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On-Line Measurements of Engine Oil Aeration by X-Ray Absorption

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ABSTRACT

The oil aeration in a V-6 spark-ignition passenger car engine under motoring condition was measured by the X-ray absorption method in the speed range of 2000-6000 rpm. Measurements were made at different locations in the sump representing the state of the oil at (1) the pump inlet, (2) the head return and (3) the timing chain return. The aeration of the block return was estimated from these measurements. At a fixed engine speed, the aeration (in % volume of air) of the head return and the chain return were about the same, and they were approximately twice the value found in the block return. This distribution did not change with engine speed. When weighted by the flow rate, however, the block flow contributed to 55% of the aeration at the pump inlet; the total contribution of the head return and the chain return was 45% (36% from head return and 9% from chain return). Further aeration observations were made by comparing the cases with and without the oil sump windage tray in place. When the tray was removed, aeration at the pump inlet was found to increase by less than 30% for all speeds.

INTRODUCTION

The presence of air in the engine oil system can adversely affect the lubrication and hydraulic functions [1-5]; in some cases, severe aeration leads to hardware failures (e.g. loss of lubrication in the rotating components [4, 5]). The degree of aeration is especially severe at high engine speeds because of the increased level of air ingestion into the oil, and because of the shorter residence time in the sump for the air bubbles to rise and escape from entering the oil pump inlet.

The solubility of air in the engine oil is governed by the Bunsen coefficient or Henry's constant (the two quantities are related; see Appendix A). The amount of air dissolved in the oil is proportional to the system pressure p. Thus if the aeration (defined as the ratio of the volume of free air to the total volume of air and oil) is high at the oil pump inlet, it will be substantially lower when the fluid is pressurized by the pump since more air will dissolve in the oil. However when the pressure is released, for example, in a rotating bearing due to the centrifugal force, air will be significantly desorbed and will have adverse effect on the system performance. Therefore, it is of interested to inventory the flow of free air into the oil pump inlet.

Measurements of aeration level were either done by sampling the oil, letting the air separate out and measuring its volume [3,4], or by monitoring the density of the fluid consisting of the free air and oil together. For the latter, the density may be measured inertially, usually by using a Coriolis flow meter [6,7], or by X-ray absorption [8]. The density measurement methods are preferred because they can monitor the engine state in real time.

This paper describes the measurement of aeration in a passenger car engine motoring at high speed by the X-ray absorption. The method was used to inventory the flow of free air in the sump pump inlet and in the return flows from the head and timing chain respectively. Also aeration level comparisons were made for the engine operating with and without the windage tray. The purpose was to quantify the sources of free air that is fed to the sump pump.

X-RAY ABSORPTION METHOD

A commercially available X-ray absorption based apparatus (Air-X from DSI-Deltabeam [8]) was used to monitor aeration in an engine. The measurement principle was based on the fact that free air has a negligible X-ray absorption cross-section compared to the engine oil. Thus if the aeration level is x, defined by

$$x = \frac{\text{Volume of free air}}{\text{Volume of free air + Volume of oil}} \qquad (1)$$

Then x is related to the measured X-ray intensities I by

$$x = \frac{\log(I/I_0)}{\log(I_1/I_0)} \qquad (2)$$

Here, I_0 and I_1 are the intensities measured at $x = 0$ (all oil) and $x = 1$ (all air) in a calibration process. See Nomenclature at the end of paper for symbol definitions.

Error Estimate

The error estimate for the aeration measurement may be obtained from Eq. (2) as:

$$(\sigma_x)^2 = \left(\frac{\partial x}{\partial I}\sigma_x\right)^2 + \left(\frac{\partial x}{\partial I_0}\sigma_{I_0}\right)^2 + \left(\frac{\partial x}{\partial I_1}\sigma_{I_1}\right)^2 \qquad (3)$$

The worst case (largest σ_x) is when $x = 0$ (all oil). Then

$$(\sigma_x)^2 = \frac{2}{\left[\log\left(I_1/I_0\right)\right]^2}\left(\frac{\sigma_{I_0}}{I_0}\right)^2 \qquad (4)$$

Since the detector counts X-ray photons, the signals are subject to shot noise, whence:

$$\left(\frac{\sigma_{I_0}}{I_0}\right)^2 = \frac{1}{\dot{C}\tau} \qquad (5)$$

where $\dot{C}\tau$ is the total count of photons received by the detector at $x = 0$ at a counting rate of $\dot{C}$ in a time interval τ. Thus the error estimate for the aeration level x is:

$$\sigma_x = \frac{1}{\left[\log\left(I_1/I_0\right)\right]}\sqrt{\frac{2}{\dot{C}\tau}} \qquad (6)$$

The error in x is proportional to $(1/\tau)^{1/2}$. Hence there is a trade off between uncertainty and time resolution.

