PLANT SURFACE STRUCTURE TO ECOLOGICAL CONDITIONS

Plants developed specific structures for effective survival in nearly all possible habitats on earth since the first plants moved from their aqueous environment to the drier atmosphere on land (Koch et al., 2009).

The plant surfaces play an important role in relating with the biotic (living) and non-biotic environment. Thus, it is not astonishing that in diverse plants and environments, a vast variety of functional surface structures has been developed including in temperate zones. Temperate zone or temperate climate has four seasons which are summer, autumn, winter, and spring. The temperature from one season to another is very distinct and affects the growth and types of plants in each season. Hence, different growth of plants such as herbaceous, deciduous shrubs and trees and some evergreen plants are found in this environment (Koch et al., 2009). Nevertheless, land-living plants show a wide range of functional surface structures and plants of the moderate or temperate zone are the typical cluster in which selection of features is less influenced by extreme climatic conditions. An enormous diversity of surface structures has been evolved in this cluster.

The land plants are more common in our daily life. They include most of the small green plant vegetation. The land plants are named as 'Embryophyta' since they raise under terrestrial habitats. They are an important part of the vicinity since they supply the majority of productions on the earth. All the land plants have their own function and character to survive against the environment in their habitats. Some biologists studied taro leaf surface, banana leaf surface, rose petals (Figure 4.4) and many more plant surfaces because they become curious by the water repellent property of those leaf surfaces. They found out that this hydrophobicity property is due to unique micro and nanostructures when observed under SEM. Since, more researchers are interested in hydrophobicity and other properties of leaves. They also extend the investigation into aqua plants.

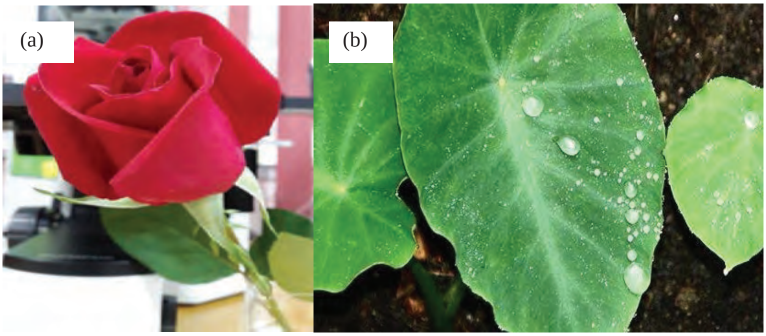


Figure 4.4: Land-living plants (a) rose and (b) taro leaf

Aquatic plants are described as plants that grow in water whether rooted in the mud or floating without anchorage. Aquatic plants normally can adapt to living in aquatic environments. They can live whether in freshwater or saltwater. The habits can be running waters, like rivers or stagnating waters like ponds (Koch et al., 2009). There are different categories of aqua plants which may be segregated based on the water body they typically found. This includes aqua plants for aquariums and those found in the ocean (saltwater) and rivers or ponds (freshwater).

The characteristics of aquatic plants can vary and differ depending on the type nevertheless there are a few that remain the same. There are millions of species aquatic plants are recorded in the world and that each species has their own behaviour as well as functions to survive in their ecosystems (Bhushan & Yong, 2007; Barthlott et al., 1997). Some of the researchers take an idea from nature to transform and mimic the things into artificial technology as in the case of lotus effect mentioned earlier (Bhushan, 2016; Lu, 2018). Figure 4.5 shows the lotus leaves which have been long studied and pistia leaves currently studied by the authors.

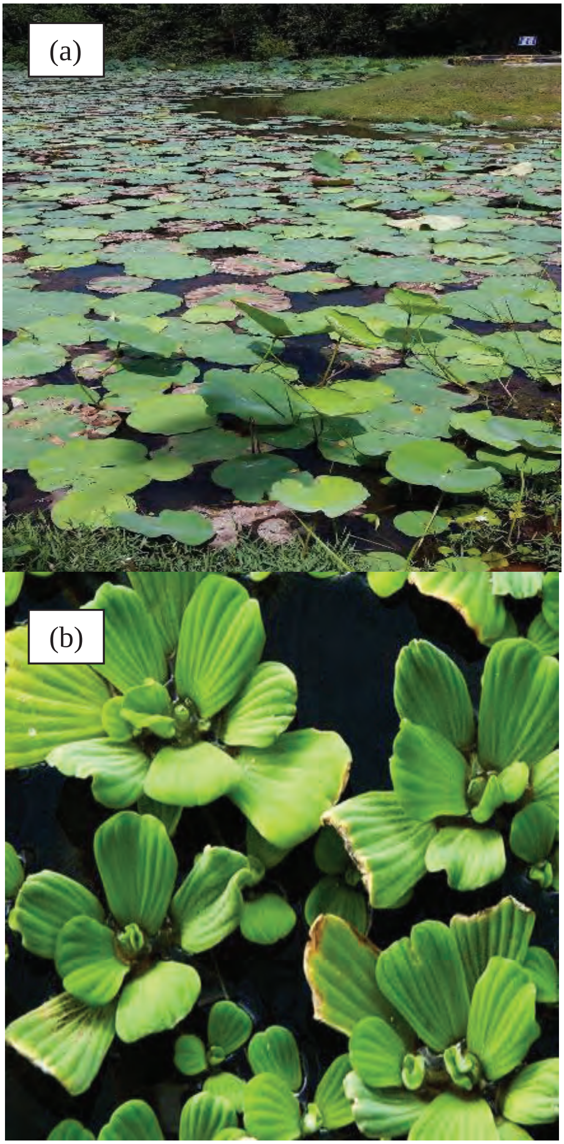


Figure 4.5: Aquatic-living plants (a) lotus and (b) pistia stratiotes

SURFACE WETTING AND CONTACT ANGLE

Typical plant leaves as well as insects, such as lotus leaf, rose petal, hierarchical leaf, leg of water strider demonstrate different wetting behaviour because of their microstructure scales. Wettability of solid surfaces with liquids is governed by the chemical properties and the microstructure of the surface (Tadanaga et al., 2000). Over the issue, scientists continue to be interested in studying the complex problem of rough surface wetting.

Some scholars found new methods for manipulating liquid droplets on the surfaces involved by changing the interfacial properties of materials to control surface wetting by liquids. The wetting properties of the surface can be examined by means of contact angle measurements.

