Engine Lubrication Oil Aeration

by
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B.S., Mechanical Engineering (2005)
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ABSTRACT

The lubrication system of an internal combustion engine serves many purposes. It lubricates moving parts, cools the engine, removes impurities, supports loads, and minimizes friction. The entrapment of air in the lubricating oil is called oil aeration. Oil aeration can be detrimental to internal combustion (IC) engines. This study attempts to determine a means to reduce the level of aeration in a typical IC engine.

Experiments were performed on a motored Ford 3.0L V6 DOHC engine which was capable of reaching speeds up to 8000 rpm. Oil was sampled from the sump in the pump pick up area. Sump temperature, oil volume, and engine speed were continuously monitored. Aeration measurements were made via an x-ray absorption technique using a machine called Air-X.

A repeatability and reproducibility (R&R) study was performed initially. This study determined that the measurement technique was sufficiently repeatable within the tolerance of the Air-X machine.

Tests were then performed which varied parameters such as engine speed, oil volume, and hardware design. Specifically, multiple designs of the windage tray, an engine component that separates the oil sump from the rotating crankshaft, were tested.

Testing revealed that within the tolerance of the Air-X machine, the extent of the windage tray open area has no significant affect on the aeration level.

Thesis Supervisor: Wai K. Cheng
Title: Professor of Mechanical Engineering

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ACKNOWLEDGEMENTS

My time at MIT has been rather short but nonetheless immensely fulfilling. I have learned a lot, not just about my academic field of study, but also and possibly more importantly, about myself and others. MIT is a very unique special place that compares to nothing else. The opportunity to be part of the MIT community is a real honor. I am extremely grateful that I was offered this opportunity.

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During my time at MIT I have come to realize what I cherish most in my life: friends and family. When life gets confusing or frustrating as it often does, the solution doesn't come from a text book or a lab notebook but from a friend, my sisters, or my parents. So, thank you to Andrea Pallante, my college friend who moved to Boston with me for a year of exploration, memory making, and general fun. I'm not sure I would have made it through that first semester without you. Thank you to Tiffany Groode, whom I met and became friends with here at MIT. Your laughter and friendship has enriched my life and I'm sure it will continue to do so. I only hope I have made an equally positive impact on your life.

Last, but most certainly not least, my family. I was blessed with wonderful, caring, fun parents and sisters. Thank you, Mom, Dad, Kelsey, and Carina, for always being there with advice, confidence, and love. You are my best friends.

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Chapter 1: Introduction and Background

Aeration is the entrapment of air in a liquid. Aeration of engine lubrication oil can be detrimental to internal combustion (IC) engines. This study is an attempt to determine a means to reduce the level of aeration in a typical IC engine.

1.1 Oil Aeration

1.1.1 Description of Oil Aeration

Air can be present in lubricating oil in three forms; dissolved air, air bubbles, and foam. In these forms the air is referred to as "bound" air because it is bound, or connected, to the oil. Dissolved air is not visible and is harmless to oil function as a lubricant; however it can be released as bubbles and/or foam. Bubbles are small air pockets entrained and dispersed throughout the oil while foam is pockets of air on the surface of the oil separated by thin liquid films [1]. Air that is separated from the oil is referred to as "unbound" or free air and can become bound air through a variety of mechanisms described below. Figure 1-1 illustrates these different interactions between air and oil. Dissolved air can become bubbles when the temperature increases or pressure decreases [2]. When bubbles rise above the surface they become foam.