For the Air-X machine, $I_1/I_0 \approx 2$; the counting rate $\dot{C}$ from the Cadmium 109 X-ray source is of the order of 50000 per second (the value is for a new source; the half life of the source is 1.3 year). The trade off between accuracy and time resolution is shown in Fig. 1. For the results in this paper, τ was set at 5 seconds. Then σ_x is of the order of 1%.

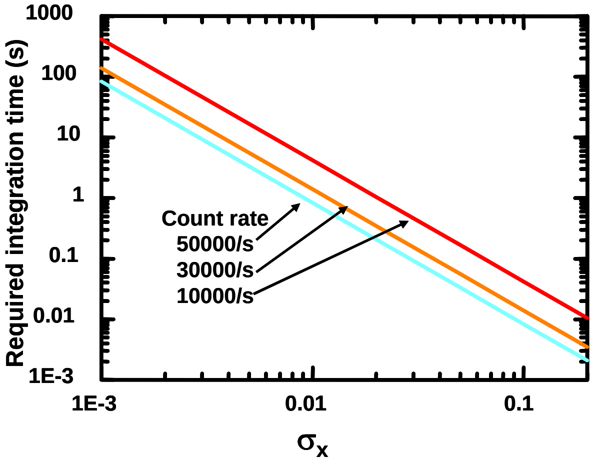

Fig.1 Required integration time as a function of standard deviation in aeration measurement (σ_x) and count rates.

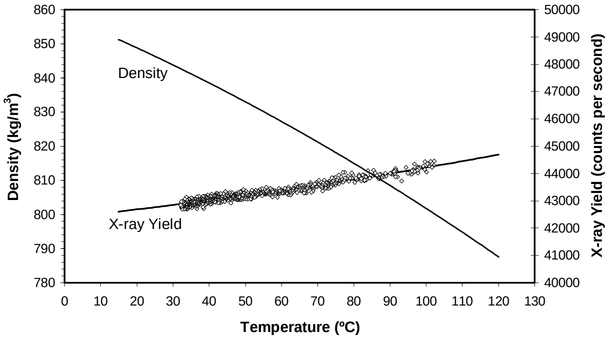

Fig.2 Air-X sensor signal as a function of oil temperature and the inferred relative density; SAE 5W-20 oil. The density was pegged at the published value at 15.6° C (60°F).

Measurement adjustments

There are two adjustments to be made to the measurements according to Eq. (2). First, the instrument may be calibrated by measuring I_0 at a different temperature than the in-use temperature. Then the thermal expansion of the oil density has to be taken into account of. The instrument was used to measure the relative density of the oil as a function of temperature (Fig. 2), and this data were stored to be used for density correction. The Air-X apparatus software has build-in functions to do this correction.

The second adjustment is due to the fact that the sample is transferred from the engine at temperature T_1 and pressure p_1 to the instrument measurement section which is at a different temperature and pressure (T_2 and p_2). Thus the measured value of aeration, x_2, has to be converted to the value x_1 in the engine by accounting for the change in volume of free air and oil due to temperature and pressure changes, and the desorption/absorption of air from the oil. Details of the calculation are described in Appendix B.

EXPERIMENTAL SET UP

A production Ford 3.0L V6 DOHC engine was used in this study. The set up has been described in a previous publication [9]; it is briefly described here for completeness. The engine was driven by a 75 hp motor with a 2.29 gear ratio chain drive so that a maximum speed of 8000 rpm was achievable. The engine was instrumented with thermocouples and pressure gauges to monitor steady state and transient conditions.

The engine was filled with 4 L of SAE 5W-20 oil. The oil properties are shown in Table 1. When the engine was not running, the oil level was 10 mm below the lowest point of the crank shaft counter weight trajectory. When the engine was operating, approximately 2.2 L of oil remained in the sump, while the rest occupied the various engine passageways.

