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Numerical Analysis of Tribological Characteristics for Textured Piston Ring-Liners in Mixed Lubrication with A Non-Circular Cylinder Bore

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Abstract: Piston ring packs are commonly found in the engine. It is a necessity for an engine to run smoothly. The function of the piston rings is to control the lubricant and prevent leakage. The interface of the cylinder bore with the piston rings will cause a tribology behavior. Laser Surface Texturing (LST) on the piston ring surface had shown positive results in previous studies. In this study, we are considering the surface texturing of the piston rings in a distorted bore. Moreover, the texturing detail on the piston ring surface is also considered by modifying the dimple size or the micro-groove on the surface. 3D modeling software, SOLIDWORKS is used to model the piston rings and a finite element method software called COMSOL Multiphysics is used to perform multiple simulations to obtain the result. The result shows that the texturing of the piston ring surface improves the tribology performance during the engine cycle. Meanwhile, for the surface texturing details, the large lateral aspect ratio gives a negative effect.

Keywords: Cylinder bore, piston ring, tribology performance, surface texture.

1. Introduction

On the engine piston, there is a piston ring-pack, containing a set of piston rings; one of them is named the compression ring. This compression ring is located at the upper part of the engine piston; it consumes almost 5% of petrol consumption to subjugate the frictional force [1]. In the automotive sector, road vehicles take up to two-thirds of the energy consumed by the whole transportation field [2]. Numerous research had been conducted to investigate the tribological characteristics of the compression rings of the piston. From the overall results of the research, it can be identified that there are various types of factors that influence the performance of the piston compression rings. For instant, Ma *et al*. [3] discovered that there are several factors that distort the circular shape of the piston ring-liner (PRL) such as pressures on the high cylinder, thermal loads, the difference in load with thrust and anti-trust side, forces of thermal clamping, and errors of manufacturing.

From the experiment of Shu *et al*. [4] which used an actual engine, it is found that the liner deformation is strongly influenced by the engine oil transport. Their observations are referred to as emissions caused mostly by the layer of lubricant left behind by the ring on the liner of the cylinder [5,6]. According to Usman *et al*. [7], the increased oil that depends on the thermal ability to transfer to the combustion chamber is aided by cylinder deformation. For a variety of bore distortions, cold engines showed an increase in oil transfer of 59.20 ± 12.90% as compared to a warm engine. As a result, it is crucial to understand the effect of the lubricant on the ring in a deformed bore.

According to Liu et al. [8], PRL lubrication using a 2D model formula, the circumferential film thickness is non-uniform. Meanwhile from the research of Hu et al. [9], they investigated a non-axisymmetric PRL convergence under variable lubrication. The results found that liner bore

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non-circularity was determined to be one of the factors of tribological performance fluctuation based on direction.

To improve the performance of the compression rings of the piston, the most identical method is to reduce the friction in the piston. According to Imai *et al*. [10], the reduction of friction induced by surface roughness is achieved through three factors, the hydrodynamic effect, a tiny lubrication spot, and the lubricant trapping effect, which functions as small storage of lubricant. Regarding the textured ring's significance in out-of-round engine cylinders, its tribological effectiveness has never been investigated. According to Dowson [11], it studied the numerical investigation of such tribological fulfillment of a texturing PRL contact with a distorted cylinder liner. The generalized Reynolds equation is used in a 2D mixed lubrication model.

Hence, this research will determine the tribological performance of a textured piston ring liner (PRL) in contact with the distorted liner of the cylinder bore with a non-circular shape. Besides that, this study also to investigate the tribological performance using COMSOL software by analysing the different parameter. Once the results obtain, it will be comparing the performance of textured and untextured piston rings from the model built by SOLIDWORKS.

2. Previous Work on Tribology Characteristics

The study of tribo-dynamic by Congcong Fang, *et al*. [12] presented a computationally efficient model that fully connects these two friction pairings to examine their tribo-dynamic relationships. It emphasizes the tribological properties of said Piston Skirt-Liner (PSL) system for a complete engine cycle without and with the Piston Pin Bearing (PPB) system considered from a tribological standpoint. In both circumstances, the thrust force exerted upon the piston skirt is overlapping and it can be observed that the minimum oil film thickness (MOFT) curves for the PSL mechanism in the two cases show significant deviation during the powered stroke.

