Cavitation in engine lubricants: visualisation experiments in both a single ring test rig and a single cylinder motored diesel engine to complement on the theoretical modeling of cavitation

1Polychronis Dellis*
1ASPETE, School of Mechanical Engineering Educators, Athens, Greece

Abstract

The importance of studying cavitation lies in the fact that it can cause tremendous damage to fluid handling machinery. Cavitation generation is largely dependent on pressure fluctuation in the turbulent flow period as well as on the presence of air bubble nuclei.

The shape and dynamic behavior of oil film in a piston-ring pack after oil film rupture are greatly influenced by revolution speed. After dead center, negative pressure involving tension arises before oil film rupture occurs. With the generation of internal cavities tension is released but negative pressure is still maintained in those cavities.

This study is focused on the presentation of cavitation imaging. Images are both taken from a simplified single-ring test rig which is purpose built so that numerous uncertainties regarding the complex tribological phenomena between the piston-ring and cylinder wall to be omitted and a single cylinder diesel engine which was modified to accommodate quartz window sections, to take images of the piston-rings and liner interface. The experimental data give an insight of the rheological phenomena occurring and try to complement the lack of experimental data on this subject. Eventually, experimental results will be used on how best to model the cavitation at the interface of the piston-ring and the cylinder wall.

Keywords: piston-ring lubrication; simulating test rig; cavitation in piston-rings; engine visualization experiments

Introduction

The formation of cavities and their subsequent disposition affects the pressure generated in the continuous thin lubricated film and hence, any integrated quantities such as the load capacity of bearings and piston-rings. With a convergent-divergent geometry in a liquid film, the occurrence of gaseous cavitation is a natural consequence under all circumstances. The mechanisms responsible for cavitation are:

1) Reverse squeezing in a converging-diverging geometry
2) Shear thinning of the liquid by modifying film thickness
3) Reciprocating speed, varying load and temperature (variable film thickness)

In reciprocating piston-rings, superambient pressures are generated in the converging wedge and subambient or negative pressures at the diverging wedge of the piston-ring. In general, two forms of film breakdown can exist: the first depends on the balance between viscous shear and surface tension forces and the second is due to vaporous cavitation which may occur if the first type of rupture allows the formation of sufficiently low pressures [1].

Body

For the visualization of cavitation two test rigs were used: a simplified single-ring test rig which incorporates a steady piston-ring section and a reciprocating flat liner and a single cylinder Lister-Petter PHW1 engine that was used for motoring tests. In the case of the single-ring test rig, a glass liner specimen was used for the visualization experiments (Figure 1(a)) and the same concept was used for the engine experiments with specially mounted quartz windows (Figures 1(b) and 1(c)). The onset and development of cavitation in the lubrication film present throughout the stroke between the piston-ring and the cylinder liner in the test rig was visualized by a charge-coupled device (CCD) camera and monitored by a miniature pressure sensor. Various transient cavitation patterns were identified

*Corresponding Author, Polychronis Dellis: pasd@city.ac.uk
during the stroke, ranging from developing fern-shaped cavities to string cavities extending gradually up to the trailing edge of the piston-ring. Both the onset and the development of these cavities seem to be affected by piston speed and load; at higher speeds cavities appear later in the stroke and are larger in size, while at higher loads they appear earlier, are more numerous and, thus, smaller in size [2].

In the series of experimental data the oil film was visualized as it was seen on the surface of the piston ring. For the single-ring test rig experiments, different test conditions were used (speed, load, temperature) and pictures were taken for different pulses of the shaft encoder and with different magnification lenses in order to capture the cavity development and the growth of specific cavities. In the published study for the single-ring test rig, some very interesting images were presented of the cavity shapes on the surface of the piston-ring specimen (Figure 2 – initiation of cavitation and Figures 3 (a) – (e) transition between different cavitating conditions). It was concluded that the lubricant film thickness has a major influence on the cavitation behavior, which in turn, affects the shape of the hydrodynamic pressure profile in the entrainment direction and consequently the ring-pack’s load carrying capacity. The use of a silicon chip ultra miniature transducer has provided both qualitative and quantitative pressure data, which proved to support the flow visualisation results, while its robustness and good repeatability offer promise for its application to the piston-ring pack of production engines [2].

Cavitation which was evident at the idealized test rig [1], [2], was also going to be observed in engine experiments and conclusions were going to be drawn regarding the phenomenon of cavitation and how it be characterized with the addition of oil film pressure measurements [1], [3]. For the purpose of visualisation, pockets had to be machined in the sides of the engine block enabling a large viewing area for the imaging process. The pockets were machined with spark erosion technique (Figures 1(b) and 1(c)).

Engine visualization experimental data were also acquired and a direct comparison of the visualization results from both test rigs is attempted. There is evidence of the string cavities that appear on the surface of the barrel-faced top compression ring of the Lister PHW1 engine. The research approach to understanding cavitation, has followed the outcome of the visualisation research study of the single-ring test rig. The idealised single-ring test rig is being used as a large scale model in contrast to the real sized engine test rig. In the case of the single-ring test rig, the ring was covered in the majority of the stroke with string cavities. During flow reversal, the cavitation is initiated by fern-shaped cavities which grow further, to form up bigger ferns and fissure type cavities. Later on in the stroke they develop to strings on the surface of the piston-ring and they grow so that they will be reaching its trailing edge [2], as mentioned above.