SAE Grade	5W-20
API Service	SJ / EC
Gravity	35 ºAPI
Density, @ 15.5ºC	851 kg/m^3
Flash Point, COC	185 ºC
Kinematic Viscosity at 40ºC	4.9×10^{-5} $\text{m}^2\text{/s}$
Kinematic Viscosity at 100ºC	8.8×10^{-6} $\text{m}^2\text{/s}$
Viscosity Index	161
HT/HS Viscosity @ 150ºC	2.65 cP
Pour Point	-45 ºC
Sulfated Ash	0.94 Wt. %
Total Base Number	7.5 TBN
ASTM Color	4

Table 1 Properties of the lubrication oil used in this experiment; from Ref. [10].

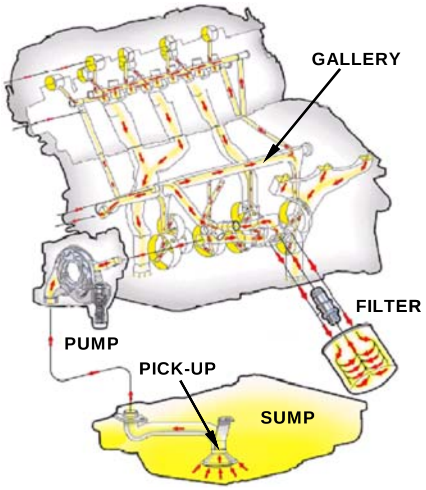

Fig. 3a Oil flow paths in engine.

The oil was externally heated or cooled to obtain a reasonable range of temperatures, but the temperature was not precisely controlled because the oil was also heated by the friction of the motoring process. Depending on the engine speed and the location of measurement, the oil temperature was in the range of 80 to 110° C.

The flow paths of the oil in the engine and in the sump are shown in Fig. 3a and 3b. There were three head return paths (two for the right-head and one for the left-head) which drained directly into the sump. The oil form the cam chain and the pump relief returned at the front side of the engine. We'll use the name "*block flow*" to refer to the oil returned from the engine components in the block (the main and connecting rod bearings, and the blow-by); this flow was nominally collected on the windage tray and drained to the surface of the sump oil.

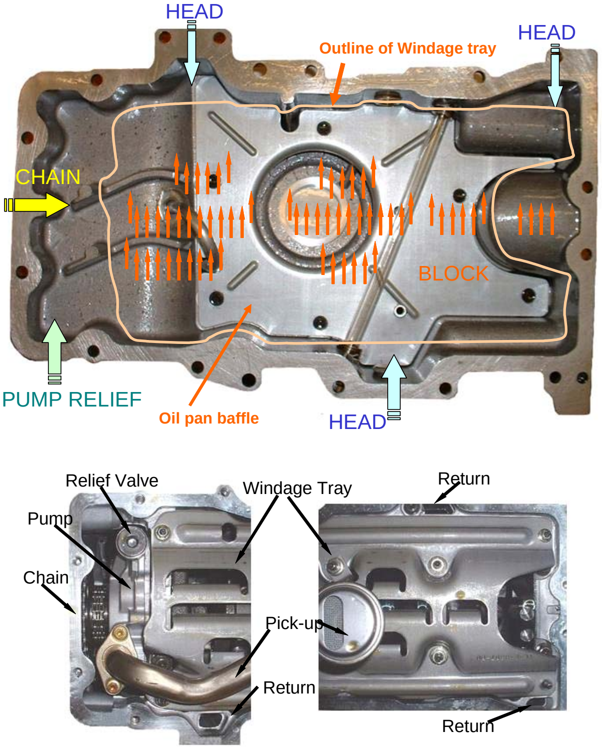

Fig. 3b Geometry of oil flow in sump. Top figure: view from top of sump with windage tray removed. Bottom figure: view from bottom of sump towards top of

Oil sampling

At first, we attempted to sample directly the oil from the head return by using a funnel to collect that oil and to feed it to the Air-X instrument. The measured aeration, however, depended very much on the sample flow rate (which was regulated by the pump of the instrument) because iso-kinetic sampling condition was not achieved. The situation is illustrated in Fig. 4. When the oil flow collected by the funnel is faster than the sample flow rate (Fig. 4a), the fresh oil spills out of the funnel; the sampling draws in the oil which has been sitting in the funnel for some time, during which some of the air bubbles rise and escape. Therefore the instrument measures a lower aeration level. When the sample flow rate is faster than the collection rate (Fig. 4b), air is ingested by the sampling system; hence the instrument measures a higher aeration level.