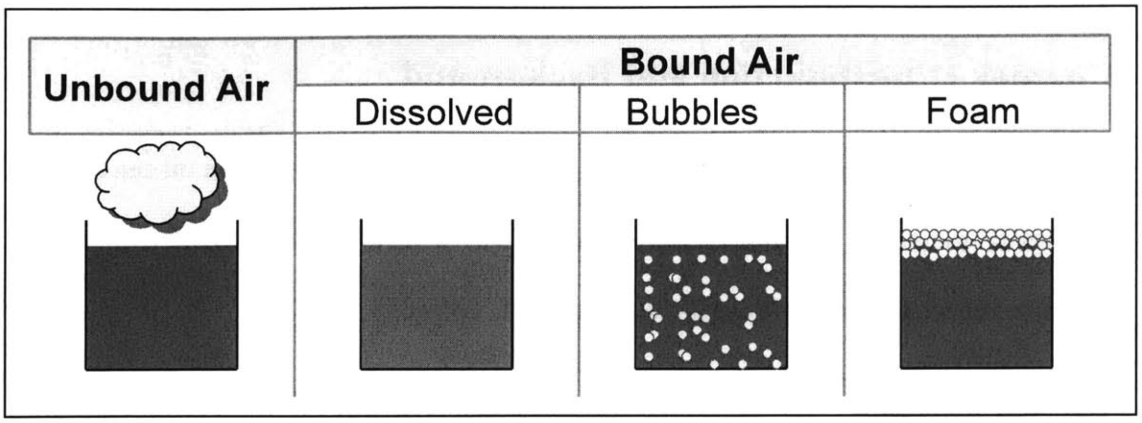


Figure 1-1 Illustration of the different interactions between air and oil

1.1.2 Causes of Oil Aeration

There are multiple factors that influence aeration in an engine. Figure 1-2 is a schematic that shows the engine parameters that influence aeration and how they are related to each other. Of these parameters, the most influential and therefore most closely followed in this study are engine speed, temperature, engine design, and oil level.

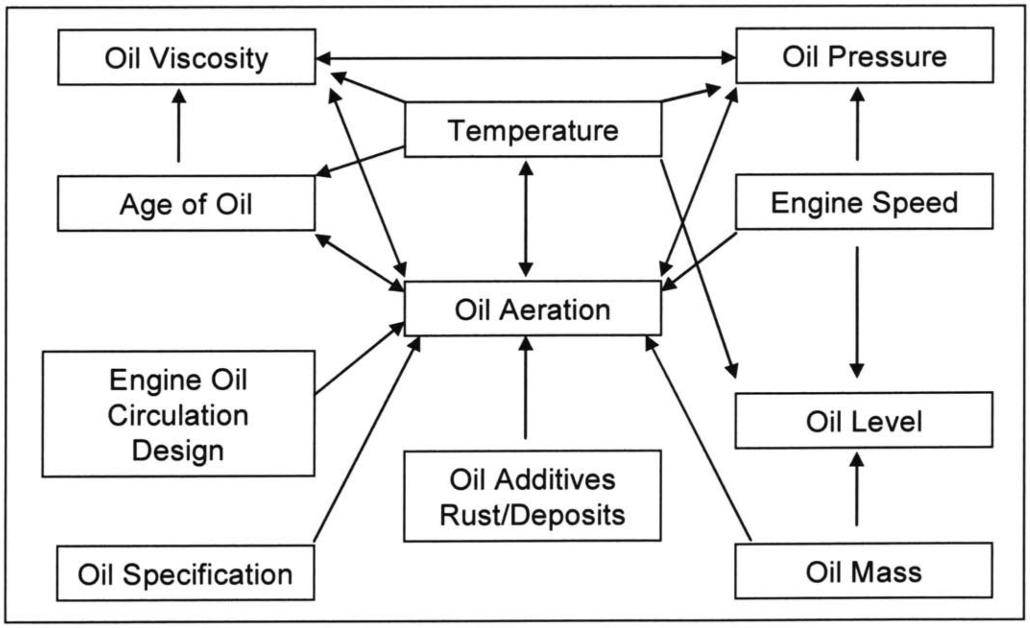


Figure 1-2 Schematic of parameters that influence oil aeration [3]

1.1.2.1 Engine Speed

Engine speed refers to the rate at which the crankshaft spins. It is normally quoted in units of revolution per minute (rpm) and will be for the remainder of this paper. Since the oil pump is driven by the engine crankshaft, the faster the engine spins the faster the lubricating oil will circulate through it. When the oil pressure reaches a certain level a part of the oil is relieved and bypasses the normal oil path. The faster the oil circulates through the engine the less time it spends in any one place including the sump. When the lubricating oil is sitting in the sump (as opposed to circulating through the engine) air bubbles have a chance to escape the oil. This time spent sitting in the sump is called the residence time. If the residence time is shorter, the oil spends less time in the sump and fewer air bubbles have the chance to escape. Therefore, as engine speed increases fewer bubbles escape the oil and hence the level of oil aeration increases. This effect can be seen in Figure 1-3, which is from tests preformed in this study.