Wettability studies usually involve the measurement of contact angles (as shown in equation 4.1) as the main data which shows the degree of wetting when a solid and liquid interact. Small contact angles ($\ll 90^{o}$) relate to high wettability while large contact angles ($\gg 90^{o}$) relate to low wettability. It is clearly shown in Figure 4.6 and Figure 4.7. Surface wetting can be divided into four categories which are superhydrophobicity, hydrophobicity, superhydrophilicity and hydrophilicity (Figure 4.7). Small contact angle is examined when the liquid spreads on the surface while a large contact angle is examined when the liquid beads on the surface. The wetting of the surface is favourable when a contact angle less than 90^{o} and the fluid will spread over a large area on the surface while contact angles greater than 90^{o} normally means that wetting of the surface is unfavourable so the fluid will minimize its contact with the surface and from a compact liquid droplet (Yuan & Lee, 2013).

$$\gamma^{SV} = \gamma^{Sl} + \gamma^{lV} \cos\theta \qquad (4.1)$$

θ is the contact angle
γ^{Sl} is the solid/liquid interfacial free energy
γ^{SV} is the solid surface free energy
γ^{lV} is the liquid surface free energy

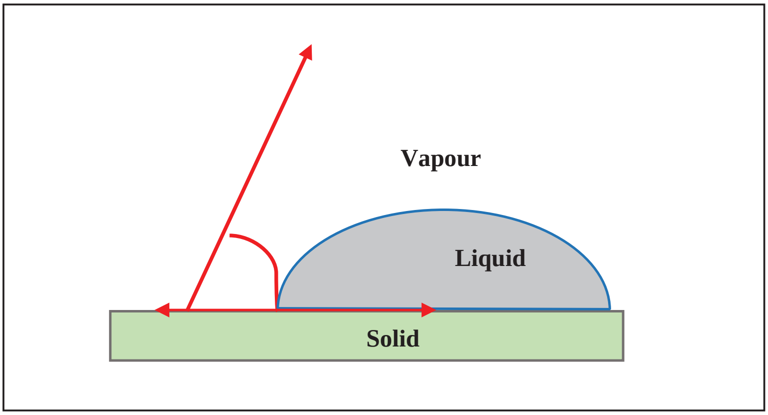


Figure 4.6: Illustration of contact angle formed by sessile liquid drop on a surface

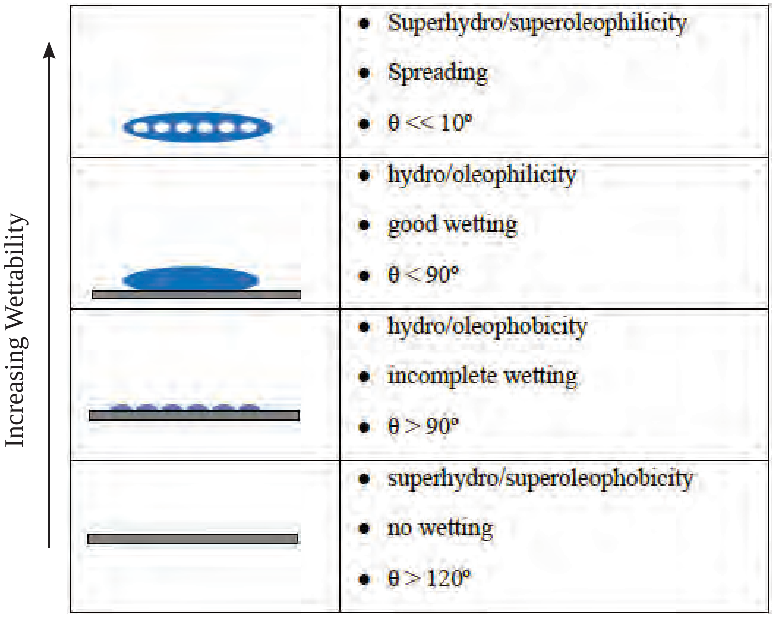


Figure 4.7: Wettability and contact angle

Figure 4.8 represents the structure and wetting behaviour of plant surfaces (Barthlott et al., 2017). The formation of cell type and dimensional wax are very much dependent on the wettability of plant surfaces in their interaction with the environment. Hence, understanding the wetting behaviour of biological surfaces is crucial and challenging to discover the biotribology of nature.

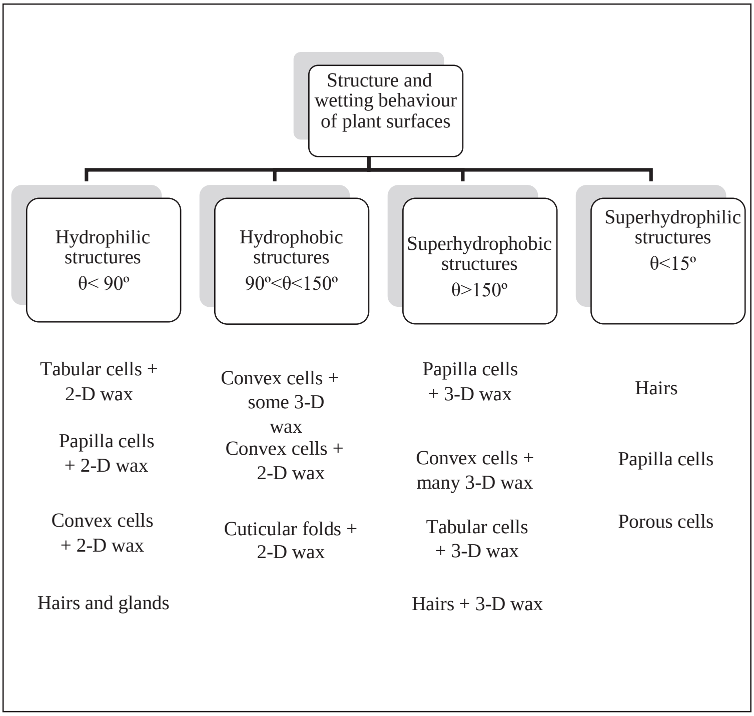


Figure 4.8: Structure and wetting behaviour of plant surfaces

CURRENT RESEARCH IN BIOMIMETIC FIELD

This study provides an exciting opportunity to advance our knowledge of oleophilicity behaviour of plant leaves' surfaces. The early dynamic wetting on oleophilicity of pistia leaves surfaces were investigated. There has been little discussion in literature about oleophilicity of hairy structure surfaces like pistia leaves.

Recently, the biomimetic tribology field has been evolving very quickly due to new opportunities to create micro and nano structures surfaces which have emerged with the advances in nanotechnology and in related area (Wang et al., 2016; Wojciechowski et al., 2017).