The final sampling configuration is shown in Fig. 5. Oil was sampled from the oil pan at points closed to where the various return oil flows entered the sump oil and at the entrance to the pump. (In principle, the oil pan acted as a large collecting funnel, but in this case, it was part of the engine instead of the sampling system so that the effects

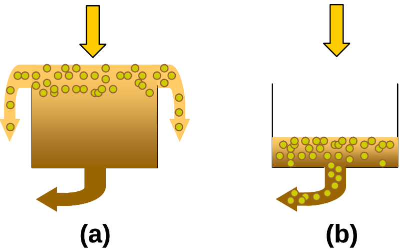
(a) (b)

Fig. 4 Non-iso-kinetic sampling of oil flow. (a) Sampling rate smaller than the collection rate – spill over; (b) sampling rate faster than the collection rate – ingestion of air.

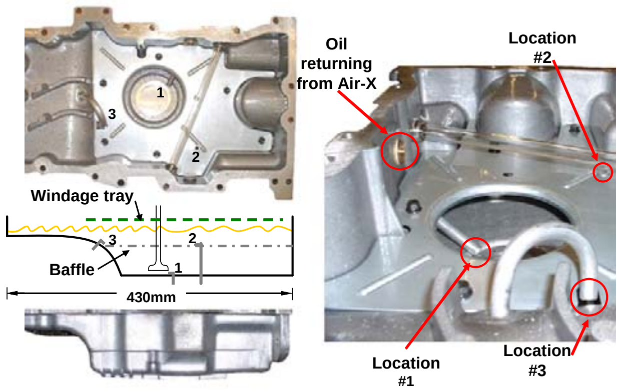

Fig. 5 Engine oil sampling points in the sump; the line drawing is to scale. The sampling locations were (1) sump pump inlet; (2) head return; (3) chain return. The glass view tube in the right picture was not used in this experiment.

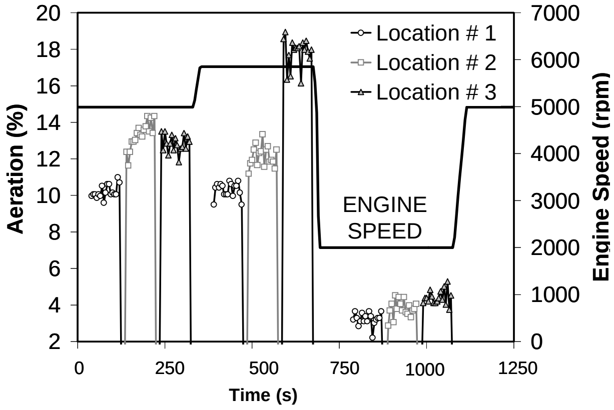

Fig. 6 Typical aeration data from the three locations shown in Fig. 5. Engine speed ranged from 2000 to 6000 rpm. Sample integration time of 5s; 1L /min sample flow.

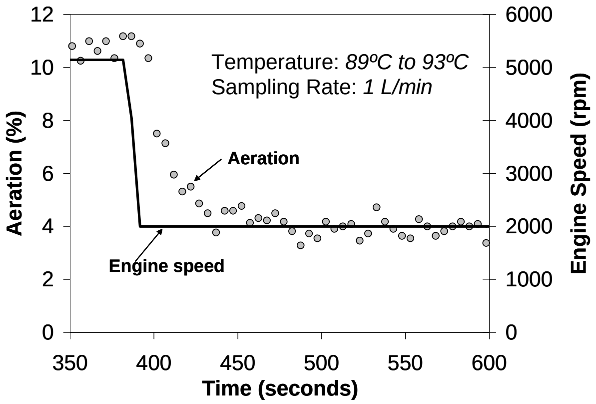

Fig. 7 Aeration measurement in a speed change. Measurement from sump pump inlet (location 1).

illustrated in Fig 4 were not relevant.) The sample locations were at:

1. Sump pump inlet
2. Head oil return path (referred to as Head return)
3. Oil return from the cam chain chamber (referred to as the Chain return)

The sampling rate was 1 L per minute. The three sample lines were selected by a set of valves to direct the flow to the Air-X instrument. The temperature drop from the sump (at 80-110^{o}C) to the instrument measurement section was approximately 4^{o}C.

