Assessing lubricating film thickness between compression rings and engine cylinders: A comprehensive comparison of theoretical predictions and experimental measurements

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Abstract

The purpose of piston rings in combustion engines is to provide an effective seal between the combustion chamber and the crankcase while allowing rapid linear movement of the piston. In this paper a review of around 50 experimental studies and 30 theoretical studies is presented. Papers describing experimental studies report lubricating film thicknesses between 0 µm to 20 µm, while papers describing theoretical results for fully flooded analyses tend to report smaller values (0 µm to 9 µm). Theoretical studies including starvation phenomena normally give even thinner films, typically between 0 µm and 5 µm. The paper presents a discussion of these discrepancies.

Keywords:

Oil Film Thickness, Piston Rings, Engine

1 INTRODUCTION

The use of internal combustion engines is extensive and constitutes one of the main sources of mechanical energy. The purpose of piston rings is to provide an effective seal between the combustion chamber and the crankcase while allowing rapid linear movement of the piston. The lubrication of the ring interface with the liner is critical and published studies on this topic are to be found from the early part of the 20th century up to the current time.

2 REVIEW OF EXPERIMENTAL AND THEORETICAL PUBLISHED DATA

A review of measured and simulated results oil film thickness data has been completed by the authors and is presented in Table 1 and Table 2. The techniques used for experimental measurements are based on electrical resistance, optical means, inductance / eddy currents, capacitance, fluorescence, strain gauge and ultrasound. The simulation models can be divided in simplified simulations, assuming fully flooded boundary conditions for the solution of Reynolds equation, and more complex approaches using starved or partially flooded conditions. This second option is more realistic since the availability of oil to fill the space between ring and liner is limited by the oil left by the previous ring passing a given point on the cylinder.

The results in Table 1 and Table 2 present oil film thickness (OFT) data for the top compression ring. The maximum and minimum value within the studies are reported. The minimum oil film thickness is normally of interest in order to calculate wear. In this case the maximum oil film thickness is also included in order to see the range of values that are reported. On the other hand, when the symbol (*) appears, it refers to the conditions marked in the same row with (*). When an additional symbol is needed in a specific row the symbol (†) is used.

2.1 Grouping the data

The sizes of the cylinders included in these tables are broadly similar. Hence, it is assumed that the order of the oil film thickness should be similar. Looking at Table 1, it is possible to divide the results in two groups, those engines whose maximum oil film thickness is high, for example above 6-10 microns and those engines which have maximum oil film thickness is in the range of 2 to 5 µm. In the first group there are more than 20 studies reporting high values of oil film thickness and many of which report also small values. This implies that there is a good chance that oil film thickness can go up to 15-20 microns since those studies include also very small values.

On the other hand the theoretical studies can be divided into those assuming fully flooded boundary conditions, which tend to have higher values (from 6 to 9 microns approximately) and those assuming starved conditions which tend to have a maximum value in the range 2 to 4 microns. It has been shown by [1] that the piston rings are frequently not operating in fully flooded conditions in the mid-stroke location so it can be concluded that theoretical simulations predict a maximum value of 2 to 4 µm.

3 DISCUSION

3.1 Discrepancies and relation with experimental techniques.

There seems to be a discrepancy in the calculated values and the measured values of published studies. While theoretical simulations predict 2 to 4 µm maximum oil film thickness in the top ring, experimental measurements are often higher than these values. A deeper analysis of the measurements is needed. There are some differences depending on the experimental technique used. Some experimental results made with laser induced fluorescence and flash induced fluorescence are close to theoretical predictions. However, two of the studies using the fluorescence technique [2, 3] still record higher values in the range of 18-23 µm. Ultrasound technique also gives higher values up to 11 µm as shown in [4]. However it is important to consider that the same research team has published an improved methodology that recorded smaller values of the oil film thickness [5] but these values are still higher than typical theoretical predictions. The eddy current method and resistance method also give very high values also although the size of the engine used for the eddy current based investigation is substantially bigger than for the other studies [6, 7]. Takiguchi et al. artificially imposes a minimum oil film thickness of 0.5 microns in their measurements, as a way to calibrate the “0” in their measurement system. This has the effect of shifting down their measurements to the lowest possible values. However, while doing this, the highest values are still of 11 μm [8].