A study on oleophilicity of pistia leaves has been conducted at the Centre for Tribology CenTrib UiTM. One of the key investigations is described. Pistia stratiotes plant is one of ten the *Salvinia* genus species that most found in South America (Mayser, 2014). They are very fast spreading, mat forming plants and pest plants in several tropical and subtropical waters. This plant is a floating fern which possesses the long-term air retention characteristic on the hairy structure leaves surface (Figure 4.9) when submerged in water caused by its peculiar microscale of structure and the related high hydrophobicity. The pistia stratiotes leaves have been thoroughly investigated from a morphological and functional point of view (Najibah & Salmiah, 2017). In this work, the hierarchical or hairy structure of the leaf's surfaces offers promising potentials superoleophilicity behavior in tribology applications.

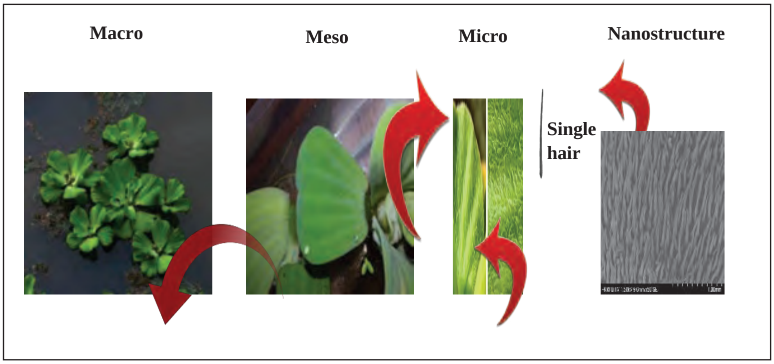


Figure 4.9: The hairy structure of pistia leaf is made apparent as it is scaled down from macroscopic scale to the nanoscopic scale

In the first step, oleophilicity behavior of various oils with different viscosity and different types of pistia leaves (young, middle, and mature) was investigated using contact angle meters. A novel fast wetting stage was found in the time scale 1 to 5 seconds as shown in Figure 4.10. It was found that the duration of this fast-inertial wetting was controlled by the softness which is the hairy structure surface of the pistia leaves and viscosity of oil itself. Mature pistia leaves surfaces recorded the worst oleophilicity with average contact angle of bio oil 69º to 72º (Najibah & Salmiah, 2017). As a result, the increase in viscosity of the oils contributes to the high contact angle value.

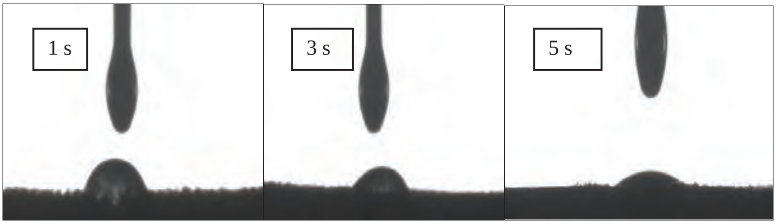


Figure 4.10: Side view of a sessile oil drop timelapse on a pistia leaves surfaces by using contact angle meter

REPRODUCTION OF DESIRABLE SURFACE OF PISTIA LEAVES

Surface modification and characterization is critical in engineering study. Technique of surface modification by mechanical and chemical treatments includes various coating and machining. In the areas of Biomimetics, certain surfaces found on plants and animals were replicated to provide solutions with desirable characteristics such as self-cleaning, self-sticking, self-healing, and self-lubricating. Being able to reproduce similar surfaces offered in nature and retain the positive characteristics is truly challenging but worthy.

Based on earlier study on pistia leaf surfaces, some desirable property in the area ofoleophilicity has been found. This has become a motivation to reproduce similar surface characteristics. The work is described subsequently.

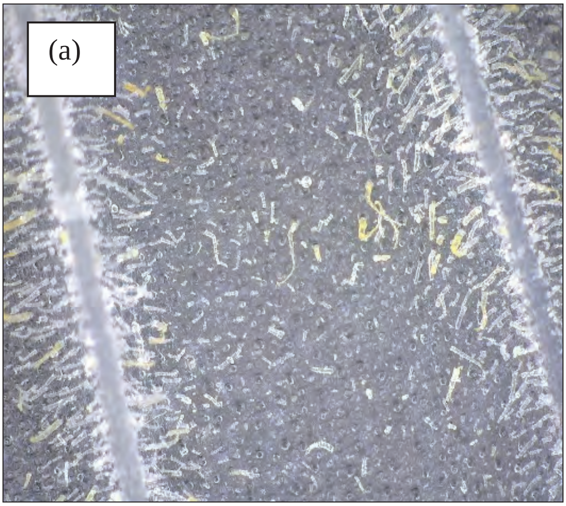
The pistia leaves have been produced using a specific technique in the lab. A casting process using polydimethylsiloxane (PDMS) soft material was deployed. This substrate was used to examine and investigate several tests like surface roughness, oil flow behaviour and ultrasonic investigation due to constraints of the real leaves.

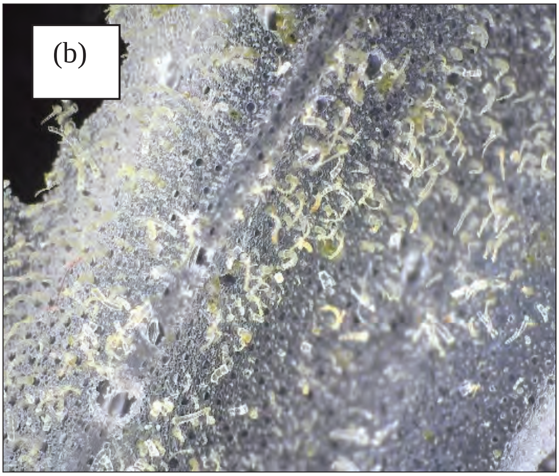
PDMS which is based on silicone is a type of transparent and elastic polymer. It is perfect material for nano-casting because of its chemical and thermal resilience as well as mechanical deformation. Before casting, PDMS and its catalyst are both viscous and transparent liquids were prepared. To get a well-patterned transfer after solidifying, the mass proportion ranging 100:2-4 was measured. As long as the mass is in the proportion range, the perfect replica should be obtained (Sue, 2005).

One of the investigations in this study is to measure the surface roughness. The 3D measurement of technical surfaces is a crucial part in checking and controlling the properties and the function of materials or engineering parts. In past decades, tactile devices have been used to make measurements of materials surface roughness. However, there has currently been a strong shift towards optical non-destructive 3D metrology devices. Three benefits were found from the smart profilometer machine which are;

i. The machine does not touch and damage the surface.
ii. The machine is able to measure whole areas instead of only surface profiles.
iii. It is typically much faster detailed measurements of large areas.