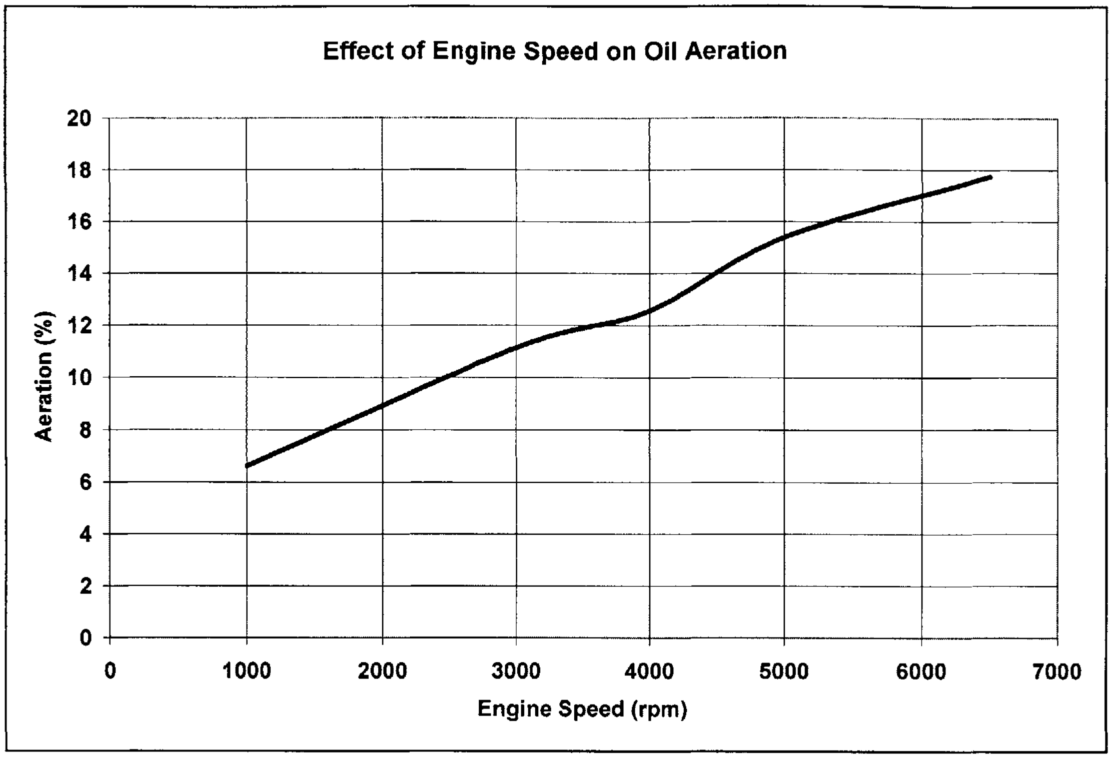


Figure 1-3 Effect of engine speed on oil aeration

1.1.2.2 Oil Mass and Oil Level

Finding the appropriate oil level is critical to oil aeration. Both too much and too little is problematic. If the oil level is too low there is a risk of air being sucked up into the oil pump which would increase aeration. This is especially relevant during vehicles maneuvers such as turning or traveling uphill. On the other hand, the more oil that is in circulation, the longer the residence time in the sump will be. As discussed previously, a longer residence time allows for more air bubbles to escape the oil and hence lowers aeration. However, if the oil level is too high there is a possibility of interaction between the sump oil and the rotating crankshaft that can cause air bubbles to become entrained in the oil and increase the aeration level. Optimization of the oil level requires good engine sump design. The design constraint is especially severe with modern engine packaging which calls for a shallower oil pan.

1.1.2.3 Engine Oil Circulation Design

Of all engine components, the oil pan, baffle, and windage tray influence oil aeration the most. The oil pan's primary function is to collect the return oil and redirect it to the oil pump. The design of the oil pan is constrained by how it will best fit within the frame of the vehicle [3]. However, great consideration must be given to the internal design of the oil pan so as to direct oil flow properly. The pan should be designed to avoid funneling, which is the depression of the oil surface due to the pumping action [4]. Funneling can cause the pump inlet to not be submerged and therefore suck in air and increase aeration. A baffle is a small wall in the oil pan that helps direct oil flow. Baffling has been shown to reduce funneling [3]. The distance between the oil pump inlet and the bottom of the oil pan can also influence aeration.

The windage tray is a perforated plate or screen that separates the oil sump from the rotating components of the engine such as the crankshaft. It has been shown that the inclusion of a windage tray is advantageous under all conditions but especially during turning, driving uphill and downhill [5]. Also, because the crankshaft is spinning very fast when the engine is running, it creates a rather strong wind. This wind causes waves in the oil sump which can increase aeration. The windage tray protects the oil sump from this wind, hence its name.

Another engine component that affects aeration is the oil return circuit. Ideally all returning oil is lead directly into the oil pan below the oil level to avoid contact with the air moving around the crankcase which could lead to aeration.