AERATION MEASUREMENTS

Typical aeration data are shown in Fig. 6 for the three sampling locations. To flush out the sampling system, the first portion of the data was not used when the sampling line was switched. The steady state data scatter was of the order of 1 percentage point.

The continuous data for a speed change are shown in Fig. 7. It took approximately 50 seconds for the measured value to re-establish steady state. This time constant was a combination of the filling/emptying time of the sampling system and the adjustment time of the aeration level in the engine. When the speed was changed, typically a 50-100 s wait period ensured steady state condition

To investigate whether the aeration level was dependent on the previous state, the following four sets of data were taken with the procedure described above:

(i) base line data in which the speed was changed from 2000 to 6000 rpm in 1000 rpm increments;
(ii) then the data was repeated with the engine speed changed in the order of 2000, 5000, 3000, 6000 and 4000 rpm;
(iii) The engine was shut down for 100 seconds after the second experiment, and (i) was repeated. The oil was given the chance to de-aerate, while the temperature was only reduced modestly;
(iv) The data were taken after a 24 hour waiting period during which the oil had completely de-aerated and cooled to ambient temperature.

The results are shown in Fig. 8. The four procedures produced essentially the same results. (Some of the data points overlapped.) Thus the steady state aeration level is an equilibrium value which does not depend on prior conditions.

The data in Fig. 8 show clearly that the aeration increased with engine speed and that location 1, being further from the oil surface than location 3, had a lower aeration level. These observations are consistent with the explanation that air bubbles rise and escape from the sump oil; so aeration decreases as a function of depth and increases with higher engine speed (shorter residence time).

To decouple the speed effect and sump residence time effect on the aeration at the pump inlet, the total oil volume in the engine was changed. The premise was that the residence time should scale as the oil volume in the sump divided by the pump flow rate. The engine oil was drained and refilled with 4, 4.5 and 5 L of 5W-20 oil respectively. When the engine was running, the amount of oil in the sump was at approximately 2.2, 2.7 and 3.2 L; thus there should be a significant change in the sump residence time at the same engine speed.

The aeration values at the pump inlet for the three different oil volumes are shown in Fig. 9. (Note that the pump relief valve kicked in at 3000 rpm; but that should not affect the results for comparing the aeration at the same rpm.) The aeration increased with speed; there was, however, no significant dependence on oil volume within the experimental uncertainty of +/-1%. Further experimental results are therefore needed to clarify the role of air bubble rise and the sump residence time on aeration.

FLOW OF FREE AIR IN THE SUMP

Fig. 10 shows the oil aeration as a function of engine speeds at the three locations shown in Fig. 5. Location 1 measured the oil at the pump inlet; location 2 measured the oil returned from the head; location 3 measured the oil returned from the chain. The oil flow through the engine was known (see Fig. 11): 12% delivered to each side of the head, 6% to the chain drive, and 70% to the main and connecting rod bearings. Since the flow at the sump pump inlet was equal to the sum of the flows returning from the head, the chain and the block, the aeration of the block flow may be estimated. In this estimate, the oil from the relief valve was assumed to be at the same aeration as the pump inlet since the entrained air that was absorbed when the oil was pressurized would be released when the pressure was relieved. Furthermore, the amount of de-aeration was assumed to be small in the sump. This assumption was supported by the insensitivity of the aeration at the pump inlet to the oil volume (Fig. 9). Nevertheless, the resulting value for the block flow aeration would be a lower estimate. Then:

$$x_b = \frac{(Q_i - Q_r)x_1 - Q_h x_2 - Q_c x_3}{Q_b} \qquad (7)$$

where

x_b = Aeration of block flow
x_1 = Aeration at pump inlet (measured at location 1)
x_2 = Aeration of head return oil (measured at location 2)
x_3 = Aeration of chain return oil (measured at location 3)
Q_i = Volume flow rate at pump inlet
Q_r = Relief valve flow rate (valve activated at 3000 rpm)
Q_h = Head (both sides) flow rate
Q_c = Chain drive flow rate

The estimated aeration, x_b, of the block flow is shown as dash line in Fig. 10.