In the case of the engine, however, the stages of cavitation inception and initial development are not clear because the size of the visualisation window has hindered imaging of the oil flow at the reversal points close to the dead centres. For comparison purposes a cavitation factor was introduced that compares the two experimental test rigs. This coefficient is the ratio of the width or the length of the string cavities divided to the piston ring width [1], [3]. Figure 4 (a), shows the most probable cavitation development in the engine during the stroke according to the images taken. The stages derived, are postulated from engine imaging and the simulation test rig results visualisation data. Figure 4 (a) is complemented with the cavitation imaging from the engine (Figures 4 (b) and 5 (a) and (b)). Figures 4 (b), 5 (a) and 5 (b) present visualization data acquired from the engine test rig with a CCD camera with different magnification lenses and distances from TDC, to focus on the findings from these experiments. Engine experiments showed unclear appearance of string cavities. The identification of oil droplets in general can be directly compared to the research that was presented by Toyota [4]. Evidence of oil mist was unclear in the images. The schematic in Figure 4 (a) also combines the probable oil film pressure for the cavities in every stage respectively. As in the case of the single-ring test rig, the cavitation inception is being accompanied by negative or sub-atmospheric pressures. In the converging wedge of the piston-ring, the pressure is the combustion chamber pressure and at the diverging wedge the pressure reading would be that of the second land. Later on in the stroke (Figures 4 (a) - (B) – irregular fern growth) the ferns grow, and they are combined with sub-atmospheric oil film pressures at the diverging wedge of the piston-ring. Again, the pressure reading at the diverging wedge ends to the pressure measurement of the second land. The string cavities (Figure 4 (a) – Visualised Cavitation Stage (C)) can reach the trailing edge of the piston-ring or they can be cut midway. The pressure reading at the diverging wedge is that of the second land. Cavitation factors were calculated for both the single-ring test rig and the engine. They showed that the engine cavitation factor is approximately 70% greater than the respective factor calculated for the single-ring test rig [1], [3]. The residence time of the cavities was also calculated but this consideration is under some serious risk.

*Corresponding Author, Polychronis Dellis: pasd@city.ac.uk
Figures & Tables:

Figure 1. (a) The glass liner in the single-ring test rig and (b)-(c) Upper and lower window, (b) anti-thrust side window visualisation area (c) front side of the Lister-Petter block [1], [3].

Figure 2. Fern growth captured using different magnification systems CF-4 magnification with extension lens (8.7x), 700 rpm, 22 mm stroke, 2843 N/m at different crank angles [2].

Figure 3 (a) – (e). Visualisation of transition between different cavitating conditions [2]

*Corresponding Author, Polychronis Dellis: pasd@city.ac.uk
Figure 4. (a) Possible cavitation stages on the Lister-Petter engine and (b) string cavities on the surface of the piston-ring [1], [3]

Figure 5. Images taken from engine visualization experiments showing string cavities (a) 576°CA exhaust stroke camera at 11.17 cm from top edge and (b) 475.20°CA expansion stroke camera at 9.17 cm from top edge [1]

*Corresponding Author, Polychronis Dellis: pasd@city.ac.uk
**Conclusion**

The obtained insight into the onset and development of cavitation in the piston-ring assembly will encourage further efforts in modelling cavitation under a much wider range of operating conditions than those examined here. It seems that a combined theoretical and experimental approach may eventually lead to a level of understanding of piston-ring lubrication which can directly influence engine design and, through this, engine performance, economy and exhaust emissions [5].

Experimental data fail to resolve clearly which boundary conditions are appropriate or whether perhaps different boundary conditions are suited to different conditions of load, speed, temperature and degree of lubricant starvation [5]. The effect of the range of different cavitation models on the tribological behavior of the single piston-ring is characterized by hydrodynamic pressure profiles, lubricant film boundaries, lubricant film thickness, lubricant flow rate and friction losses between the piston-ring and the cylinder wall.

The research approach to understanding cavitation that was identified in engine imaging has followed the outcome of the visualisation research study of the single-ring test rig. The idealised single-ring test rig is being used as a large scale model in contrast to the real sized engine test rig. In the case of the single-ring test rig, the ring was covered in the majority of the stroke with string cavities. During flow reversal, the cavitation is initiated by fern-shaped cavities which grow further, to form up bigger ferns and fissure type cavities. Later on in the stroke they develop to string cavities on the surface of the piston-ring and they grow so that they will be reaching its trailing edge [1], [2].

In the case of the engine, however, the stages of cavitation inception and initial development are not clear because the size of visualisation window has hindered imaging of the oil flow at the reversal points close to the dead centres. On one hand, the quartz sectioned liner provided cavitation images that resemble the ones recorded for the single-ring test rig, on another, the overall size and their span compared to the stroke length is not adequate to “scan” the whole of the engine stroke length. In the visualisation parametric study for the single-ring test rig, it was evident that as speed increases, the fern cavities appear later on in the stroke and in the case of the load increase, the opposite happens. For the motoring tests, it was not possible to have a good picture of the squeeze film effect and how does cavitation initiation change in the case of speed and load increase. Although speed was maintained in quite low levels its inception was not captured. For higher speed imaging, where the cavities are formed later on in the stroke, still no clear signs were identified. The visualised cavity shapes are not uniform. It should be pointed out, though, that for the case of the anti-thrust and front side windows, for the same speed and load, different cavitation initiation points in the stroke should be considered, as the load on the ring changes along the circumference due to piston tilt.

Engine experiments showed, for the motoring tests, that top compression ring operates under serious conditions of lubricant starvation.

**References**


*Corresponding Author, Polychronis Dellis: pasd@city.ac.uk*