1.1.2.4 Oil Composition

Oil formulation has been shown to have an effect on oil aeration at high speeds and high temperature conditions [6]. Viscosity, density, degree of refinement, and age all have some affect the level of aeration; however, their effect is relatively small compared to operating speed, pressure, temperature, and the oil circulation path design. Oil contamination by surface active components can also cause aeration to increase [1]. Anti-foam agents, blow by gases, sediment, and wear particles may also influence aeration but has yet to be investigated [7].

1.1.2.5 Oil Temperature

Temperature has a substantial influence on liquid-gas interactions. As the temperature of a liquid-gas mixture increases, gas that was dissolved in the liquid escapes and forms bubbles in the liquid. In an open container these bubbles can rise to the surface and escape the liquid. In a study performed by Deconninck and Delvigne an agitator was installed in an open tank for the purpose of creating controlled oil aeration. When the temperature of the oil in the tank was increased from 20°C to 100°C aeration was observed to decrease [8]. The environment of an operation engine is much different than an open container for the lubricating oil. As the oil circulates through the engine its temperature increases causing dissolved air to become bubbles. Unlike the open container, however, there is no escape path for the air bubbles. The bubbles remain trapped in the oil and increase aeration. This was observed in a study by Yano and Yabumoto. At constant engine speeds of 3000, 4000, 5000, and 6000 rpm, as oil temperature increased oil aeration also increased [9]. Bregent found similar results in his tests which were also conducted on a running engine [10]. In a running engine, therefore, it can be said that oil aeration increases with oil temperature. Usually, however, a rise in temperature is caused by an increase in speed. The affect on aeration due to temperature is small compared to the affect due to engine speed.

1.1.2.6 Oil Pressure

Air solubility in oil is dependent upon the oil pressure and can be described by the Henry-Dalton-Law [5] shown below. This shows that the amount of dissolved gas is directly proportional to the system pressure [8].

$$V_{air} = \frac{B * V_{oil} * (P_a + P_s)}{P_a}$$

Where V_{air} is the volume of air at 10^5 Pa and 273 K
B is the Bunsen Coefficient
V_{oil} is the volume of oil
P_a is the ambient pressure
P_s is the system pressure relative to ambient

The Bunsen coefficient, B, is a proportionality factor that describes how much gas can be dissolved in a given liquid. Every gas-liquid combination has a specific Bunsen coefficient. For air in lubricating oil under usual engine conditions the Bunsen coefficient is considered to be constant at about 9% [11]. This proportionality factor is essentially the saturation limit of the oil.

Figure 1-4 graphically shows this relationship between pressure and air solubility. As the oil pressure raises so does the amount of air it can absorb (air solubility). Likewise, a reduction in pressure results in a reduction of the amount of air it can absorb (air solubility).

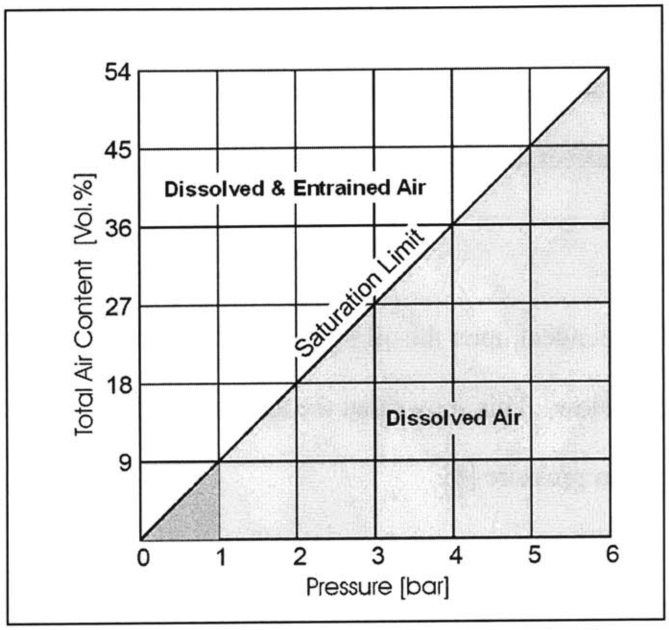


Figure 1-4 Air saturation limit of engine oil [4]

If there is a drop in pressure a portion of the dissolved air will become bubbles. Since dissolved air is potential bubbles it is considered dangerous for the engine [10].

Pressure also effects bubble size which influences aeration. Bubble size is determined primarily by the pressure of the lubricant. At constant temperature, Boyle's Law, shown below, describes this relationship [8].

$$P * V = K$$

Where P is the pressure of the liquid
V is the volume of the bubble
K is a constant

Bubble size is affected exponentially by bubble diameter according to Stokes equation [7]. Smaller bubbles rise very slowly or not at all and remain suspended in the oil. Larger bubbles rise faster and can escape the oil which decreases aeration.