Here in this work the optical metrology device Infinite Focus profilometer Alicona was used. It is based on the Focus Variation principle and offers a large range of different applications due to its special measurement principle (Danzl et al., 2011). Figure 4.11 shows the findings of surface roughness measurement using Alicona profilometer based on the real samples as seen in Figure 4.11 (a) and Figure 4.11 (b). The corresponding colour distributions for samples (a) and (b) are given in Figure 4.11 (c) and Figure 4.11 (d) respectively. The colour contour represents the different height and depth of the sample surface. The distribution of peaks and valleys represented by the colour is important in gaining better understanding on how surfaces with similar surface roughness values produce different oleophilicity and oleophobicity characteristics. This is likely to affect oil flow and thickness established by the hairy structure on the surface.





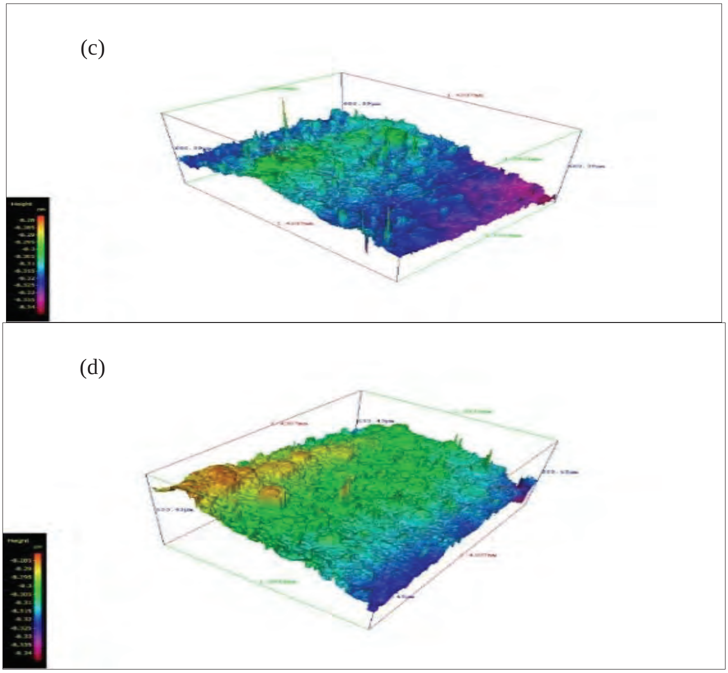


Figure 4.11: Pistia leaves inspired surfaces for two samples (a) and (b) and the corresponding surface profile in (c) and (d) using Alicona

ACHIEVEMENTS AND WAY FORWARD

The work on pistia leaves has produced one PhD graduate and one Final Year Project. There are several publications arising from this work such as Latif et al., 2019a; Latif et al., 2019b; Latif et al., 2019c; Latif et al., 2018a; Latif et al., 2018b; Latif and Kasolang, 2017. One of the outcomes entitled, Oleophilicity Properties on Pistia Stratiotes Leaves, was presented in Invention, Innovation & Design

Exposition (IIDEx) 2016 and won a Silver Medal. A copyright on the formulation and processing of pistia inspired surfaces are in progress and are expected to complete by early 2021. Future work will look into the second and third phases of the planned work as described in Section 4.0. It is expected to train at least two more Postgraduate Students. For this to materialize, a research grant is needed and attempts for creating research proposals and submission are also planned for midyear of 2021 as the current FRGS Grant for Self-Healing Materials are still in progress which will be 75% completed by midyear next year.

CONCLUDING REMARKS

There are horizons of knowledge to explore in areas related to Biomimetics as there are a tremendous amount of species in flora and fauna all around the world. Future work of Biomimetics are promising and more researchers are welcome into this wonderful source of knowledge offered by nature which is often a masterpiece in design. Applications in engineering could be extended to automotive, aerospace, biomedical, electronics, petroleum, surface engineering, machine tools, power, chemical engineering, construction industry, and the list goes on. Numerous successful applications described in such studies like in lotus effect, spider web silk, bat wing structure, gecko effect, whale fin, shark skin, bee's hives, and shark skin provide a promising future in Biomimetics for everyone. The study on pistia leaves by the author as intertwined in this chapter has been motivated by the unlimited potentials offered by nature as found in Malaysia ecosystem.

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Chapter 5
Biotribology: Heart and Skin

INTRODUCTION

In this chapter, one of the disciplines associated with tribology and biological systems are presented to the understanding of how these systems interact with each other. Biotribology are important considerations for a study on devices involving motions in medical applications. Progress study in this field is discussed from selected journals in this area. A current work on pulsating pump for heart support devices is also presented describing the objective, methodology and some selected results. This is partly to address current issues on heart diseases faced by many around the world. Another important work is on human skin, specifically human face. Skin diseases such as dry skin, eczema, acne, and pigmentation are faced by many around the world. This has affected the quality of their lives to some extent. This chapter describes a technique for skin analysis using 3D analyser and basic parameters for characterizing skin. These two biotribology works are still in progress and supported by two separated FRGS grants obtained in 2018 and 2019. They are subsequently described onwards beginning with Pulsating Pump for Heart followed by Skin Analysis.

BIOTRIBOLOGY AND RESEARCH INTEREST

Biotribology was first used and defined by Dowson in 1970 as those aspects of tribology concerned with biological systems (Dowson & Wright, 1973). The studies on wear and friction of the human biological system were found earlier even before the biotribology concept was established. In materials study of biotribology, scientists have made significant progress in this aspect (Ingham& Fisher, 2005; Singh et al., 2010; Variola et al., 2011). There are many findings of the biotribology studies published in reputable journals such as Biosurface and Biotribology, Wear, Biotribology, Tribology International, Journal of Biomechanics, Computational Modelling of Biomechanics and Biotribology in the Musculoskeletal System, Journal of the Mechanical Behaviour of Biomedical Materials, Journal of Bionic Engineering, and Tribology Series. Figure 5.1 shows the trend in the study of biotribology from 2000 to 2020. The highest trend for publications is from 2015 to 2017. After 2018, the trend has not bounced back to the performance of 2017.