Bo Zhao, *et al*. [13], simulate and analyze the greased piston skirt-liner contact using multiphysics coupling. The COMSOL Multiphysics software was used to combine the heat flow of the cylinder and piston, multibody mechanics of the crank-connecting rod-piston cylinder mechanism, and hydrodynamics lubrication of the skirt-cylinder interaction, heat, and elastic deflection of the piston-cylinder system, and the rheology of lubricating oil. Another interesting finding on tribology behaviour found by Ajith Kurian Baby, *et al*. [14], which carried out an experimental investigation on the influence of honing angles on tribological behaviour. The purpose of their research is to see how honing angles affect border lubrication. Experiments were carried out at two different speeds, 0.2 m/s, and 0.3 m/s, to show the state of an engine's top dead centre. The friction coefficient was the primary reaction obtained from the ring-liner specimens' slide wear testing (COF). The study's major parameters were the angle of honing and the sliding frequency, with the rest of the variables remaining relatively constant. With variation height parameters, the influence of the tribological processes on the cylinder liners interface was studied, and they noticed a reduction in the amplitude of the height variable. With increasing groove angle, COF values typically increase. Nevertheless, the lowest value for 40 was discovered, while the greatest value for 80 was discovered.

For bearing tribology, Nathália Duarte Souza Alvarenga Santos, *et al*. [15] was the concluded that the automotive industry faces a continuing technological difficulty in the search for a more highly durable bearing that is both technically and economically viable for use in engine moving element foundations. It also suggests that recent technological improvements have contributed to a better knowledge of friction, lubrication, and wearing of vehicle bearings, which can be used to start-stop systems. Support by Xiang Rao, *et al*. [16], from the standpoint of tribosystems, online monitoring systems and self-repairing strategies for in-service diesel cylinder liner-piston ring components (CLPRs) is one of the best ways to overcome the problem. The study's focus is on monitoring lubricating oil conditions, vibration conditions, and various other methodologies used in diesel CLPR monitoring systems, such as temperature parameters and instant angular velocity studies.

In term of material for piston ring, Love Kerni, *et al*. [17] investigate the tribological characteristics of several Al alloys used for piston and cylinder systems under lubricated conditions. The investigation is limited to the aluminium alloys Al, Cu, Mg, and Si, that are used. These alloys can be heat treated. The main benefit of using this variety is it is lightweight, has good mechanical qualities, and the texturing on the surfaces of aluminium alloys enhances tribological capabilities. Cayetano Espejo *et al*. [18] studied the role of molybdenum dithiocarbonate (MoDTC) tribo-chemistry in engine tribology performance. Their research focuses on how the friction modifier of MoDTC affects the performance of a car engine. A Friction Torque Test (FTT) was used to carry out the motored test to achieve representative and high accuracy measurements. According to them, this is the first time Raman microscopy has been used to conduct a detailed analysis of most engine components in the tribological interface.

For a method for piston dynamics and lubrication analysis, the thrust depends mainly on the crank speed [19]. In addition, it should be noticed that the viscosity of the lubricating oil has a significant impact on the skirt cylinder system's performance. The skirt cylinder system's lubrication performance will be improved by the micro surface shape and texture on the interface. According to Gula, *et al*. [20], the studies are using a cylinder liner-piston ring combination and high-frequency reciprocating rig (HFRR) and four-ball tribo-testers, the tribological features of cotton bio-lubricant mixes with commercial-used lubricant (SAE-40) were studied in this work. The tribological performance of the cylinder and piston rings was tested by HFRR under various bio-lubricant samples (0-50%) mixes of CBL with SAE-40.