1.1.3 Effects of Oil Aeration

Oil aeration is considered detrimental to engine performance. As dissolved air, it has no effect. However, when aeration is in the form of bubbles it can affect various aspects of an internal combustion engine. Aeration can cause pump cavitation, loss of precision control, vibration, filter blocking, and loss of head in centrifugal pumps [7]. Noise and loss of horsepower have also reportedly been caused by oil aeration [1]. Aeration has also been shown to cause increased engine wear, although minimally [6].

Aeration can also alter the oil's ability to perform all the intended functions. If the air bubbles are large enough they could potentially block oil flow and cause a decrease in lubricity which is the oil's primary function. The lubricating oil also acts as a coolant for the engine. When oil is aerated its thermal conductivity is reduced. This lowers the oils ability to contribute to engine cooling. This could lead to hot stops with in the engine.

It is also thought that oil aeration indirectly increases oil ageing. Air bubbles that may enter at oil pump intake are suddenly compressed in the high pressure space in the oil pump. Explosive oil-gas aerosols are formed in the compressed gas bubbles. If these aerosols are ignited the temperature would rise and negatively influence the oil [5].

Of all the potential effects of oil aeration, potential component failure is perhaps of greatest concern. Hydraulic systems such as lash adjusters, journal bearings, and con rod bearings are especially affected by aerated oil.

1.1.3.1 Journal Bearings

Models have been developed which predict that highly aerated oil increases effective oil viscosity due to the surface tension of the air bubbles [12]. These models have been verified with experimental findings [13]. Utilizing this information, additional models have been created which predict that aeration increases the load carrying capacity of journal bearings by a factor of two [12]. Yet, experimental investigation suggests that oil aeration reduces the load capacity of journal bearings [14]. However, this finding is not yet considered to be conclusive and additional testing is needed. Although it is clear that the effective viscosity increases with aeration, the effect of this increase is not clear.

1.1.3.2 Hydraulic Lash Adjusters

Hydraulic lash adjusters (HLA) are place between the valves and their cams [15]. Their purpose is to ensure direct contact between all components of the valve train [16]. This reduces noise and eliminates the need to manually adjust the cam routinely. Lubricant oil acts as force and motion transmitter in a HLA. If the oil is aerated, its bulk modulus is reduced which in turn reduces the stiffness of the HLA. This can cause malfunction, noise, and damage of the valves train [16].

1.1.3.3 Con Rod Bearing Lubrication

The rotation of the crankshaft causes centrifugal forces on the oil supply bore. This results in a negative pressure gradient in the supply bore. Air can come out of the oil as bubbles at the point of minimum pressure which is at the minimum distance to the pivot of crankshaft shaft [5]. Figure 1-5 is a schematic of this phenomenon.

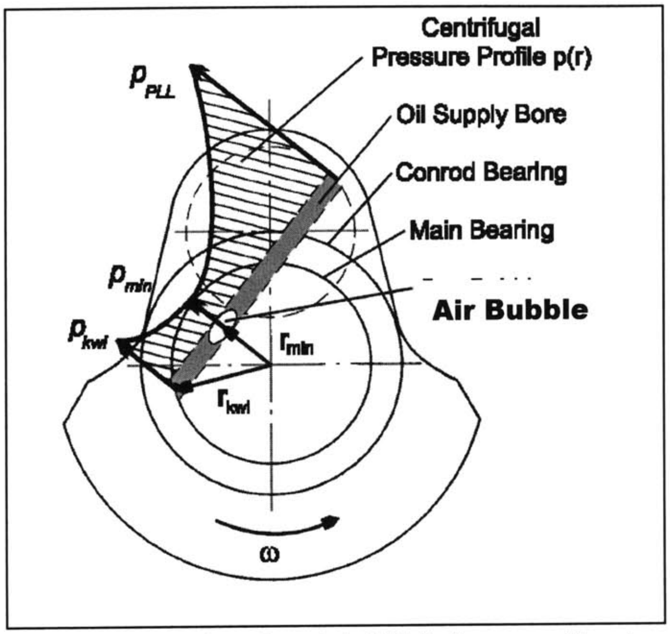


Figure 1-5 Formation of an air bubble in the con rod bearing supply bore [5]

1.2 Engine Lubrication System

Engine lubricating oil serves multiple functions within an internal combustion engine. It reduces frictional resistance, protects again wear, contributes to cooling, removes impurities, and keeps gas and oil leakage to a minimum [17]. The lubrication system used in this study is shown in Figure 1-6. It is Ford's 2003 3.0L DOHC Duratec lubrication system. The lubrication path begins in the sump which is approximately at atmospheric pressure. Oil is drawn into the pick up through a screen which blocks any large solid particles from entering the oil lines. The oil then flows through the filter which removes smaller particles and into the main gallery. From here the oil path diverts sending oil to the chain, the main and con rod bearing, and both the left and right head. The oil in each head lubricates the cam bearings, and hydraulic lash adjusters. All oil then drains back to the sump through various return lines.