On the other hand, looking at the more recent theoretical analysis, a new study proposes a modified boundary condition for the simulations that seems to give a higher value of the predicted oil film thickness, although authors do not discuss the discrepancy, instead they consider different ring sizes [9].

3.2 Initial thoughts

In general, experimental results are slightly higher or much higher than theoretical predictions. It is clear that either the experimental measurements are failing to properly measure the gap between ring and cylinder or the theoretical models are not taking into account some effects that happen in the real world.

Some theoretical models are very comprehensive. These models tend not only to give small values of oil film thickness, but trials with at least one commercial package appear to indicate that the oft values cannot go as high as those sometimes measured. This arises because the hydrodynamic pressure to support the ring load, when operating with such large gaps, cannot be generated. Experience also shows that liners and rings are worn out during operation, this also would not be possible if oil film thicknesses are as high as sometimes is reported. These issues suggest that experimental measurements may not give a complete picture.

Year	Ref.	Authors	OFT Min (μm)	OFT Max (μm)	Cylinder size (Litres)	RPM	LOAD	OIL	Temp °C	Ring Pack	Sensor
1961	[10]	Furuhama, Sumi	0.7	**14**	0.4 Rig	1900					Resistance
1969	[11]	Greene	3.8	**24**	Rig	1200					Optical
1972	[12]	Wing, Saunders	0	**5** **12***	0.6 Diesel	1330 *1300	6 BHP *0	Shell Rotella T30	100-160 Rings	3 R.	Inductance
1974	[13]	Hamilton, Moore	0.4-2.5	**7.0**	0.6 Diesel	200-950					Capacitance
1975	[14]	Allen, Dudley et al.	9.1*	**16.8**	Diesel	*1000 2200					
1975	[15]	Hamilton, Moore	0.5	**7**	0.6 Diesel	1500			72		
1975	[16]	Parker, Stafford et al.	0.3	**19.4**	Perkins	1000					Capacitance
1976	[17]	Wakuri, Ono et al.	0.7*	**4.5**	Flat Rig	*267 857					Optical, interferometry
1977	[18]	Brown, Hamilton	2*	**15**	0.6 Diesel	*100 400					Capacitance
1978	[19]	Brown, Hamilton	4.5		0.6 Diesel	200					Capacitance
1978	[20]	Moore, Hamilton	2	**4**	0.6 Diesel	1500	4.6 BHP	SAE30 119.5cSt (38C) 11.9cSt (99C)	48	4 R.	Capacitance
1979	[21]	Moore	0.3*	**2.5**	2.2 Diesel	*1000 1800	*8.3 BHP 38 BHP				Capacitance
1980	[22]	Moore, Hamilton	0.2 1.2*		Diesel	1500-2250	3.3 BHP *18 BHP				Capacitance
1981	[23]	Moore, Hamilton	0.5-2.7		0.6/? Diesel	950	0.84 BHP				
1981	[24]	Moore	0.8-2.5		0.5 Diesel	750	3.13 BHP				Capacitance
1983	[25]	Dow, Schiele et al.	0.7	**4.5**	Rig				90		Inductance
1983	[26]	Shin, Tateishi et al.	0.7	**14** **8***	2.3	1300	0% *100%	SAE30 10.5cSt	60-120	4 R.	Capacitance on ring, long sensor
1983	[27]	Furuhama, Asahi et al.	0.5-3	**5-8**	2.3 Diesel	1000-1900	0-100%	8.5cst 10.5cst	-	4 R.	Capacitance on ring, long sensor
1985	[28]	Moore	0.5	**2.5** **6.5***	0.6 Diesel	1000	0.6kW per Cyl.	SAE40 SAE5W SAE10W40		4 R. *1 R.	Capacitance
1990	[29]	Grice, Sherrington et al.		**6-10**	0.6 Motored	35	Motored	-	room	3 R.	Capacitance