Meanwhile, in HFRR tribological analysis, the friction coefficient decreases when the bio lubricant content in the SAE-40 mix grows up to 30%, but afterward, it is relatively steady. Hideaki Aoki, *et al*. [21] was study the grooves formed by machining on the face of the piston skirt affect lubrication performance. Their method for this study is mainly by using the Taguchi Method. Based on the surface shape, material, and two interfering objects' load under dry conditions, the displacement and surface pressure of the items were initially computed elastically using the finite element method. Experimental work by Venkateswara *et al*. found the effects of positive texturing on friction and wear reduction of piston ring and cylinder liner system [22]. Positive texturing reduces friction and wear in the piston ring/cylinder liner (PR/CL) system under lubricated settings by promoting a rotational slipping movement between the textured ring and the untextured lining, according to this study.

In term of texturing effects and friction characteristics, Jian Li, *et al*. [23], presents an equivalent design of two-stroke traditional crankshaft engines (TCE) based on an existing free-piston engine generator (FPEG) prototype size. The research conducted using the MATLAB/Simulink to establish simulation models of FPEG and TCE. The in-cylinder thermodynamic model is divided into six processes, inlet, and outlet emission, scavenging compressing and expensing, combustion, thermal transmission, and gas leakage. Another method proposed by Nandakumar, *et al*. [24]. They used laser surface texturing (LST) of the piston skirt primary thrust edge as a way of restoring compression in an aged engine. The obvious advantage of lasers is targeted heating followed by rapid solidification, providing the textured surface casing hardened effect. The laser texturing further investigates by Ezhilmaran, *et al*. [25]. They study on the laser texturing of the piston ring and its tribology effect characteristics. The laser wavelength of 532 nm was used for texturing to generate dimples with different sizes, aspect ratios, and area densities. ranging from 40 μm to 130 μm, 0.1 to 0.3, and 5% to 38%, respectively were measured experimentally by using a reciprocating tribometer. For the analysis of wear, the effect of textured and non-textured ring specimens with varied dimpled region density on the liner's wear rates at different dimpled sizes which are 40 m, 80 m, and 130 m, in comparison to the textured samples, the liner with the non-textured ring sample had a higher wear rate.

3. Methodology and Modelling

For surface modification, the ring profile used is the barrel-faced profile. Because of the squeeze film flow, a flatter ring provides a capacity at shows a greater ability to withstand load at stroke ends, a barrel-faced ring could be able to deliver the best frictional response. Thus, surface texturing has influenced the performance of the barrel-shaped ring. Because texture shape has a minor impact on tribo-characteristics, the texturing patterns have a stepped depth. Due to the proven benefits, a symmetrical texture design with 60 percent of the ring surface textured is chosen. The non-roundness of the cylinder bore is intentionally ignored to observe the effect of texture. As a condition of the symmetrical textured distributions in both the axial and circumferential directions, only a unique strip can run the length of the piston ring which is highlighted blue in Figure 1(a), shows a slice of a modified ring surface, with the groove geometry nomenclature applied to the surface texture. Figure 1(c) shows a non-circular hole in the transverse direction that causes separation in a ring-liner texturing.

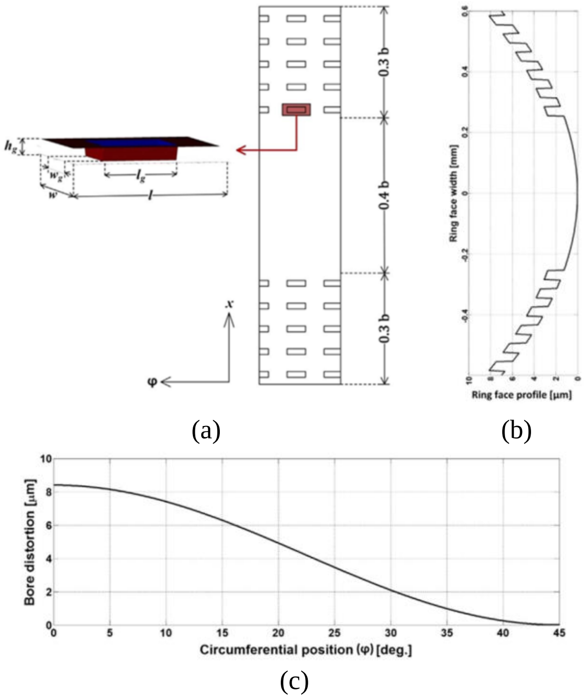


Fig. 1 – Geometric details of a PRL interface with no cylinder pressure

3.1 Lubricant viscosity and flow rate

Table 1 shows the parameter of the engine oil which is SAE 10W-30 oils used for this present work. The Vogel equation is utilised to calculate temperature-dependent viscosity at various liner positions, while the Roeland's viscosity pressure equation is used to calculate the immediate isothermal equation for each crank angle.