The data in Fig. 10 show that the aeration of the head return and the chain return oil were about the same; they were approximately twice the values found in the block flow. This distribution did not change with the engine speed.

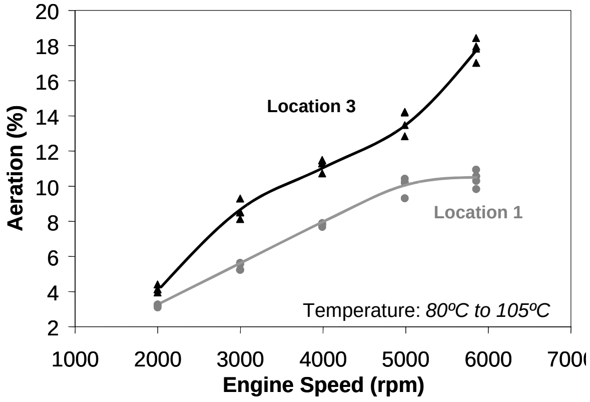

Fig. 8 Aeration at different engine speeds for locations 1 and 3 in Fig. 5. The four data points at each speed for each location correspond to the values obtained from the four procedures described in the text.

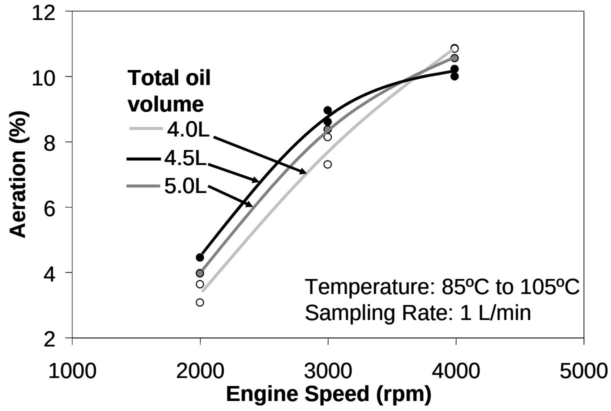

Fig. 9 Aeration at sump pump inlet (location 1) for total engine oil volumes of 4.0, 4.5 and 5.0 L (corresponding to 2.2, 2.7 and 3.2 L of oil in the sump when engine was running).

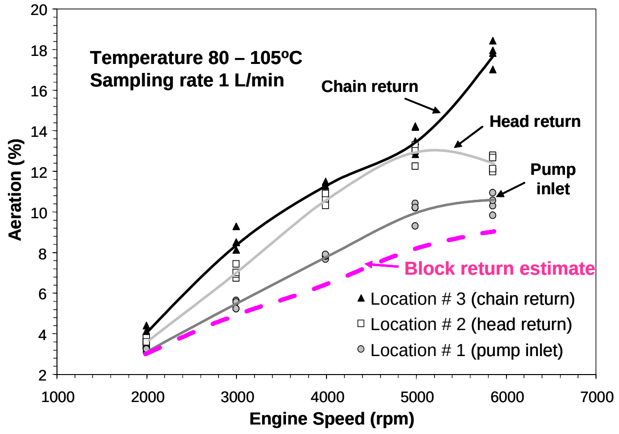

Fig. 10 Aeration measurements as a function of engine speed at different locations in the sump.

When weighted by the flow rate, however, the block flow contributed to 55% of the aeration at the pump inlet; the total contribution of the head return and chain return was 45% (36% from head return and 9% from chain return), see Fig. 12. (Since the oil flow from the relief valve was assumed to have the same aeration as the pump inlet, it was not considered as a primary source of aeration, and therefore not included in this accounting.) Thus both the block return and head return were major contributors to the flow of trapped air to the sump pump. The chain return contribution was much less because of the low volumetric flow rate.

MEASUREMENTS WITHOUT WINDAGE TRAY

To assess the effect of the windage tray on aeration, measurements were made with the windage tray removed. The results are shown in Fig. 13. When the tray was removed, the aeration at the sump pump inlet increased by less than 30% for all speeds.

The windage tray blocks the majority of the oil drops in the crankcase from striking the oil in the sump. Only 20% of the windage tray area was open for venting (see Fig. 3). If the oil drops from the moving crank and the blow-by were a major source of aeration, a much bigger difference in aeration would be expected when the windage tray was removed.