1990	[30]	Myers, Borman et al.	0	**20**	1.2 Diesel					4 R.	Capacitance TDC
1991	[2]	Richardson, Borman	2	**18**	1.2 Diesel	2000		SAE30			Laser Induced Fluorescence
1992	[31]	Grice, Sherrington et al.	1	**8**	0.6 Diesel	900-1650	Motored	-	140	4 R.	Capacitance
1993	[32]	Sanda, Saito et al.		**5.5** **2.5***	0.5 Petrol	800-1200	Motored *Full	-	80	3 R.	Laser Induced Fluorescence Scanning
1993	[3]	Phen, Richardson et al.		**6** **23*** **14-18†**	1.7 Diesel	700 *1900 †1900	Motored	SAE15w-40 (14.4cSt 100C 100cSt 40C)	89 *52 †89-52	3 R.	Laser Induced Fluorescence In situ calibration
1995	[33]	Mattsson	1	**20**	1.4 Diesel	1000-2000	0-80Nm per Cyl.	-	80	3 R.	Capacitance
1995	[34]	Taylor, Brown et al.		**1.8**	2.2 Diesel CAT1Y73	1000-1800	Low 20Nm per Cyl.	15W/40	63-97	4 rings	Laser Induced Fluorescence
1995	[35]	Dearlove, Cheng	0.5	**4**	Test rig from liner sector Stroke 67	100-600	Motored	49cP – 357cP	Room	1 R.	Laser induced fluorescence
1995	[36]	Arcoumanis, Duszynski et al.	1	**10**	Test rig Stroke 50	200-600	Motored 973N/m Load of R.	-	25-100	1 R.	Capacitance Fully flooded
1995	[37]	Inagaki, Saito et al.		**3**	0.4 Petrol	1500	Motored	API SG ECII 10w30 (coumarin-6 fluores.)	80	3 R.	Flash Induced Fluorescence
1997	[38]	Sanda, Murakami et al.	0	**4** **6***	0.5	1000-2000	Full *Motored	0.02 Pa s	-	3 R.	Laser Induced Fluorescence Scanning.
1998	[39]	Arcoumanis, Duszynski et al.		**<5**	0.7 Diesel	2000	40% (7.2 MPa)	Many	-	4 R.	Laser Induced Fluorescence
2000	[40]	Yoshida, Kobayashi et al.	1	**2.5**	0.5 Petrol	2500	Full	-	-	3 R.	Laser Induced Fluorescence
2000	[41]	Seki, Nakayama et al.	0.3	**3.5**	0.3 Diesel	2000	75% 8 MPa	SAE 30	80	3 R.	Laser Induced Fluorescence
2000	[8]	Takiguchi, Sasaki et al.	0.5*	**11*** **9*†**	1.2 Diesel	1600-2800	No load † Full	10.87cSt	100-140	3 R.	Capacitance on ring, *It assumes 0.5 µm
2001	[42]	Ducu, Donahue et al.		**1.93**	1.5 Diesel	1300	40%	-	-	-	Capacitance
2003	[43]	Weimar, Spicher	2	**5**	0.5 Petrol	800-1500	-	-	40-80 oil	3 R.	Laser Induced Fluorescence
2004	[44]	Bolander, Steenwyk et al.	0	**4** **0.2***	Rig (60° Sector) Bore 137.2 Stroke 66.7	240 *15	-	ISO VG46	room	1 R.	Twin-Fiber Optic mounted in the rails
2004	[45]	Taylor, Evans	1	**4.5**	2.2 Diesel CAT1Y73	1000-1800	20-190 Nm Per Cyl.	SAE50 SAE30 SAE10W	100-200 Pist.	4 R.	Laser Induced Fluorescence
2006	[6]	Tamminen, Sandström et al.	1	**19**	8.7 Diesel	900	10-100%	SAE40	85-120 Pist.	3 R.	Inductance