$$\mu'_o = \mu_o \alpha e^{\frac{k_1}{(T-k_2)}}$$
$$\mu_1 = \mu'_o \exp\left(\left[\ln(\mu_o)+9.67\right]\left[1+\left(1.51\times10^{-9}\right)p\right]^z - 1\right) \quad (1)$$

where k_1, and k_2 are oil-dependent constants, μ_0 is the viscosity atmospheric temperature, and z is defined as follows,

$$z = \frac{1\times10^{-8}}{\left(5.1\times10^{-9}\right)\left(\ln(\mu'_o)+9.67\right)} \quad (2)$$

Table 2 – Engine oil parameter

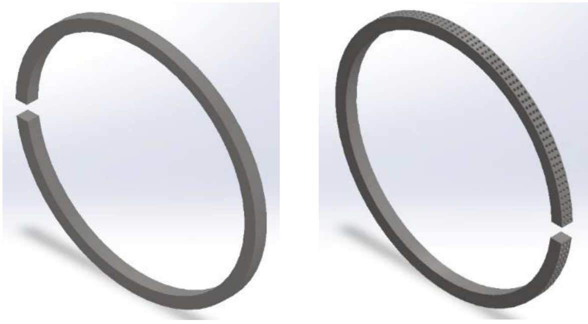
Oil	α (Pa s)	k_1	k_2	μ_2/μ_1
SAE 10W-30	1.5331×10^{-7}	4986.60	-349.82	0.76

Fuel consumption across this segment has a major influence on the emission of the engine's outlet in the current study. Symmetric boundary restrictions by borders in the circumferential direction are applied to lower the computation domain. In this study, oil leakage at the edge of the ring clearance is neglected. The number of engine lubricants left behind the ring is presented below.

$$q(\theta)=\int_{0}^{2\pi r}\left(\frac{Uh}{2}-\frac{h^3}{12\eta}\frac{\partial p}{\partial x}\bigg|_{x=x_t}\right)dy \qquad (3)$$

where x_t is the trailing edge position of the ring.

For the model, the textured piston rings have been surfaced textured with micro-grooves or dimples on the ring surface, shown in Figure 2. This texturing process makes significant differences in multiple aspects as expected.



Untextured ring Textured ring

Fig. 2 – Simulation model for piston ring

3.2 Numerical simulation

In this present work, finite element method-based software is used for the simulation, which is COMSOL to solve the governing equation. An absolute tolerance of 0.1% for each crank angle and relative tolerance of 1% for consecutive iterations are used to meet the convergence criterion. When balancing radial forces, absolute tolerance refers to the amount of error that can be accepted, whereas relative tolerance relates to the difference between the computed unknowns in two rounds. As governing equations are solved using a direct solver, tolerances become relatively negligible. To solve the governing equations for the whole engine cycle, the time-dependent solution is modelled for 0.08 s. At each time step, COMSOL will use a monolithic approach to solve the system of nonlinear equations and constraints, which involves simultaneously solving equations to obtain a solution for all dependent variables by using the Newton

Raphson iteration scheme and the generalized alpha time stepping algorithm. The mesh dependence test was then run to check that the results were accurate. At the same time, to create the model of the piston rings, a 3D modelling software called SOLIDWORKS had been used to create a model for both textured and untextured piston rings. The values of the parameters used in the numerical simulation are presented in Tables 2 to 4, while the flow chart for the numerical simulation shows in Figure 3.

