Demonstration of the benefits of SAE 30 stationary gas engine oil in full scale engine tests

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Abstract

This paper evaluates the benefits of an SAE 30 monograde stationary gas engine oil (SGEO) in comparison with SAE 40 monograde SGEOs with the focus on two main areas. First, to demonstrate and quantify the positive impact of lower viscosity on the fuel consumption rate, and second to demonstrate the faster lubrication of hard to reach points in the engine during startup. The current industry recognised fuel efficiency test methods for passenger car and on-road diesel engine sectors are not suitable for evaluating the fuel efficiency performance of a gas engine oil because of the significant differences in fuel type, engine operating conditions, and oil formulations. This paper, therefore, describes comparative studies of three different gas engine oils in a modern MAN E3262 E302 gas engine that was carefully adapted and fully instrumented. The performance of each oil with respect to fuel efficiency was assessed in an extensive program comprising endurance testing, stationary tests on various load/speed points and dynamic tests running the engine fired as well as non-fired (motored).

Another part of the test program explores the lubrication of hard to reach points in the engine, e.g. valve guide. The paper describes how the SAE 30 monograde oil results in faster lubrication of these parts during startup in comparison with the SAE 40 oils.

Keywords: Stationary gas engine oil, viscosity, SAE 30, fuel efficiency, start-up lubrication, wear reduction

Nomenclature

SGEO	Stationary gas engine oil
OEM	Original equipment manufacturer
BMEP	Break mean effective pressure
HTHS	High temperature high shear
CHP	Combined heat and power

1. Introduction

Natural gas is recognised as a critical engine fuel for the 21st century. Its market share of the global energy consumption significantly expands due to its environmental and economic benefits including lower emissions, steady supply, and very high overall efficiency, converting up to 90% of the fuel energy into useful power and heat.[1] While CO_2, NO_x, and SO_2 emissions from stationary gas engines are significantly lower than comparable diesel engines, there is a growing concern that engine emissions especially methane slip has to be addressed.[2] Natural gas original equipment manufacturers (OEMs) are constantly introducing changes to engine design, operation, and catalytic after-treatment to address emissions and comply with stricter environmental regulations.

Stationary gas engines used in power generation, gas compression and other industrial applications are typically lubricated with an SAE 40 monograde SGEO. Such oil does not contain the VI improver additives (polymer) nor the friction modifier additives that are present in automotive multigrade lubricating oils and its content of Extreme Pressure/Anti Wear additive and dispersant is significantly lower than that of an automotive engine lubricant. Gas engine OEMS have been reluctant to apply lower viscosity oils, fearing that reduced oil film thickness in bearings may increase wear.[3] But the global race to reduce CO_2 emissions that has resulted in the development of lower viscosity engine oils in the automotive industry[4] may also give rise to a market demand for fuel- efficient stationary gas engine oils.

Despite the historic preference of gas engine OEMS for SAE 40 monograde oils, several gas engine designs are capable to run safely on SAE 30 monograde oils. This awareness and stricter governmental policies on carbon emissions and rising fuel costs may necessitate the need for SAE 30 monograde SGEOs that positively effect fuel economy and the environment in the stationary gas engine market over the coming few years.

In addition to energy efficiency, another main area that can benefit from an SAE 30 SGEO is the current energy market, which is in transition with an increasing role of wind and solar energy. In this market, gas engines are often providing reserve power. This leads to a need of fast engine ramp up and down and multiple starts and stops per day. Low operating hours and high start rates are becoming the new normal. In such operating conditions, faster supply of oil to critical hard to reach points in the engine, e.g. valve guide during engine startup, will prevent wear and tear. This can be another advantage of an SAE 30 monograde gas engine oil over an SAE 40 oil.