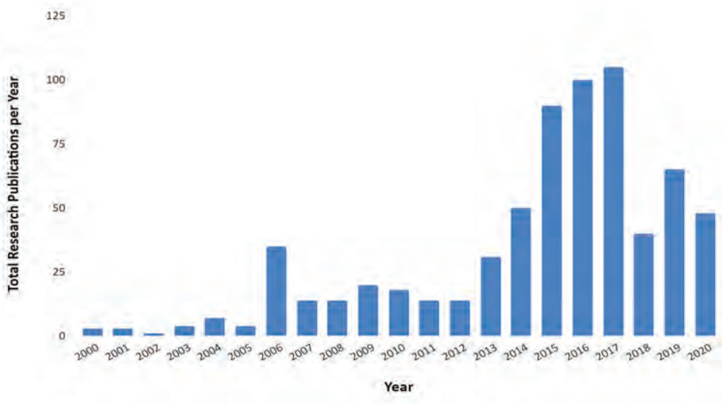


Figure 5.1: Distribution of number of publications found in biotribology areas from 2000 to 2020

Interdisciplinary studies of tribology in the biological system consists of wear, friction and lubricants which engineering aspects of their reported approach are integrated with biomechanics, physiology, chemistry, pathology, and other medical devices. In human body, Zhou and Jin (2015) classify the system into three main areas; joint tribology, skin tribology and oral tribology as well as other representative biological systems in which their findings of research were presented in international forums, workshops and symposia have been held on biotribology or related to biotribology. It is reported that the largest forum of biotribology was the International Conference on Biotribology (ICoBT) held in London (2011) and in Toronto, Canada (2014). The general classification of biotribology is summarized in Table 5.1.

Table 5.1: General classification of biotribology

	Classification	Description/Example
i	Medical Devices	Cardiovascular devices, Implants in blood vessels, Vessels reconstruction
ii	Human Joint	Synovial joints, Artificial Joint, Knee replacement, Hip
iii	Human and Animal Skin	Synthetic skin, skin care product, sports shoes
iv	Oral/Dental Tribology	Human teeth, Implants teeth, toothpaste
v	Human Tissue	Disease related to cancer, hair, bones, blood vessels
vi	Biomaterials	Biocompatibility materials, friction and wear, and low creep deformation materials to adapt the increasing demand of biomedicine
vii	Optical	Biomechanics of human eye, implants, and applications

CARDIOVASCULAR DEVICES FOR HEART DISEASE

Tribology study in cardiovascular devices may have a combination of bio-tribology covering all aspects of tribology integrated with biological systems. The technology of cardiovascular devices has significantly contributed to the advancements in cardiovascular disease treatment in modern medical solutions. However, researchers put less focus on friction and wear of cardiovascular devices which may cause damage and bring to serious complications, such as haemolysis, blood clot, thrombus and so on.

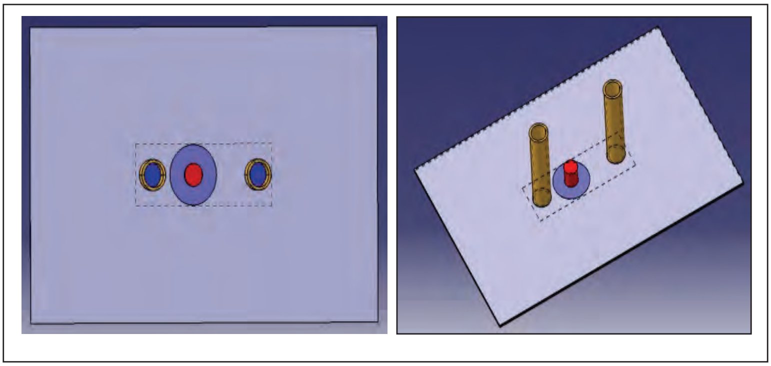
The current experimental study in the Tribology Laboratory in the faculty of Mechanical Engineering, Universiti Teknologi MARA is focusing on the solution of the abovementioned problem. By providing alternative solutions using valve-less pumps of cardiovascular devices, it is expected that the complication arose may be minimized in the real application.

From the activity carried out, the first part focuses on analysing the equation of magnetic force numerically in order to investigate the suitable magnetic force needed to provide safe operation of the pump. The radius and thickness of the magnet were varied in order to identify the parameter that was suitable for the pump operation. The value of the parameters used is predetermined except for magnetic force needed as the magnetic force is the main parameter that is going to be discussed. This problem was computed by using MATLAB Software and the geometrical model is designed and modelled by using CATIA V20 at micro scale to show the structure of the pump. Based on the MATLAB computation result, it shows that stroke volume increases as the ratio of diaphragm and magnet radius increase. The relationship between magnetic for and volume of magnet used also the same. The numerical analysis proved that permanent magnet and micro-coil actuators can provide a satisfying diaphragm displacement and stroke volume of the system in a safe pump operation state.

In the experimental research the objective is to study the effect of structural parameters on the elastic tube and the flow behaviour generated by periodic pinching at an asymmetric location. The effects of tube structure to the flow rate based upon different thickness and the relationship between flow rate and pinching position were determined. The closed loop impedance pump system was set up to demonstrate a blood flow circulatory system where the mixture of glycerine and water was used as a test rig. The experiment was conducted with different lengths of elastic tube such as 200 mm and 260 mm, whereby each length came with different thickness of 1 mm and 3 mm, respectively.

NUMERICAL APPROACH

The design process of the pump was done in CATIA V20, and the dimensions of the pump were decided after a few papers were studied in order to find the most suitable size of the pump that can produce the output yet have a safe pump operation (Figure 5.2). Membrane actuator mechanism is used because this mechanism can produce a large stroke volume thus will give high diaphragm displacement. A polydimethylsiloxane (PDMS) is chosen as the material for the diaphragm because it has good flexibility and high yield strength which is important to provide safe pump operation.



(a) (b)

Figure 5.2: Pump (a) top view (b) isometric view

This pump consists of four different layers; the first layer contains PDMS diaphragm with embedded permanent magnet on top, followed by an upper glass plate, a microchannel and a bottom glass substrate which contain micro-coil on top of it. With these four layers in total, the size of the pump in length × width × height is 29 mm × 19 mm × 7.24 mm, respectively. Meanwhile the size of the microchannel is 11.35 mm in length × 4 mm in width × 0.05 mm in height.

In analysing the electromagnetic actuator micropump, the objectives were to investigate the effect of different thickness and radius of magnet to the force exerted by magnetic actuation pump and to determine the maximum deflection and stroke volume due to force variation in the scope of safe pump operation.

Table 5.2: Set of different parameters involved

Parameters	Radius of the magnet, *c* (µm)	Thickness of magnet, h_m (µm)	Radius of the diaphragm, *a* (µm)	Thickness of the diaphragm, *h* (µm)
Data	600-800	1100-1500	1950	70

As mentioned from the previous section, the deflection of the diaphragm depends on the difference in electromagnetic force produced by the permanent magnet and the coil. And the difference in the force intensity results in the diaphragm to resonate thus producing stroke volume. Therefore, by varying the parameter of the magnet (Table 5.2), different amounts and intensity of the electromagnetic force can be studied.