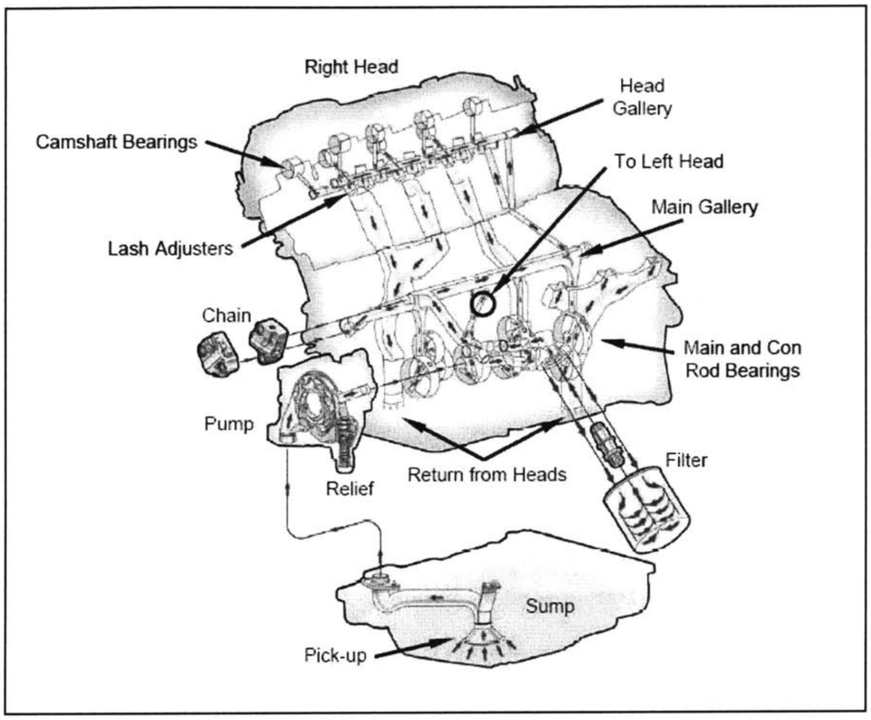


Figure 1-6 2003 3.0L DOHC Ford *Duratec* engine lubrication system

Below 3000 rpm the oil flowrate into the pick up is approximately linear with engine speed. At 3000 rpm the pump relief valve opens and the oil flowrate through the engine remains constant with engine speed [4]. An approximate break down of oil flow to the heads, chain, and main and connecting rod bearings is shown. These values were approximated by Manz for a firing engine with an oil temperature of 140 °C at 6000 rpm.