In this paper, we explore the development of a test procedure for evaluating the potential benefits of a Petro-Canada Lubricants branded SAE 30 monograde SGEO in an R&D engine test bed. The focus has been on two areas, *a)* demonstrate and quantify the effect of lower viscosity grade on the fuel consumption rate, and *b)* demonstrate the faster lubrication of hard to reach points in the engine during startup. Although there exists industry recognised fuel efficiency test methods for passenger car and on-road diesel engine sectors,[5-7] these methods are not suitable for evaluating the fuel efficiency performance of a gas engine oil because of the significant differences in fuel type, engine operating conditions, and oil formulations.[8]

This paper describes comparative measurements of three different gas engine oils, one Petro-Canada Lubricants branded SAE 30 monograde oil and two SAE 40 monograde oils, one Petro-Canada Lubricants branded product and one from another reputable supplier, in a modern MAN E3262 E302 twelve-cylinder gas engine. This engine was on a fully instrumented and controlled R&D test bed at Adapt Engineering in Germany. The performance of each oil with respect to fuel efficiency was assessed in an extensive program comprising endurance testing, stationary tests on various load/speed points and dynamic tests running the engine fired as well as non-fired (motored) under controlled repeatable conditions. The energy efficiency of the SAE 30 oil compared to the SAE 40 oils has been assessed, not only by measuring fuel consumption but also by looking into indirect indicators of better fuel efficiency such as manifold pressure, exhaust gas temperature, heat absorbed in the lubricating oil, friction torque, and engine run down time after stopping fuel supply. Another part of the paper describes how the use of an SAE 30 oil results in faster lubrication of hard to reach points (e.g. valve guide) during startup in comparison with the SAE 40 oils.

2. Materials And Methods

2.1 Test engine

The test engine that has been used for this study was a MAN E3262 E302 naturally aspirated gas engine, installed at the R&D test bed of Adapt Engineering in Nordhausen, Germany. This engine is operated at 1500 rpm in 50 Hz markets and at 1800 rpm in 60 Hz markets, and is typically operated at full output in the field. The manufacturer has therefore optimised its performance for this single operating point. Table 1 shows the specifics of the test engine and its operating parameters.

Table 1: Engine Specifications and Parameters

Engine Specifications and Parameters	**Value**
Build	12-Cylinder 4-stroke V-type engine
Bore x Stroke	132 x 157 mm
Output@Speed	275 kW@1500 rpm (50 Hz application) 300 kW@1800 rpm (60 Hz application)
Mean Effective Pressure	8.5 bar@1500 rpm 7.8 bar@1800 rpm
Compression ratio	12.0
Combustion	Atmospheric Homogeneous Lambda=1
Oil capacity	80 liter
Oil Pump	Two engine driven pumps Positive displacement type Capacity of each pump: 180 liter/min @ 1800 rpm 150 liter/min @ 1500 rpm
Spark plug	MAN series M18 (Bosch R6 953 Double Iridium)
Throttle valve	MAN series (51.13105-6018)
Knock sensors	MAN series (51.27421-6009)
Firing order	1-12-2-11-3-10-6-7-5-8-4-9
Gas mixer	VariFuel2 30.45.140-80D with FB52.5 mm
Control unit	VariStep3 31.01.960
Ignition system	MIC4
Fuel	Natural gas
Intake air temp	≈25 °C
Ignition timing	22° crank angle before TDC
Braking system	Dynamometer: UHTD 355.3x-4, Co. AHK (Pmax. = 650 kW /Mdmax. = 4300 Nm /nmax.= 6000 rpm)
Fuel flow meter	F-106BI-PBD-03-V, Co. Bronkhorst, 0…100 m^3N/h
Temperature	Thermal elements: Nickel-Chromium-Nickel Resistance thermometer: Pt100
Pressure	Measurement capsules: ACQ5 A103-PRE, WIKA S10 Co. Wika Midas C08, Co. Jumo
Air flow	Mass flowmeter: Sensy Flow FMT 700-P, Co. ABB, 0...4000 kg/h
Air humidity	Hydrothermal sensor: TFK 30J, Co. Jumo, 0...100 % rel. humidity
Exhaust gas	FTIR, Co.AVL
Air/Fuel ratio	Lambda meter: LA4, Co. ETAS (1x bank 1 and 1x bank 2)
Accumulator for dynamic oil pressure measurements	Volume 0.45 liter Orifice 1.2 mm

The engine was fully instrumented with temperature and pressure sensors for all media at every possible location, allowing full evaluation of engine performance, exhaust emissions and heat balance. The suction air temperature was controlled, but not the suction air pressure and humidity, which followed ambient conditions.