Table 2 – Engine oil parameter

Parameter	Value
Circumferential position of maximum bore distortion	1.60 rad
Connecting rod length	240 mm
Crank radius	60 mm
Nominal bore radius	45mm
Bore distortion order	4
The radial thickness of the ring	3mm
BDC temperature	86 °C
Circumferential position of maximum bore distortion	1.60 rad
Circumferential position of maximum bore distortion	1.60 rad
Connecting rod length	240 mm

Table 3 – Piston ring properties

Lateral Aspect Ratio ε_1	12.25
Increment of ratio	ε_1, 5ε_1, 10ε_1, 15ε_1, 20ε_1, 25 ε_1
Material	D2 tool steel
Length of groove, lg	6.125 mm
Width of groove, wg	2 mm

Table 4 – Mechanical and surface properties

Parameter	Value
Average roughness of liner	0.26μm
Average roughness of ring surface	0.235 μm
Measure of asperity gradient (N′β′σ)	2.034×10−3
Roughness parameter (σ/β′) 1/2	0.027889
Young's modulus of liner	92.3 GPa
Young's modulus of ring	203 GPa
Average roughness of liner	0.26μm
Average roughness of ring surface	0.235 μm
Average roughness of liner	0.26μm
Average roughness of ring surface	0.235 μm

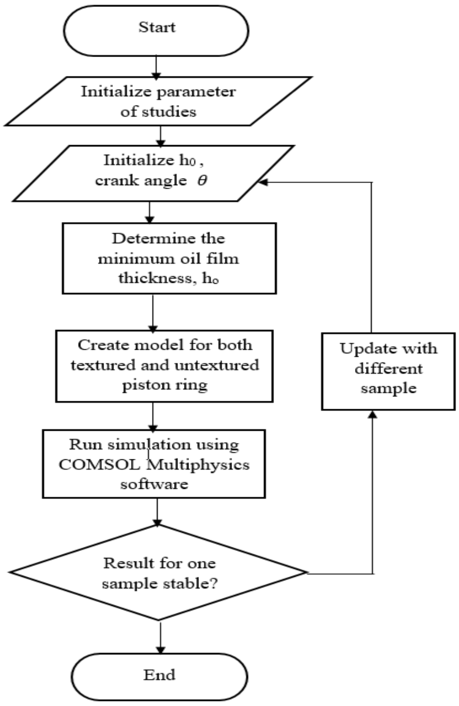


Fig. 3 – The flow chart for numerical simulation

4. Results and Discussion

The simulation of the piston rings is to simulate the characteristics of both the textured and untextured piston rings. This process simulates the 1000 Pa pressure applied on three different axes of the piston rings surface. Results from the simulation, the velocity magnitude on texture and untextured piston ring shows in Figure 4.

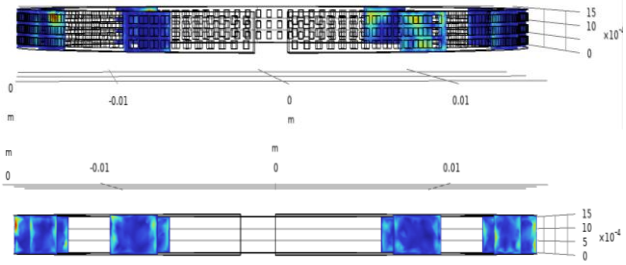


Fig. 4 – Velocity contour for textured (above) and untextured (below) of simulated piston ring

The blue color indicator indicates the low velocity of the lubricant when flowing through the piston ring surface meanwhile the red colour indicator indicates the high velocity of the lubricant when flowing through the piston ring surface. From the result obtained, we can observe that the surface of the textured piston ring is almost all blue colour indicator. This can be explained that lubricants barely flow by or flow on the piston ring surfaces. Meanwhile, for the untextured piston ring, we can observe that there is an obvious red indicator on the left edge of the surface. This can be explained that there are positions that this untextured piston ring model is used in this simulation that allows the high-velocity flow of lubricants through the piston ring. We can conclude from the above results, textured piston rings are more effective in preventing leakage of lubricant than untextured piston rings, as the main function of compression piston rings is to seal up the piston from leakage. To study deeper on the velocity, the graphical result for each *x*, *y* and *z*-axis shown in Figure 5.