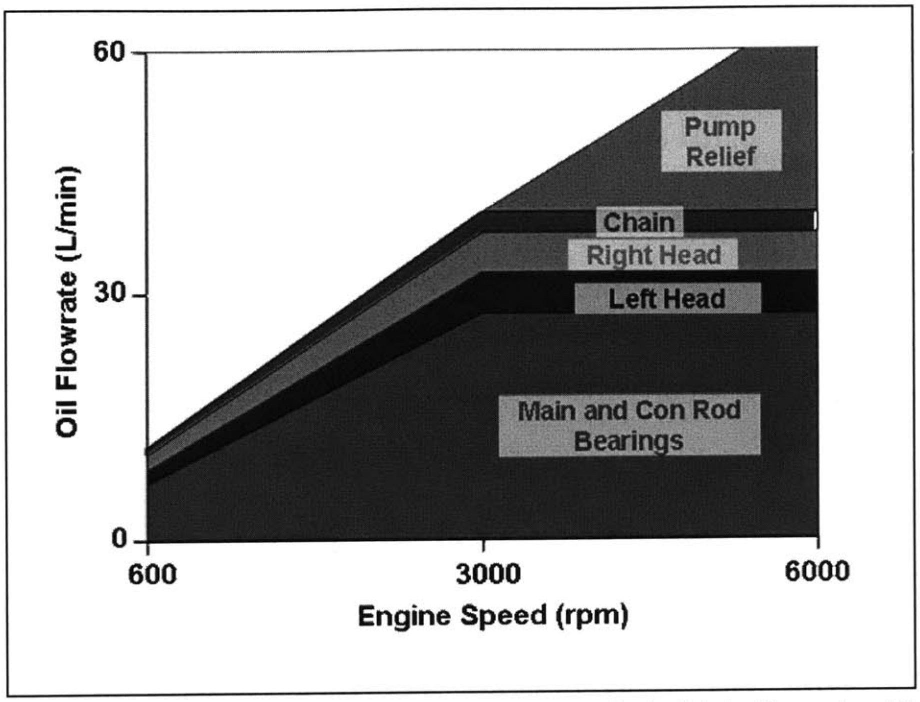


Figure 1-7 Engine oil flow through the various passages in the lubrication system [4]

Oil flows back to the sump from the various areas of the engine as show in Figure 1-8. The front of the engine (where the can drive belt is) is to the left in the schematic. The oil returning from the right head has two points of entry while the left head only has one. Chain return is located at the front of the engine and returns oil from the timing chains. The pump relief return is in the front left corner and returns excess oil to the sump from the pump when the relief valve opens. The crankcase return is oil from the connecting rods and main bearings that returns via droplets flung from the crankshaft.

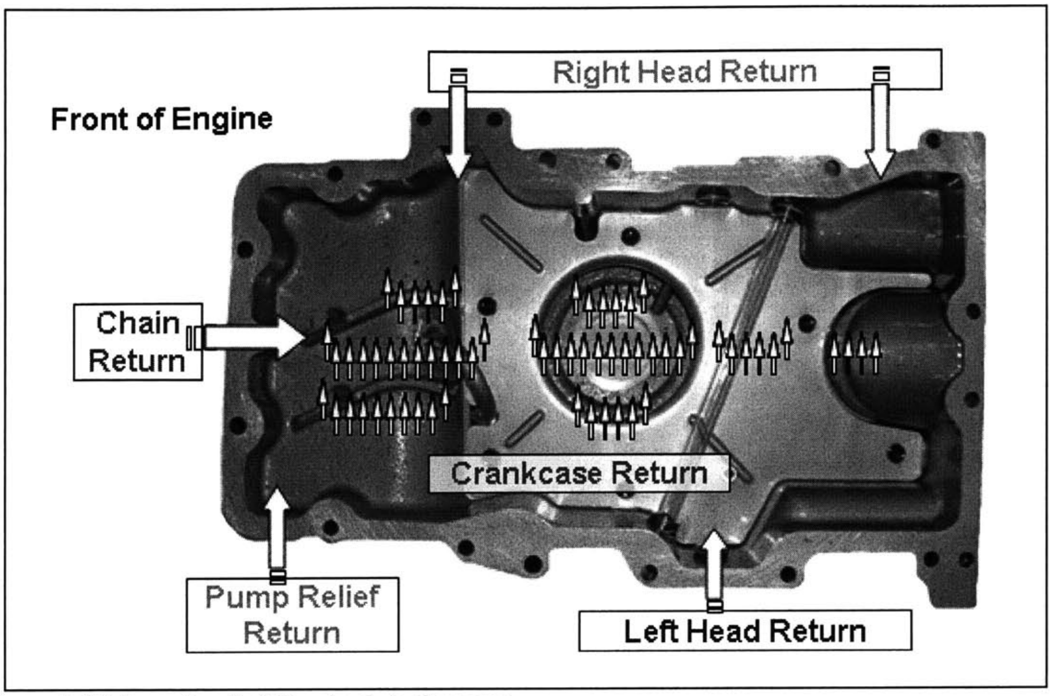


Figure 1-8 Schematic of oil flow back to the sump

After returning to the sump all the oil mixes and resides in the sump until it is drawn into the pump again and circulates through the engine again. If 4 liters of oil is used in the engine, approximately 2.2 liters remains in the sump while the engine is running [4]. This indicates that the oil lines hold 1.8 liters of oil while the engine is running. At 3000 rpm, the oil flow rate is 40 L/min. Therefore the average residence time is 2.2/40 which is 0.06 minutes or 3.3 seconds.

Chapter 2: Experimental Set-up

2.1 Test Engine Set-up

All experiments for this study are performed on a production Ford 3.0 L V6 duel overhead cam (DOHC) engine. The engine is not fired; it is motored by a 75 hp variable speed control motor. The motor itself is capable of speeds up to 3600 rpm. Since this study requires much higher speeds the motor was coupled to the engine via a Ramsey Silent Chain assembly (RPV-308, 9.525 mm pitch, 50.8 mm face width, 2.29 gear ratio) [4]. A schematic of the coupling is shown in Figure 2-1. With the chain drive in place the engine is capable of running at a maximum speed of 8000 rpm.