The fuel used was pipeline gas quality from the German grid. In the course of the test program, gas samples were taken and analysed. The (small) variations in lower heating value have been taken into account in fuel efficiency results.

Air fuel ratio was adjusted manually based on composition of the exhaust gases using Brettschneider equations.[9]

In order to investigate if the SAE 30 SGEO flows faster through the engine than the SAE 40 SGEOs, the engine oil system had been equipped with an accumulator, connected to the pressurised oil system over an orifice *(Figure 1)*. The pressure build up in the accumulator reacts as a first order system, contrary to pressure build up in the pressurised oil system of the engine. The pressurised oil system is a hydraulically closed system and therefore pressure build up is instantaneous. The accumulator simulates in a qualitative, not quantitative manner, the oil supply to engine parts that are not included in the pressurised oil circuit of the engine, such as the valve guides.

Figure 1: Accumulator and Orifice

2.2 Test oils

Table 2 shows typical physical and chemical properties of the three different SGEOs that were used in this program. The High Temperature High Shear (HTHS) viscosity that influences fuel economy is also shown.

Table 2: Test Oils Characteristics

	Oil1 SAE 40	Oil2 SAE 30	Oil3 SAE 40
KV100, cSt, ASTM D445	13.6	10.7	12.9
Viscosity Index, ASTM D2270	102	130	107
HTHS, mPa.s, ASTM D4683	3.97	3.26	3.82
Pour Point, °C, ASTM D5950	-33	-42	-24
Sulfated Ash, Wt%, ASTM D874	0.7	0.7	0.7
%Ca, ASTM D4951	0.190	0.190	0.182
%P, ASTM D4951	0.027	0.027	0.029
%Zn, ASTM D4951	0.034	0.034	0.034
%S, ASTM D294	0.234	0.217	0.219
Noack at 250°C, %loss, ASTM D5800	3.3	4.4	4.4
TAN, mgKOH/g, ASTM D664	1.3	0.6	1.5
TBN, mgKOH/g, ASTM D2896	6.5	6.5	7.5

Oil1 and Oil2 are Petro-Canada Lubricants branded products and use the same additive chemistry, Oil3 is using different additive chemistry. All three oils are monograde and do not include VI improvers or friction modifiers in their formulation. Oil1 and Oil3 are formulated with heavy neutral Grp II base oils while Oil2 is using Grp III base oil in its formulation. Lubricants of same additive chemistry and different

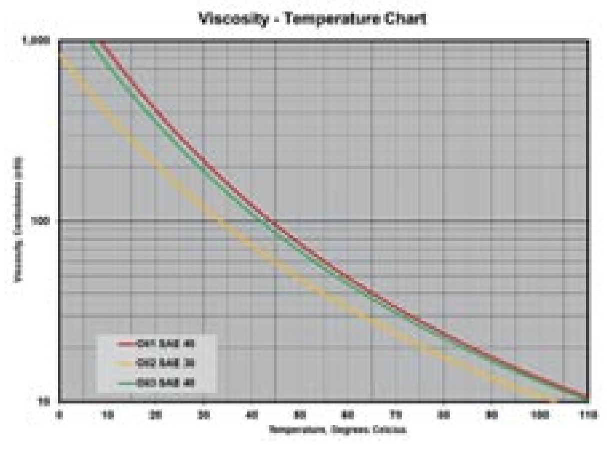

Figure 2: Viscosity – temperature relationship for the oils tested

viscosity grade (Oil1 and Oil2) were selected to evaluate the effect of viscosity on gas engine efficiency. Lubricants of same viscosity grade and different additive chemistry (Oil1 and Oil3) were selected to explore any additive effects of SGEO formulations on gas engine efficiency.

The viscosity-temperature relation of the test oils is given in Figure 2.

2.3 Test methods and measurements

The test program consisted of four elements:

1. Endurance test of 100 hours at full load and 1500 rpm with Oil1 and Oil2.
2. Engine performance measurements over a map of load/speed points with all three oils: measurements at 1500 rpm and 1800 rpm were each performed at 100%, 75% and 50% load points.
3. Recording of driving torque of the unfired engine at operating temperature at two different speeds (1500 and 1800 rpm) with all three oils. Assessment of oil pressure build-up (time response) in different boundary conditions with all three oils.