To explain this observation, it was conjectured that a significant amount of aeration was produced by the droplets striking the oil layer on the windage tray. Therefore, the difference between the cases with and without the windage tray in place was only in the interaction of the oil drops from the crankcase with the oil layer on the tray and with the oil in the sump. Hence not a big difference was found.

CONCLUSIONS

The oil aeration in a motoring V-6 spark-ignition passenger car engine was measured by X-ray absorption. The method was used to inventory the flow of free air to the sump pump inlet from the return oil flows. The following observations were made.

1. At a fixed engine speed, the aeration (as % volume of free air in the air/oil mixture) of the head return and the chain return were about the same, and they were approximately twice the value found in the block flow. This distribution did not change with engine speed.
2. When weighted by the flow rate, however, the block flow contributed to 55% of the aeration at the pump inlet and the head return contributed to 36%. The chain return contribution of 9% was much smaller because the volume flow rate was much less.
3. There were no significant changes in aeration at the sump pump inlet when the total engine oil volume was changed from 4 to 5 L, which corresponded to a sump oil volume 2.2 and 3.2 L under running condition.

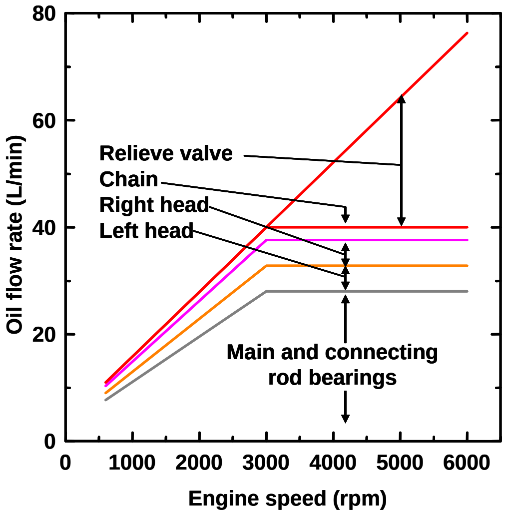

Fig. 11 Oil flow distribution in engine. Sump pump relief valve activated at 3000 rpm.

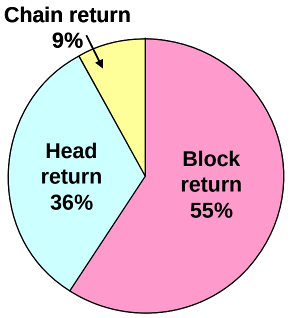

Fig. 12 Distribution of air transport from the returns.

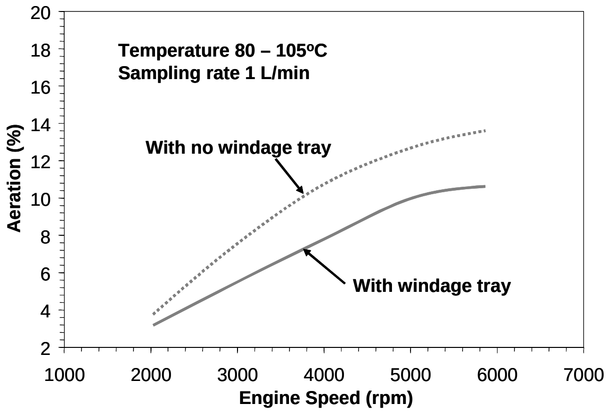

Fig. 13 Aeration at sump pump inlet as a function of engine speed: with and without windage tray in place.

4. When the windage tray was removed, aeration at the pump inlet increased by less than 30% over all engine speeds.

The X-ray absorption method was found to be a very effective means of measuring oil aeration in an engine.

ACKNOWLEDGEMENT

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NOMENCLATURE

’	denotes quantities dissolved in oil
B	Bunsen coefficient
$\dot{C}$	X-ray counting rate at detector
H	Henry’s constant
I	Measured X-ray intensity
I_0	Measured X-ray intensity at x = 0
I_1	Measured X-ray intensity at x = 1
N_0	mole of oil
N	mole of free air
N’	mole of dissolved air
p	Absolute pressure
p*	Reference pressure (1 bar)
Q_i	Volume flow rate at pump inlet
Q_r	Relief valve flow rate (valve activated at 3000 rpm)
Q_h	Head (both sides) flow rate
Q_c	Chain drive flow rate
R	Universal gas constant
T	Temperature
T*	Reference temperature (293^o K)
V_{oil}	Volume of oil
V	Volume of air
V*	Volume of dissolved air when released to the reference condition of T* and p*
x	Aeration level; ratio of volume of free air to total volume of free air plus oil
x_b	Aeration of block flow
x_1	Aeration at pump inlet (measured at location 1)
x_2	Aeration of head return oil (measured at location 2)
x_3	Aeration of chain return oil (measured at location 3)
ρ_0	Molar density of oil
σ	Standard deviation
τ	Integration time of X-ray detector