2007	[7]	Saad, Kamo et al.	1	**15** **11***	2.3 Diesel Sing. Cyl.	1400	56Nm *165Nm	15w40	148 93	3 R.	Voltage drop (resistance)
2009	[46]	Dhar, Agarwal et al.	0.7	**8.3**	0.4 Diesel	1300-1400	Motored	-	110 Oil	4 R.	Capacitive
2009	[47]	Söchting, Sherrington	5.5	**14**	0.9 Diesel	2000	60-160 Nm	SAE20 SAE50 SAE5W50	90-115	3 R.	Capacitive
2010	[48]	Dellis	0.5	**4** **2.5***	Test rig Moving liner	400	3371N/m Load of R.	0w30 10w40 0w20	50 *70	1 R.	Capacitive
2012	[49]	Avan, Spencer et al.	0.2	**1.5**	Rig Bore 130 Stroke 15	10 Hz	40-200 N (vertical)	37cSt (40C) 6.5cSt(100C 85.6cSt	22	1 R.	Ultrasound
2012	[4]	Mills, Avan et al.	3.2	**6** **11***	0.2 Petrol	2230	90% (7Nm) *Idle	15w40	>100	3 R.	Ultrasound
2013	[50]	Bulsara, Bhatt et al.	0	**5**	0.1	500	Motored	10w30 64cSt (40C)	Room	3 R.	Contact to ring Strain Gauge
2013	[51]	Bulsara, Bhatt et al.	0	**5** **4***	0.1	500 *200	Motored	10w30 64cSt(40C) 0.117†Pa s	†Room	3 R.	Contact to ring Strain Gauge
2014	[5]	Mills, Vail et al.	0	**6** **5***	0.4 Petrol	3200	25Nm *35Nm	10w40	-	2 R.	Ultrasound Deconvoluted

Table 1 Compilation of published results of experimental measurements. Top compression ring.

Year	**Ref**	**Authors**	**OFT Min**	**OFT Max**	**Cylinder size**	**RPM**	**LOAD**	**OIL**	**Temp**	**Ring Pack**	**Comment**
1959	*[52]*	*Furuhama*	*0.8* *2.3**	***2*** ***4.3****	*0.4*	*500* **3000*	*6180N/m* *R. Load*	*20.5x10-8 Kg s /cm2*	*80*	*1 R.*	*Fully Flooded, Oscillating Cyl.*
1979	*[53]*	*Ruddy, Dowson et al.*		***12***	*8.9 Diesel* *2-Stroke*	*290*	*-*	*-*	*-*	*3 R.*	*Starved*
1979	*[54]*	*Rohde, Whitaker et al.*	*1*	***4.3***	*0.2 No head*	*3000*	*Motored*	*6.89x10-3 Pa s*	*-*	*1 R.*	*Fully Flooded*
1980	*[55]*	*Ruddy, Parsons et al.*		***11***	*-*	*-*	*-*	*-*	*-*	*1 R.*	*Log scale. No commented.*
1980	*[56]*	*Rohde*		***2.5***	*0.6*	*1400*	*0.4-0.7 MPa* *BMEP*	*6.89x10-3 Pa s*	*-*	*1 R.*	
1981	*[57]*	*Ruddy, Economou et al.*		***15***	*-*	*Medium*	*-*	*SAE 40* *SAE 50*	*-*	*4 R.*	*Log scale* *Fully Flooded*
1982	*[58]*	*Richez, Constans et al.*	*1.6*	***3.3*** ***6****	*0.8 Petrol*	*800* **2400*	*Motored*	*13 x10-3 Kg/m/s*	*-*	*3 R.*	*Fully Flooded*
1983	*[27]*	*Furuhama, Asahi et al.*	*2-5*	***9***	*2.3 Diesel*	*1000-1900*	*0-100%*	*8.5cst* *10.5cst*	*-*	*4 R.*	*Fully Flooded*
1983	*[26]*	*Shin, Tateishi et al.*	*2*	***9***	*0.5*	*1000*				*4 R.*	*Fully Flooded*
1992	*[31]*	*Grice, Sherrington et al.*	*1*	***4***	*0.6 Diesel*	*900-1650*	*Motored*	*-*	*140*	*4 R.*	*Fully Flooded, bore distort.*
1995	*[59]*	*Ma, Smith et al.*	*0*	***5.5***	*0.6 Diesel*	*1500*	*5.5 MPa*	*SAE20*	*150* *80*	*4 R.*	*Fully Flooded*
1995	*[60]*	*Ma, Smith et al.*	*0*	***7***	*0.6 Diesel*	*1500*	*5.5 MPa*	*SAE20*	*150* *80*	*4 R.*	*Fully Flooded, ring twist*
1996	*[61]*	*Ma, Sherrington et al.*	*0*	***2-4***	*0.6 Diesel*	*1500*	*-*	*SAE20*	*150*	*4 R.*	*Starved*