3. Fuel Efficiency Measurements

3.1 Endurance Test

The Petro-Canada Lubricants branded SAE 40 and SAE 30 oils have been used in a 100-hour endurance test. The purpose of this test was to demonstrate long-term influence of the oil viscosity on engine fuel efficiency, as well as its influence on oil consumption.

The results clearly demonstrate a reduced fuel burn with the SAE 30 oil. This can be seen in Figure 3 that shows the fuel energy input as a function of air/fuel ratio. Each cloud comprises 1200 measurement points. The fuel burn with SAE 30 was 5.8 kW of fuel lower heating value below that with SAE 40, which equates to an improvement of 0.8% of the total fuel burn with SAE 40 oil.

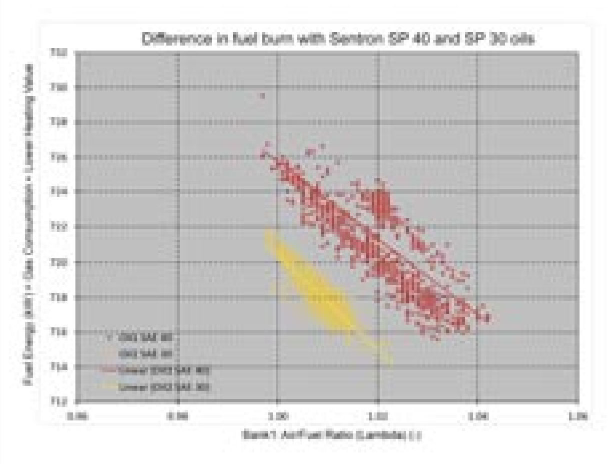

Figure 3: Difference in fuel burn with SAE 40 and SAE 30

The better fuel burn was also confirmed by the lower manifold pressure with the SAE 30 oil, i.e. the pressure of the mixture after throttle valve, before cylinder. The throttle valve equalises variations in ambient pressure, the resulting mixture pressure represents the amount of energy that enters the cylinder during the inlet stroke at a given air/fuel ratio. This effect is shown in Figure 4. Other indirect parameters that confirmed better fuel efficiency with the SAE 30 oil were reduced air- and exhaust gas flow. Exhaust gas temperature cannot be used as indicator for fuel consumption as the engine was operated at Lambda = 1.

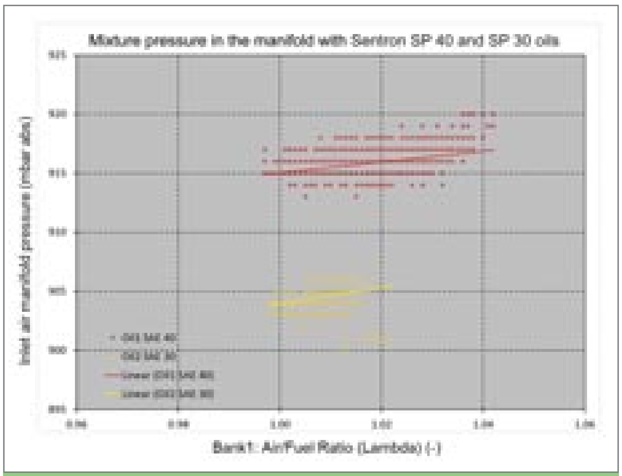

Figure 4: Mixture pressure in the manifold with SAE 40 and SAE 30

The effect of oil viscosity on lubricating oil consumption could not be demonstrated in 100 hours with the measurement method applied. Values measured were extremely low at 0.021 g/kWh for Oil1 SAE40 and 0.027 g/kWh for Oil2 SAE 30. The difference found is well within the accuracy of the measurement method (repeated weighing of oil above a certain level in the oil sump) which was demonstrated by the large spread in the individual amounts weighed during the repeated measurements.