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APPENDIX A:

Relationship between Henry’s constant and Bunsen coefficient

Henry’s constant H and Bunsen coefficient B are two ways of assessing the solubility of air in a liquid. Consider N_0 mole of oil in thermodynamic equilibrium with air at absolute pressure p. Then the number of moles of dissolved air, N’, is governed by the Henry’s constant H:

$$p = H\frac{N'}{N_0 + N'} \tag{A1}$$

The Bunsen coefficient B is defined by the following:

$$V^* = B\,V_{oil}\frac{p}{p^*} \tag{A2}$$

where V_{oil} is the oil volume and V* is the volume occupied by the dissolved air when it is released to a reference condition at p* and T* (1 bar and 293^o K). Thus,

$$N' = \frac{p^* V^*}{RT^*} \tag{A3}$$

where R is the universal gas constant. Comparing Eqs. (A1) to (A3), the Bunsen coefficient and Henry’s constant are related by:

$$B = \frac{\rho_0 RT^*}{H - p} \tag{A4}$$

where ρ_0 is the molar density of the oil. For N_0>>N’ (equivalent to H>>p), which is usually the case, Eq.(B4) simplifies to:

$$B = \frac{\rho_0 RT^*}{H} \tag{A5}$$

Typical values for air dissolving in lubrication oil are:

$\rho_0 = 1.76$ kmol/m^3
B = 0.09
H = 476 bar

APPENDIX B:

Relationship between aeration level at sample inlet and at instrument measurement section

At the sample inlet, the instrument draws in N_1 mole of free air and N_1' mole of dissolved air which is contained in N_0 mole of oil at temperature T_1 and pressure p_1. The free air occupies a volume of V_1 given by:

$$V_1 = \frac{N_1 R T_1}{p_1} \tag{B1}$$

where R is the universal gas constant. The aeration level x_1 at the inlet is given by:

$$x_1 = \frac{V_1}{V_1 + N_0/\rho_{0,1}} \tag{B2}$$

where $\rho_{0,1}$ is the molar density of oil at the inlet condition. This sample (free air + oil + dissolved air) is transferred to the measurement section of the instrument which is at temperature T_2 and pressure p_2. Here the volume of free air is V_2. The aeration level x_2 at the measurement section is given by

$$x_2 = \frac{V_2}{V_2 + N_0/\rho_{0,2}} \tag{B3}$$

where $\rho_{0,2}$ is the molar density of oil at the measurement section.

To calculate x_1 from x_2, two physical effects have to be accounted for: (i) the change in gaseous and liquid volumes via the ideal gas law and coefficient of expansion of the oil; (ii) desorption/absorption of air by the oil. The calculation applies Henry's law (Eq.(A1), assuming that N_0>>N') to relate the free and dissolved quantities of air, and notes that the total moles of free and dissolved air are conserved:

$$N_2 + N'_2 = N_1 + N'_1 \tag{B4}$$

After some algebra, x_1 is related to x_2 by:

$$x_1 = \frac{\xi}{1+\xi} \tag{B5}$$

where

$$\xi \equiv \left(\frac{p_2}{p_1}\frac{T_1}{T_2}\frac{\rho_{0,1}}{\rho_{0,2}}\right)\frac{x_2}{1-x_2} + \frac{\rho_{0,1}RT_1}{H_1}\left(\frac{p_2}{p_1}\frac{H_1}{H_2} - 1\right) \tag{B6}$$

The subscripts 1 and 2 refer to the inlet and measurement section conditions respectively. The first term in the ξ expression in Eq. (B6) represents the effect of changes in gaseous and liquid volumes. The second term represents desorption/absorption effect. For T_2, P_2 the same as T_1, P_1, the expression reduces to $x_1 = x_2$.