									80		
1995	*[34]*	*Taylor, Brown et al.*		***4***	*2.2 Diesel CAT1Y73*	*1000-1800*	*20Nm per Cyl.*	*15W/40*	*63-97*	*4 R.*	*Partially*
1997	*[38]*	*Sanda, Murakami et al.*	*1*	***3*** ***4****	*0.5*	*1000-2000*	*Full load* **Motored*	*0.02 Pa s*	*-*	*3 R.*	*Starved*
1997	*[62]*	*Ma, Sherrington et al.*	*0.3*	***2***	*0.6*	*950*	*3.2MPa*	*SAE30*	*150* *80*	*3 R.*	*Partially flooded*
1997	*[63]*	*Ma, Smith et al.*	*0.3*	***2.3***	*0.6*	*950*	*3.2 MPa*	*SAE30*	*150* *80*	*3 R.*	*Partially flooded* *Bore distort.*
1998	*[64]*	*Liu, Xie et al.*	*1*	***4***	*0.8*	*2000*	*3.5MPa*	*0.003 µm ?* *0.008 µm ?*	*-*	*3 R.*	*Starved,* *(13 µm with roughness, inconsistency)*
2000	*[65]*	*Sawicki, Yu*	*0.4*	***3***	*0.5*	*2000*	*-*	*0.0069 Pa s*	*-*	*3 R.*	*Fully flooded, cavitated*
2000	*[66]*	*Priest, Dowson et al.*	*0.3-0.6*	***3-4.5***	*2.2 Diesel* *CAT1Y73*	*1200*	*1.4 MPa* *BMEP*	*SAE30 4mPas-13mPas*	*-*	*4 R.*	*Starved and cavitated*
2001	*[67]*	*Frølund, Schramm et al.*	*1.5** *0.2*	***6.5**** ***1.5***	*0.4 Petrol*	*2500*	*66%*	*SAE 10W30*	**Cold* *Warmed*	*3 R.*	*Starved*
2002	*[68]*	*Tian*	*0.1*	***0.8***	*2.0 Diesel*	*1200*	*100%*	*10W50*	*137-160*	*3 R.*	*Partially flooded*
2002	*[69]*	*Piao, Gulwadi*	*0.3*	***1.5*** ***3.5**** ***8†***	*0.5 Petrol*	*2000* **†6000*	*-*	*-*	*-*	*3 R.*	*Partially flooded* *† liner ramp and ring inertia*
2003	*[70]*	*Gamble, Priest et al.*	*0.3*	***3*** ***1.7****	*0.5*	*2500*	*0.5 MPa* *BMEP*	*SAE30*	*-*	*3 Rings*	*Fully* **Partially flooded*
2003	*[71]*	*Harigaya, Suzuki et al.*	*0.5*	***7.5*** ***8.4**** ***9.5†***	*1.2 Diesel*	*1600* *†2800*	*0%*	*SAE30*	*132* **102* *(ring)*	*1 R.*	*Fully flooded*
2005	*[72]*	*Bolander, Steenwyk et al.*	*0*	***6.5***	*Rig (60° Sector)* *Bore 137.2* *Stroke 66.7*	*30-300*	*1 – 8 Kgf*	*SAE 30* *0.20 Pa s*	*20*	*1 Ring*	*Fully flooded,* *Effects of speed, load*
2006	*[6]*	*Tamminen, Sandström et al.*	*0*	***6***	*8.7 Diesel*	*900*				*3 R.*	*Ricardo RINGPAK 4.2*
2006	*[73]*	*Harigaya, Suzuki et al.*	*0.4* *0.47†* *2**	***5.5*** ***7.3†*** ***16****	*1.2 Diesel*	*1600* *†1600* **800*	*100%* *†0%* **0%*	*SAE 10W50*	*150* *†105* **30*	*1 R.*	*Fully flooded*
2008	*[74]*	*Wannatong, Chanchaona et al.*	*0.1*	***4***	*0.5 Diesel*	*1200*	*Full* *5.7MPa*	*0.012* *Pa s* *(T_amb)*	*100* *Liner*	*3 R.*	*Starved* *(6 µm Oil Control Ring)*
2013	*[75]*	*Morris, Rahmani et al.*	*0.1*	***2.7***	*0.5 Petrol*	*2000*	*5.6 MPa*	*55.99 cSt (40C)* *9.59 cSt (100C)*	*-**	*3 R.*	*Fully Flooded with *thermal*
2014	*[76]*	*Yuan, Feng et al.*	*0.5*	***3***	*0.3*	*Free Piston Gen.*	*8.5 MPa*	*-*	*-*	*2 R.*	
2015	*[77]*	*Taylor*	*0.5**	***5.8***	*0.5 Petrol*	*2500*	*3.2 MPa*	*SAE 15W40*	*100-150*	*3 R.*	*Fully Flooded* **Squeeze*
2015	*[9]*	*Shahmohamadi, Mohammadpour et al.*	*0.7*	***10.8***	*0.5*	*1500*	*-*	*-*	*-*		*Inlet flooded with reversal and cavitation*
2015	*[78]*	*Usman, Cheema et al.*	*0*	***6.5*** ***3****	*0.8*	*1000*	*6MPa*	*0.016Pa s (T_amb)*	*100*	*1 R.*	*Fully flooded,* **Distortion*