Other observations were:

1. Oil pressure with SAE 30 averaged 3.91 bar, oil pressure with SAE 40 averaged 4.53 bar. Given that the oil pump is of positive displacement type, this already indicates that oil is flowing through the engine easier with SAE 30. With both oils, the system was well above the oil pressure alarm and shut down values of 3.0 and 2.5 bar, respectively.
2. The use of SAE 30 resulted in a 0.7 degrees C lower oil temperature, both before and after

engine. Surprisingly the oil temperature increase with the SAE 30 was exactly the same as with SAE 40. Even when taking into account different specific heat capacity of the SAE 30 and SAE 40 oil at operating temperature, the lower friction losses were not completely visible in the amount of heat absorbed in the oil.

3.2 Performance Tests

With all three oils, the engine performance was tested at two speeds times three load points. The order of testing was Oil1 SAE 40, Oil2 SAE 30, Oil3 SAE 40, to ensure that results are real and not due to sensor drift or bias over time. Results are presented in Tables 3 and 4.

Table 3: Fuel burn versus engine load @1500rpm

1500 rpm Fuel heat input (kW)	**100% load**	**75% load**	**50%load**	
Oil1 SAE 40 before endurance test	724.5	576.5	432.5	kW
Oil1 SAE 40 after endurance test	724.9	578.7	432.2	kW
Oil2 SAE 30 before endurance test	718.2	573.7	427.1	kW
Oil2 SAE 30 after endurance test	718.3	570.2	426.4	kW
Oil3 SAE 40	724.8	576.7	432.1	kW
Delta fuel heat input SAE 30-SAE 40	-6.5	-5.3	-5.5	kW
Fuel consumption improvement in %	0.89	0.92	1.28	%

Table 4: Fuel burn versus engine load @1800rpm

1800 rpm Fuel heat input (kW)	**100% load**	**75% load**	**50%load**	
Oil1 SAE 40 before endurance test	808.7	651.1	491.8	kW
Oil1 SAE 40 after endurance test	811.2	653.1	494.2	kW
Oil2 SAE 30 before endurance test	803.7	647.8	487.8	kW
Oil2 SAE 30 after endurance test	802.6	646.9	485.9	kW
Oil3 SAE 40	810.0	652.6	493.1	kW
Delta fuel heat input SAE 30-SAE 40	-6.8	-5.0	-6.3	kW
Fuel consumption improvement in %	0.84	0.76	1.27	%

Just like in the endurance test, the fuel savings with the SAE 30 oil have also been confirmed by lower manifold pressures.

The savings in fuel burn at 1500 rpm full load point corresponded well with the savings found in the endurance test.

The fuel savings with the SAE 30 oil at 1800 rpm were very similar to the savings at 1500 rpm, whereas one might have expected higher friction losses at higher engine speed. This may be explained by the engine operating in the fully hydrodynamic section of the Stribeck curve, therefore the friction coefficient at 1800 rpm would only be marginally higher than that at 1500 rpm. Also at 1800 rpm the engine runs at lower Brake Mean Effective Pressure (BMEP) than at 1500 rpm, resulting in lower normal forces. The reduced normal forces may offset the effect of higher speed, apparently resulting in very similar friction losses at both speeds.

3.3 Friction Torque Tests

In order to determine if the fuel savings found are the result of lower friction, friction torque tests were executed. The test sequence consisted of three phases:

Phase 1: The engine operates at full load and full speed. This is to ensure that all engine operating parameters are stable at normal levels. That includes the oil temperature.

Phase 2: Fuel supply and ignition are stopped and the throttle valve is fully opened, the generator acts as a motor and continues to drive the engine at full speed. The torque required to drive the engine represents friction and pumping losses.

Phase 3: The generator stops acting as a motor, the engine and generator speed runs down freely. The time it takes for the genset to come to a complete stand still is recorded. Longer run down time indicates less friction losses.

Theoretically, the difference in driving torque with the different oils during phase 2 is purely due to a difference in friction torque, as the pumping losses are the same. In practice, there is an effect of ambient pressure on the pumping losses.