EXPERIMENTAL APPROACH

There were several procedures needed to be considered while performing the experiment. The main components and the experimental setup were described in Mazwan et al. (2013). An elastic tube of 200 mm long and 1mm thick were deployed with details described in Table 5.3. The water pipe was completely filled into the whole circuit via T-tubing barb. The pincher location was set about 20 mm from the left side of the elastic tube. Before starting the experiment, the voltage of the direct current (DC) motor was set up to 2.0 V. The electrical power supply was switched on to let the pincher press the elastic tube. When the pincher pressed the elastic tube section, the water inside the rigid tube flowed through the flow meter. The flow rates of the flow meter were recorded. After that, the steps were repeated using a 3-mm thick elastic tube with different applied voltage values of 3.0, 4.0, 5.0 and 6.0 V. The steps were repeated using 260 mm length of elastic tube.

Table 5.3: Detail specification of experiment variables

Part	Parameter	
Elastic tube	Outer Diameter, mm	30.0
	Thickness	1.0 and 3.0
	Length, mm	200.0 and 260.0
Actuator	Length, mm	150.0
	Diameter, mm	10.0
	Thickness, mm	10.0
Electrical DC motor	Voltage, V	2.0, 3.0, 4.0, 5.0 and 6.0

Other parameters considered are voltage of the DC motor, the length of elastic tube and the pinch location. Some of the results are presented subsequently. Figure 5.3 shows the dependence of flow rates on different thickness of elastic tubes with different voltages. They were two samples of different thickness with the same length being tested. The elastic tube length was 200 mm. From Figure 5.3, it can be seen that those two samples of different thickness give out the same flow rate pattern over voltage. This was expected because the rotational speed of the motor increases as voltage increases. Hence, the kinetic energy delivered towards the elastic tube automatically increases. Due to this condition, the working fluid tended to flow faster. In terms of various thicknesses, it was found that if the wall thickness of the elastic tube increases, the volume flow rate of the working fluid decreases. The sample with thickness of 1 mm has higher flow rates compared to that of 3 mm thick due to reduction in the inner diameter as the thickness increased. Since the area of the specimen had decreased, the volume flow rate of the fluid decreased as well.

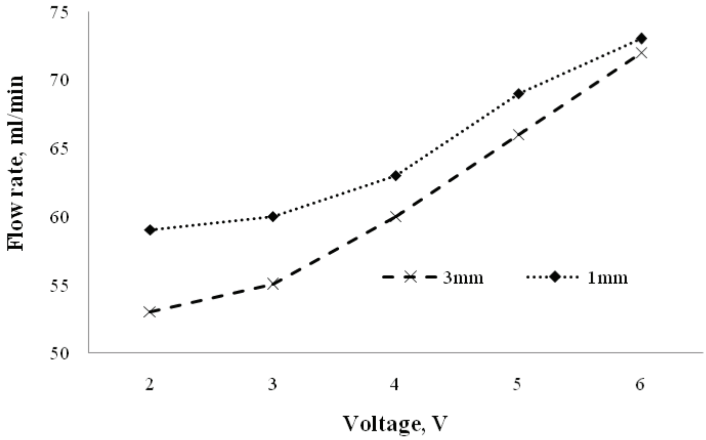


Figure 5.3: Effect of voltage on tube thickness for 200 mm tube length

The dependence of flow rate on different thickness of elastic tubes with different voltage curve profiles are shown in Figure 5.4. The difference with the previous graph is the length of the sample of the elastic tube. The length of the sample is replaced by 260 mm long. The purpose of this change is to identify whether it affects the volume flow rate of the liquid or not. The trend in Figure 5.4 is somewhat different from those in Figure 5.3. The length of the tube does affect the flow rate for both cases of thickness values.

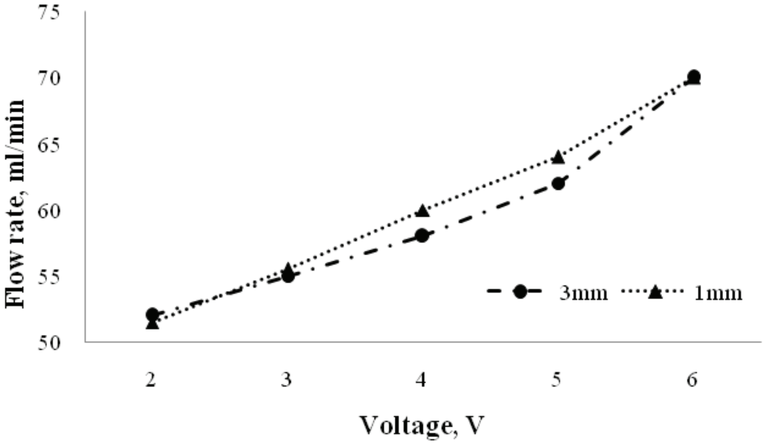


Figure 5.4: Effect of voltage on tube thickness for 260 mm tube length

Another important parameter is the pinch location. Investigation on the dependence of flow rate on different pinch location with varied voltage is depicted in Figure 5.5. There is one sample of elastic tube that is being tested. The elastic tube was 200 mm long and 1mm thick. From Figure 5.5, the profiles over pinch locations are almost the same for all values of voltage. On a closer look, the change in the flow rate is more pronounced between location 40 mm to 60 mm. This suggests that the system becomes responsive within the region and hence can be manipulated to give the best out of the system. From that graph also, it can be concluded that the closer the pinch location to the centre of the elastic tube, the smaller the recorded flow rate. Figure 5.5 shows that elastic tubes with thickness of 1 mm and length of 200 mm with the pinch location about 20 mm produces the desired flow rates of 81 ml/min at applied voltage of 6.0 V.

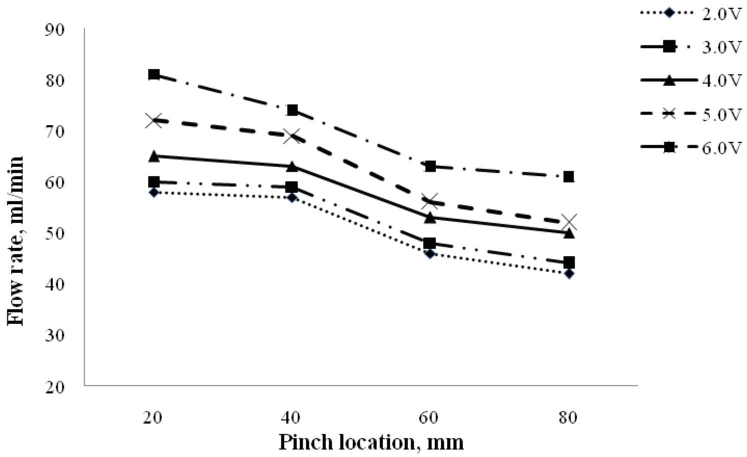


Figure 5.5: Effect of pinch location for 200 mm tube length with 1 mm thickness

ACHIEVEMENTS AND WAY FORWARD

Currently, there is one PhD student in progress working on Pulsating Pump for Heart Disease with three publications (Mahat & Kasolang, 2018; Mahat et al., 2015; Mahat et al., 2013) this far. There are also a few proceeding papers presented in conferences. With the application in mind, there is an ongoing collaboration with Hospital UiTM Sungai Buloh regarding this matter. One new paper on Numerical Analysis of Pin on Disc Structural Parameters Using Finite Element Method Simulation, which is a spin off from this work, is on the way. This work is partly supported by FRGS Grant awarded in 2019. The author and the research team are in debt to all parties involved in this project directly and indirectly.