Table 2 Compilation of published results of computer simulations. Top compression ring.

3.3 Identifiable trends

The compilation of a summary of almost 50 articles reporting measurements of oil film thickness in Table 1 gives an opportunity to investigate some trends. One trend that is quite clear, is reported by eight of these studies, that an increase in the load of the engine will tend to reduce the maximum values of oil film thickness measured commonly in the stroke or in the upper part of the stroke [4, 5, 7, 8, 12, 26, 32, 38]. However, a small number of investigations have also noted that sometimes the opposite effect also occurs, that is the OFT may increase when load increases [6, 8, 33, 47].

Analysis of OFT data has shown there is no correlation in the data between OFT and cylinder size, OFT and fuel type or OFT with the year of the study. However, it may be reasonable to anticipate that a more modern design would tend to have smaller oil film thicknesses since it probably operates a less viscous lubricant (with more additives to reduce the wear caused by an increase in the asperity contacts). When all the data is presented in a single graph it is found that the distribution of measurements follow a log-normal distribution as shown in figure 1.

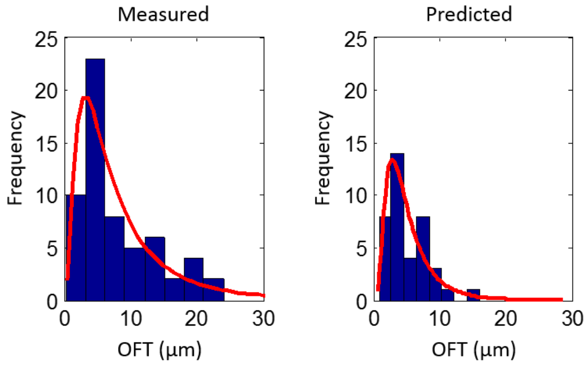

Figure 1: Histogram of measurements and predictions of maximum OFT data.

It is clear that, on average, predicted values of OFT cover a much smaller range than experimental measurements. This suggests that either (a) there are errors in many experimental measurements that lead to over evaluation of OFT, or (b) that there are real effects in experimental data that lead to the detection of large separations between rings and cylinders (such as limited ring conformity in out of round cylinders) or (c) that there is a fundamental error in simulations that evaluate OFT. These authors believe that the latter issue is very unlikely. Additionally, it does not appear to be possible to generate sufficient hydrodynamic pressure to support the prevailing loads with thick films in these systems.

4 SUMMARY

An extensive review of published data has been carried out. Experimental measurements of OFT tend to be greater than those predicted by simulations. It demonstrates that there is a consistent discrepancy between the range of the OFT data obtained in experimental and theoretical investigations that is not fully explained. Additionally, there are many experimental studies reporting that increasing load of the engine makes oil film thickness values in the upper stroke smaller, but a small number of investigations have also noted that sometimes the opposite effect also occurs.

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