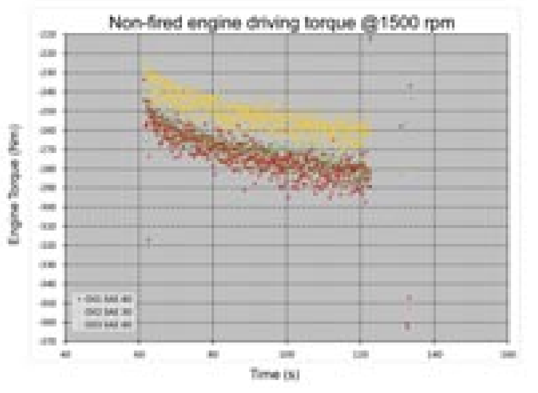

Figure 5: Non-fired engine driving torque @1500rpm

The results of Phase 2 of these tests are shown in Figure 5 (1500 rpm) and Figure 6 (1800 rpm), with engine torque delivered on the Y-axis. The engine torque depicted is negative as it is the generator driving the engine rather than the engine driving the generator.

One can observe that the generator driving torque increased over time as the oil passed the oil cooler and therefore cooled down by about 7°C over the 60 seconds period of observation.

The two SAE 40 oils required the same driving torque. The SAE 30 oil however required a reduced driving torque, at 1500 rpm the difference is 20 Nm. This represents 3.1 kW shaft output. With 38.0% engine efficiency, this would represent 8.3 kW = 1.1% fuel input saving.

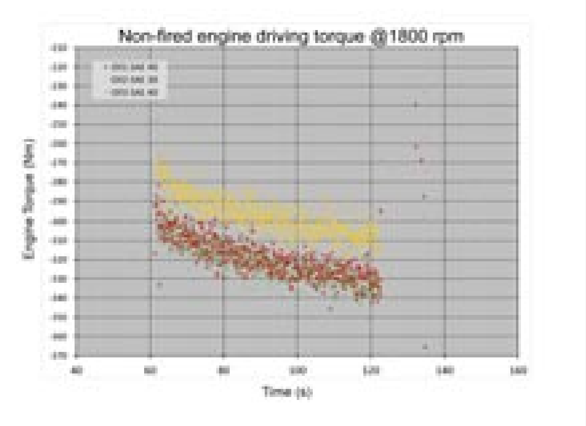

Figure 6: Non-fired engine driving torque @1800rpm

At 1800 rpm, the SAE 30 oil required 23.5 Nm reduced driving torque compared to the SAE 40 oils. This represents 4.4 kW shaft output. At 37.1% engine efficiency, this would represent 11.9 kW = 1.5% fuel input saving.

In Phase 3 the free run down time of the engine has been recorded. The result is shown in Figure 7. The speed reduction is due to the combined effect of pumping losses (compression) and friction. The time to reach 400 rpm in a free run down from 1800 rpm has been assessed, because below 400 rpm the compression and expansion effects in individual cylinders cause vibrations.

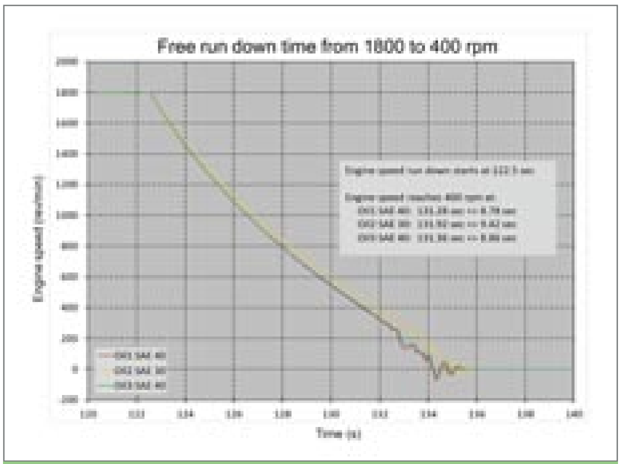

Figure 7: Free run down time from 1800 to 400 rpm

It can be clearly seen that the free run down time with the SAE 30 oil is longer than with both SAE 40 oils, which is another indication of less friction with SAE 30.