SKIN ANALYSIS AND MEASUREMENT PARAMETERS

Skin Tribology has captured the interest of many researchers around the globe. There are many instances where interactions of skin in a defined system become a concern. Among the current interests and work of the authors on skin are related to Cosmetic effects on skin and management of skin disorders using appropriate skin care products and cosmetics. A relatively new study on Skin Tribology was officially initiated at the Centre for Tribology, Faculty of Mechanical Engineering UiTM after receiving FRGS Grant award in 2019. The interest in Skin Tribology specifically Skin Disorders is growing, and this is evident by the publication profiling for the last 20 years from 2000 to 2020 as shown in Figure 5.6. The trend was produced on Science Direct Search Engine using keywords "common human skin disorders" and only focused on published research articles. Profile in Figure 5.6 may not be extensive, but it does give a general indication on the interest of the research community and public on Skin Disorders. With the current trend, it is strategic to pursue this study.

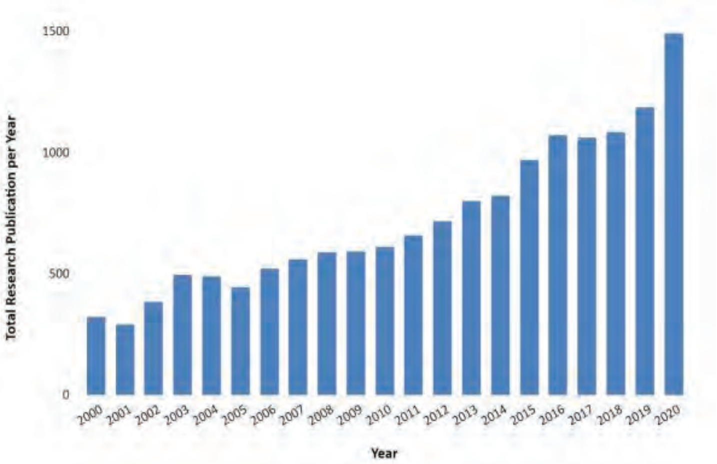


Figure 5.6: Research trend on skin problem for 20 consecutive years from 2000 to 2020 using Science Direct Search Engine based on a specific keyword, 'Common Skin Disorders'

The highest jump is from 2019 to 2020. The current Pandemic Covid19 has perhaps influenced the observed trend as they might have shifted their energy from conducting experiments to writing and publishing research papers. Skin Disorders are a concern to many people around the world regardless of age, gender, and race. It is related to the dysfunction of skin's components or defects found in the layers of human skin. It is strategic to pursue this study and a review of skin disorders was published by Kasolang et al., (2020) and this provides basic understanding of the current context such as research trends, skin facts, and types of skin disorders.

SKIN BASICS

The largest part of humans is skin which covers the entire body with a surface area of 2 m^2, average thickness of 1.2 mm, average volume of 3.5 dm^3 and it takes about 16% of the body weight (Agache & Humbert, 2004). Imagine a human without skin; it must be grotesque to look at. Though skin is needed for beauty, there are other more critical functions such as protection from harmful things in the surrounding, a chemical barrier by limiting the entry of foreign substances as well as preventing water and depletion of endogenous fluids. Skin to human also means potential; people with good skin condition are more likely to be confident in socializing with others compared to those with chronic skin diseases. People with beautiful skin may even use it for getting jobs in specific industries where beauty matters such as in film making, modelling for cosmetics, and clothing, and similar stuff.

Skin like any other part of the human body has its own characters and the ability to heal itself is one of the amazing potentials designed by the Creator. This self-healing property allows skin to, over time, maintain and repair itself. The outermost layer, Epidermis, can be subdivided into five layers or Stratum: Corneum (outermost), Lucidum, Granulosum, Spinosum, and Basale (innermost). Skin cells mature as they move up from a basale layer to corneum. Two terms are often used in describing skin aging time. Skin Turnover Time (STT). The first term is Transit Time, the time required for a basal cell to reach the granular layer (second layer). Renew Time is the second term which describes an average time for all basal cells to reach the corneum layer (first layer). Generally, the common renewal time for skin cells is 27 to 28 days. On deeper investigations, in some literatures, different values of turnover time were reported. Grove & Kligman (1983) found that the transit time for young adults and older adults was 20 days to 30 days, respectively. This explains why damaged skins of younger people heal faster than those of older ones. Some other reported STT values vary from 13 to 18 days (Epstein & Maibach, 1965), 26.7 days (Pinkus, 52), 14 days for innermost layer and 52 to 75 days for total Epidermis of normal skin (Halprin, 1972).

The author believes that the cyclic skin renewal process is influenced by other factors such as the menstrual period experienced by women as well as the condition of hormone in their body. A work on this matter is in progress and earlier findings were presented in Proceedings of Mechanical Research Day 2020 (Adlina & Kasolang, 2020). Other skin functions are for exerted immune function, sensory function, body temperature regulation, and the production of vitamin D (Agache & Humbert, 2004; Kolarsick et. al, 2011; Nicol, 2005). Skin Anatomy consists of three main layers: Epidermis (outermost), Dermis (middle), and Hypodermis (innermost). When people lubricate their skin with moisturizer or other skin care, they actually prepare the Epidermis. The benefits may or may not extend to the low layers. This is another concern worth investigating to be sure of the quality of any skin care products offered in the market. Epidermis is made up from keratinocytes, melanocytes, Langerhans cells and Merkel cells while dermis is made up of the fibrillar structural protein or known as collagen. Epidermis is the thinnest, followed by dermis and finally hypodermis with 0.01 cm, 0.19 cm, and 0.60 cm respectively (Yusoff & Jaafar, 2012).