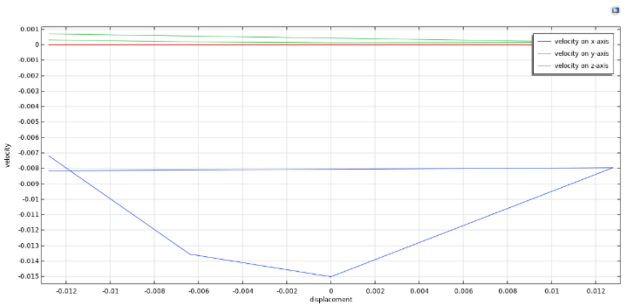


Fig. 5 – Velocity on different axis on the ring surface

From the figure, fluid velocity of the lubricant on a different axis of the textured piston rings. Neglecting the negative value of the velocity of the x-axis of the piston ring surface, we can observe that only the y-axis shows a very low velocity of the lubricant. We can also observe this from the figure, the green indicator that indicates low velocity. Throughout the simulation, the velocity on the *x* and *z* axis shows no velocity through the ring surface.

This can be explained that the direction of both axes effectively seals the piston ring with the cylinder bore. However, it is not ideal that a piston ring completely prevents flow through of lubricant but from the magnitude of velocity on the y-axis, it can be said that the magnitude is relatively small or can be neglected. We can explain that the tribology characteristics of the texturing of the piston ring with the cylinder bore, effectively prevent the leakage of the lubricant through piston rings and the cylinder bore.

4.1 Piston ring with distorted bore

For this section, we will analyze the results when a non-circular or distorted cylinder bore is used by using both textured and untextured rings in term of effect on the minimum oil film thickness.

Figure 6 below shows the minimum oil film thickness in the cylinder piston liner that contacts with the textured and untextured pistons ring in circular and distorted, which also can be identified as the non-circular cylinder bore. As we observed, we can determine that there is a significant decrease in minimum oil film thickness with both textured and untextured piston rings in the distorted cylinder bore, which are indicated with red colour lines on the graph. A three-dimension effect has resulted from the non-circularity of the cylinder bore. However, the ideal shape of the cylinder bore shows a higher rate of minimum film thickness for both textured and untextured piston rings. Moreover, textured ring on both circular and distorted cylinder bore shows greater minimum film thickness than untextured piston rings.

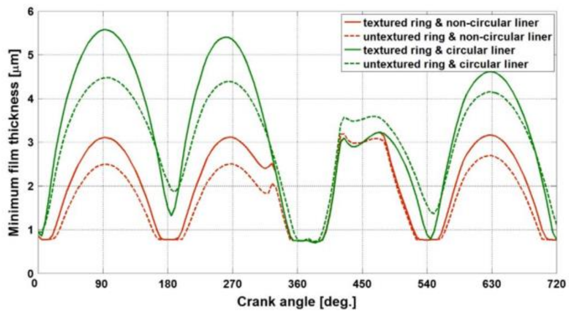


Fig. 6 – Minimum oil film thickness tested with untextured and textured piston rings on circular bore liner and distorted(non-circular) bore liner

Instead of the graphical results for effect on the minimum oil film thickness, Figure 7 shows the lubricant flow from the 45° vortex to the 0° vortex region under a gradient of pressure. The result shows that the textured piston rings result in lower hydrodynamic pressure with both circular and distorted bores. Hydrodynamic pressure is the pressure of a fluid, in this study is the lubricant, exerted on an object via the motion of that certain object through the fluid. Therefore, we can conclude that this is the result that shows texturing on the piston ring surface help to improve the load carrying capacity. From the indicator in the figure above, we can also observe that non-circularity or distorted bore increases the hydrodynamic pressure at 45° vortex.