3.4 Discussion

The tests have consistently demonstrated that in this engine type, the Petro-Canada Lubricants branded SAE 30 oil offers less friction than both SAE 40 oils, resulting in a fuel efficiency improvement of at least 0.8%. Tests have also revealed that different additive packages in Oil1 and Oil3 do not produce measurable effects on fuel economy. It is important to take notice of the following:

- The saving in fuel burn of 0.8% represents an improvement of the engine efficiency of 0.3-0.4 percentage points, e.g. at 1500 rpm engine efficiency increases from 38.0 to 38.3%.
- The same engine is also available in a turbocharged lean burn version, supplying 450 kW @ 1500 rpm, i.e. 14.0 bar BMEP. In that engine type, SAE 30 will provide reduced friction losses, the absolute reduction will be at least the same as in our test engine (in non-fired engine tests they would be exactly the same), maybe somewhat higher thanks to higher normal forces. If absolute savings are the same, the percentage savings are lower. Where in the test engine the fuel saving with SAE 30 can be around 0.8%, the percentage saving will be lower in engines running at higher BMEP.
- The reduced fuel burn at given electrical output means less heat transferred to lube oil, cooling water and especially exhaust gases. For combined heat and power (CHP) or COGEN installations, this means less heat can be recovered and sold. This partially offsets the savings in fuel burn. The exact overall financial benefit will be a function of fuel cost and of the selling prices of electricity and heat.

4. Speed of lubrication during engine cold start

4.1 Test description and results

Another element of the test program was to investigate the speed of oil distribution through the engine during a cold start.

When the engine is started, the engine driven oil pumps will start to supply oil. It takes time for the oil to flow through the engine and reach lubrication points. The easier the oil flows, the faster such lubrication points can be reached. Critical parts are not only bearings, but especially lubrication points that are not included in the pressurised oil system of the engine such as the valve guides. These are lubricated with oil that has been freely flowing over the valve deck after seeping out of the rocker arm assembly.

In order to investigate how fast oil flows through the engine, a pressure vessel was installed at the far end of the engine (with respect to the oil inlet), on the oil supply bore to the turbocharger which is not present on this atmospheric version of the MAN E3262. This accumulator was connected with the oil system via an orifice. When the engine is standing still, the accumulator is empty. When the engine is started the accumulator will fill up with oil. The air in the accumulator is being compressed and the air pressure measured. The rate of pressure build up is an indication of the flow rate over the orifice, and qualitatively simulates the ease of oil flow to engine components that are not part of the pressurised oil system. It does however not quantitatively predict the time for the oil to reach the valve guides.

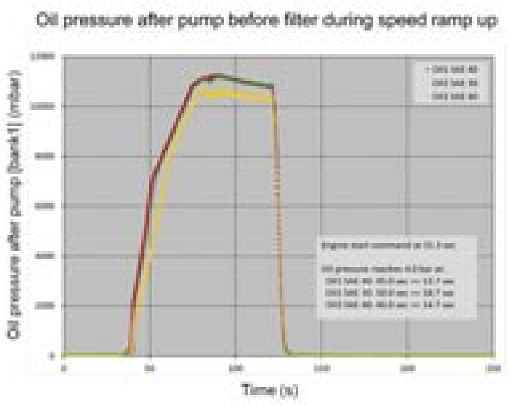

Figure 8: Oil pressure after pump during cold speed ramp up

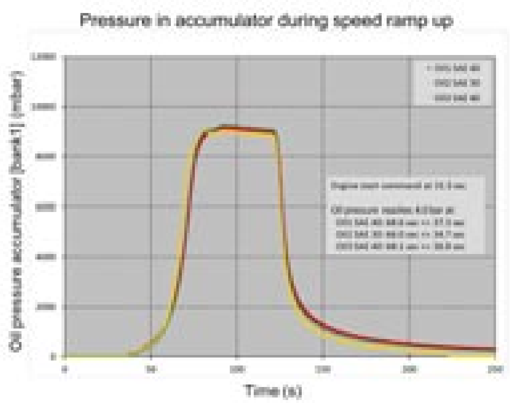

Figure 9: Oil pressure accumulator during cold speed ramp up

The test procedure was as follows. The engine had been standing over night and was cold, the temperature of all three oils was between 20.1 and 20.2°C. The generator was used to ramp up the engine speed from 0 to 1800 rpm in 60 seconds. The engine was not fired or started, but kept running for another 60 seconds driven by the generator. Figure 8 shows the oil pressure after pump before filter during the test.