In the context of skin tribology, wear, and tear of skin manifests as aging and skin disorders while introduction of skin care and cosmetics offers solutions in managing skin aging and disorders. There are similarities worth noticing between machine lubrication and skin lubrication. In many applications involving motion, introduction of lubricating film is mainly to reduce friction and the context of its application has been described in many studies (Latif et al., 2019a; Syahirah et al., 2015; Ahmed et al., 2014; Kasolang et al., 2011, Kasolang et al., 2020). A review of skin disorders in Kasolang et al., (2020) is an early work to appreciate the past and current work by other researchers on skin and cosmetics.

SKIN ANALYSIS

Kasolang et al. (2020) describes common types of skin disorders into three main categories: Dry Skin (Eczema, Xerosis, Atopic Dermatitis and Psoriasis), Hyperpigmentation (Post-Inflammatory, Vitiligo and Melasma) and Acne. In a recent study (Shah & Sheth, 2019), the statistics pointed to three top skin diseases namely Eczema, Xerosis, and Acne with a specific percentage of 32%, 21%, and 16% respectively. By the amount of publications for 3 consecutive years from 2017 to 2019, Dry Skin remains high with recorded numbers of 623, 716, and 884 respectively; the numbers for Acne are 153, 134, and 208 and for Hyperpigmentation 71,77, and 136 over the years from 2017 to 2019.

One of the main aims of the current study by the author is to improve the quality of lives of those having skin disorders. One technology that can be deployed to empower them is through 3D Skin Analyser which are available in many Aesthetic clinics. A Skin Management Model will be proposed at the end of the study which includes the use of a 3D analyser for controlling and monitoring of skin condition and needs.

The 3D Skin Analyzer enables users to assess the quality of skin conditions in terms of skin parameters such as pore, sebum, wrinkles, moisture, elasticity and pigmentation (Figure 5.7). Big pores are not desired by many women not only because of the aesthetic reasons but most importantly it may create secondary problems such as clogged pores and eventually acne. Appearance of wrinkles to many women is a nightmare and they are more visible at the forehead, under the corner of the eyes, and around the smile lines. Naturally, the appearance wrinkle can be reduced or slowed down with proper habits of eating, skin care routine and exposure to factors detrimental to skin such as UV rays. Understanding skin needs as well as strength and weakness will help in creating a successful Skin Management which is unique from one individual to another.

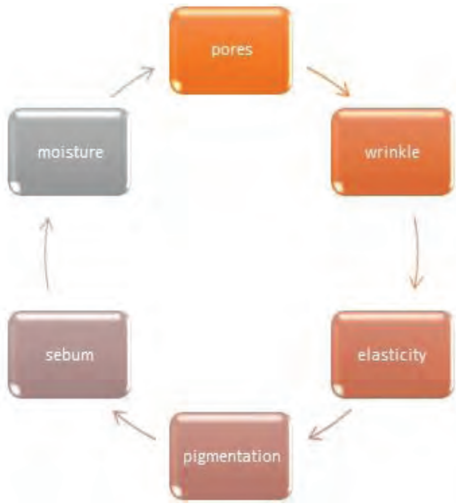


Figure 5.7: Assessment parameters given by a 3D skin analyser

Adlina and Kasolang (2020) found that the use of skincare products coupled with specific treatment produced better results in terms of skin pigmentation and elasticity. For skin with treatment, the majority of participants' skin pigmentation gradually reduced, and the skin became more elastic. Further study is needed to look into the synergy of treatments and the critical steps. As an analogy, for very dry soil, it is necessary to water more than once. The first time, much of the water will just pass through and hence a second time is needed before the soil can absorb and retain moisture. Similarly, the moisture routine for very dry skin needs to be observed to identify the necessary modification for best results.

ACHIEVEMENTS AND WAY FORWARD

For Skin Tribology, there is one PhD student in progress with two publications (Kasolang et al., 2020; Adlina & Kasolang, 2020) this far. Future planning is to have collaborations with local and international cosmetic companies for various initiatives including attachment of the PhD student for a period of two to four months, getting a new formulation and testing of skincare products, and planning an overseas visit to Korea Beauty Industry through relevant government agencies. The next project is to see the synergy of skincare andconsumed products (food supplements) as intervention to promote healthy skin and also as solutions for those having skin diseases. This will open more topics for postgraduate and undergraduate students in future. One paper entitled, *Golden spice: A review of turmeric effect on skin* is in progress.

CONCLUDING REMARKS

Biotribology is another important branch of tribology. In this chapter, two areas of biotribology have been described. The study for heart application was carried out numerically to find the characteristic of micropump for safe pump operation. It can be concluded that the best radius of the magnet that needs to be used for the micropump is between 600 to 700 µm while the thickness that suits it to be used are between 1100 to 1300 µm for best stroke volume and best deflection. It also proved that by using permanent magnet and micro-coil as the actuator, it can provide enough actuating force for large diaphragm displacement. From the experiment, it was found that the best parameter which provided the optimum fluid flow rate is the elastic tube with the thinnest and shortest characteristic. Elastic tubes with thickness of 1mm and length of 200 mm with the pinch location about 20 mm produced the optimum flow rates of 81 ml/min at applied voltage of 6.0 V. The voltage cannot be further increased as the flow will become reversal flow with negative recorded values.

Skin Tribology looks into skin basics and skin common disorders. The interest in skin tribology has shown growing interest as evident from the increasing publication number over the recent years. One of the important layers in skin anatomy is the most outer layer known as Epidermis with five sublayers. A preliminary study shows that two skin parameters namely pigmentation and elasticity were affected by the type of skincare used and treatment chosen. This suggested that with specific treatment of skin problems, the appearance of skin condition could improve. It is in the interest of the author to investigate how factors such as menstrual cycle time affects the skin turnover time in future. Findings from the study may guide the establishment of a Skin Management Model tailored to the specific needs of the user.

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My Story of Tribology contains five chapters on different but related tribology themes. Chapter 1 is dedicated to introducing Tribology including economic importance, how tribology affects our lives, and the GURUs. In Chapter 2, the theme is Journal Bearing, a machine component deployed by the author in her PhD work. Some of the topics highlighted are basic design, functions, bespoke journal bearing, benefits, and Raimondi & Boyd Charts. Journal bearing has to be supported with a hydrodynamic lubrication system, discussed in Chapter 3. Some important topics are leading lubricant companies, engine oils, Stribeck Curve, and properties of lubricants. In Chapter 4, Biomimetics is introduced and the intention is to learn from nature. Discussions include plant surface structure, adaptation of plants, surface wetting and surface angle as well as current research work. Chapter 5 ends the book with a discussion on Biotribology, exploring the use of a pulsating pump for cardiovascular devices.

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ISBN 978-967-363-707-2

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