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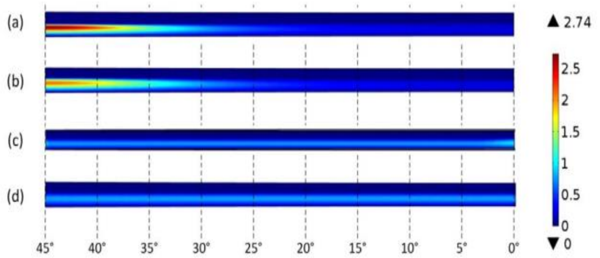

Fig. 7 – Hydrodynamic pressure on piston ring (a) untextured piston ring with distorted bore (b) textured piston ring with distorted bore (c) untextured piston ring with circular bore (d) textured piston ring with a circular bore

4.2 Effect of lateral aspect ratio

The lateral aspect ratio is one of the most important variables in this study. It is the ratio of the size of the dimple or micro-groove on the texturing surface of the piston rings. According to its formula, it is the length of the micro-groove divided by the width of the micro-groove. In this study, we use the lateral aspect ratio of 12.25, by modeling each of the micro-groove with 6.125mm length and 2mm width. Figure 8 shows the hydrodynamic pressure with different lateral aspect ratios from ε_l (a) with an increment of $5\varepsilon_l$ until $25\varepsilon_l$ (f).

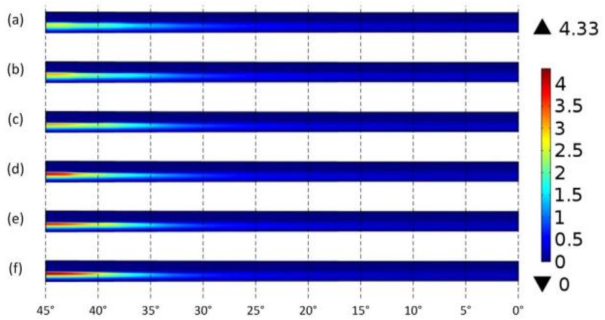

Fig. 8 – Hydrodynamic pressure with different lateral aspect ratios

The figure shows the hydrodynamic pressure on the textured piston rings with different lateral aspect ratios. This simulation is to study the effect of the lateral aspect ratio on the tribological behaviour of the piston rings. From the result obtained the initial lateral aspect ratio, which is 12.25 results in the lowest hydrodynamic pressure. When the lateral aspect ratio increases by $5\varepsilon_l$ for each stage, there is a significant increase in hydrodynamic pressure in the 45º vortex. As mentioned in the previous study, the lower hydrodynamic pressure is the ideal condition for the piston ring interface with the cylinder bore. Therefore, increasing the lateral aspect ratio is not recommended as it gives high hydrodynamic pressure from the result obtained, which is the red colour indicator at 45º vortex. In the other words, the dimple size on the piston ring surface is not ideal to be long in length (l_g) as it influences the magnitude of the lateral aspect ratio. We can conclude that from the variation of the lateral aspect ratios used in this study, the initial lateral aspect ratio is the most ideal dimple size to be used and it is the evidence from the previous work.

5. Conclusion

In conclusion, the objective of the study on the tribology analysis of textured rings has been achieved. The first objective is to study the tribology performance of both untextured and textured rings using COMSOL software. Multiple parameters had been applied such as the lubricant properties and lateral aspect ratio of the dimple on the piston ring surface. The second objective is also achieved successfully. The result obtained had shown the obvious differences in different aspects for both textured and untextured rings. First, the model of the piston rings, with and without surface texturing as well as the model of the crankshaft was drawn and assembled on the 3D modelling software, SOLIDWORKS. This process is necessary as we need to import the model into the COMSOL software to undergo simulation. From the simulation, we can observe the tribology characteristics of different aspects.

First, the simulation had been done on the piston rings with and without a textured surface. Results had been obtained and discussed in the previous chapter. Then, the crankshaft had been imported to COMSOL software to undergo different simulations to obtain other results such as the hydrodynamic in different bore liners. Thus, this study can be effective for the automotive manufacturers of piston rings, crankshafts or even the whole engine to be considered. It is because the result obtained will help to improve the engine performance in the automotive industry.

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