It can be seen that the pressure build up with the SAE 30 oil lagged behind the pressure build up with the SAE 40 oils. This is simply because the SAE 30 oil flows more easily through the engine. It reaches lubrication points earlier. This is nicely demonstrated by the pressure build up in the accumulator, see Figure 9. It fills up faster with SAE 30 than with both SAE 40 oils.

4.2 Discussion

Figure 10 shows the torque that the generator has to deliver to bring the engine up to speed. It can be seen that with the SAE

30 oil significantly less torque was required to take the engine through the programmed speed ramp.

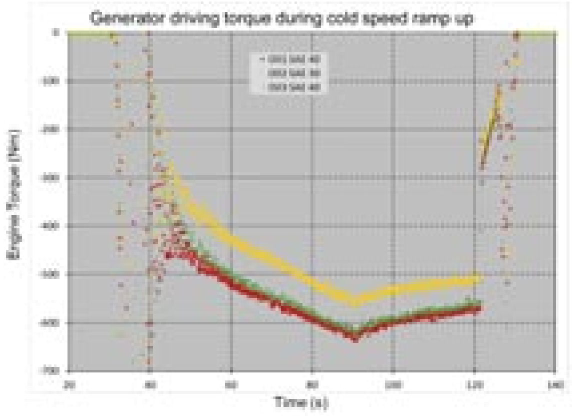

Figure 10: Generator driving torque during cold speed ramp up

This means that in normal operation, with a starter motor bringing the engine up to speed instead of the generator, the engine will speed up faster with SAE 30 than with SAE 40. And as a consequence the oil pump will supply oil faster. Moreover, the oil pressure after pump with SAE 30 will build up faster than what we have seen in this test and the same with the pressure in the accumulator. In hindsight, we should have used the engine starter motor instead of the generator in this test to demonstrate the advantage of SAE 30 even more clearly.

The numeric values obtained in this test only demonstrate the principle of oil supply to far away points that are not part of the engine's pressurised oil system. They are by no means a quantitative simulation of oil supply to the valve guides.

The advantage of better wear protection with SAE 30 oil during cold start only applies to engines that are not equipped with a pre-lubrication system, or with a lubricating oil preheating system.

5. Conclusions

All tests executed, have consistently demonstrated that the Petro-Canada Lubricants branded SAE 30 oil offered a fuel saving over SAE 40 oils and the effect of different additive chemistry in Oil1 and Oil3 on fuel economy was fairly neutral. The lower fuel consumption of the SAE 30 oil has also been confirmed by indirect parameters.

- Based on fired engine tests, SAE 30 provided a full load fuel saving over SAE 40 of 0.8-0.9% in this engine type.
- Measured reduction of friction losses with SAE 30 in non-fired engine tests corresponded to 1.1-1.5% fuel savings in this engine type.
- SAE 30 resulted in an overall lower oil temperature and oil pressure in the engine, which is allowable and desired for this engine type.
- The percentage savings will be lower for engines running at higher BMEP, however absolute savings will be there.
- In CHP installations, the better electrical fuel efficiency results in reduced heat production, which may partly offset the fuel efficiency savings.

In comparison with SAE 40 oils, the tests have demonstrated that the Petro-Canada Lubricants branded SAE 30 oil results in faster supply of lubricating oil to critical lubrication points in the engine during cold start. This is considered a major advantage as fast lubrication will help to reduce wear in start/stop operation, which is typical for the heat demand driven CHP applications where such engines are often applied.

The expected advantage of lower oil consumption with SAE 30 could not be demonstrated, probably because of the extremely low oil consumption of the engine, the relatively short test time, and the repeatability of oil weighing procedure.

Authors would like to emphasise that not all gas engine types in the market have been designed to run with SAE 30 oils, and that the benefits demonstrated can only be achieved with engines for which SAE 30 oils are deemed suitable by the engine manufacturer.

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