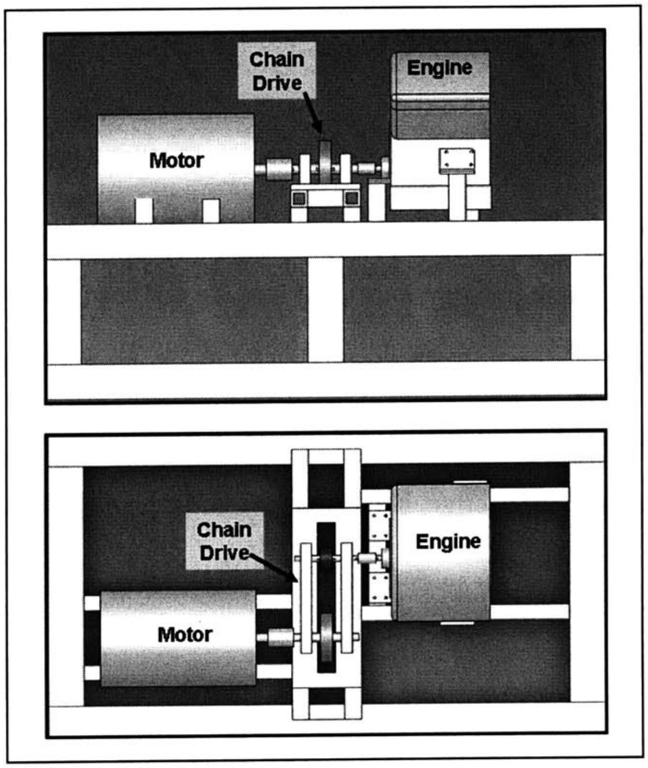


Figure 2-1 Schematic test apparatus coupling [4]

A picture of the engine, chain drive, and motor apparatus is show in Figure 2-2 below.

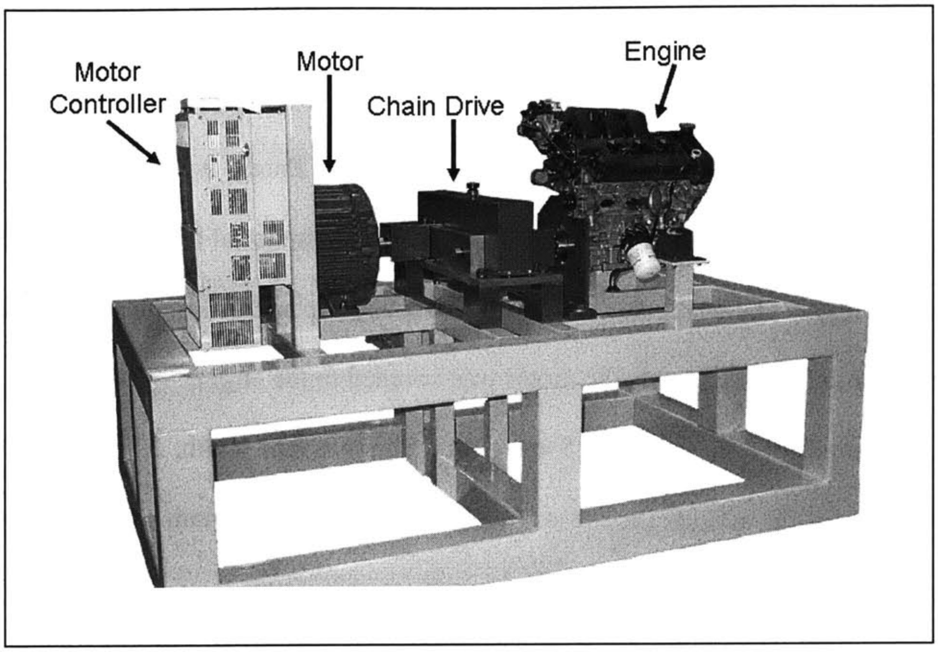


Figure 2-2 Photograph of test apparatus

The oil pan was modified to allow for oil sampling during engine operation. There are three sampling locations although only location 1 is used extensively in this study. Location 1 is at the oil pump pick-up, location 2 is at the left head return, and location 3 is at the chain return. The interior of the modified oil pan is depicted and labeled in Figure 2-3. A sight glass was installed in the bottom of the oil pan for visualization purposes but proved to be ineffective; it also appears in the photograph of Figure 2-3.

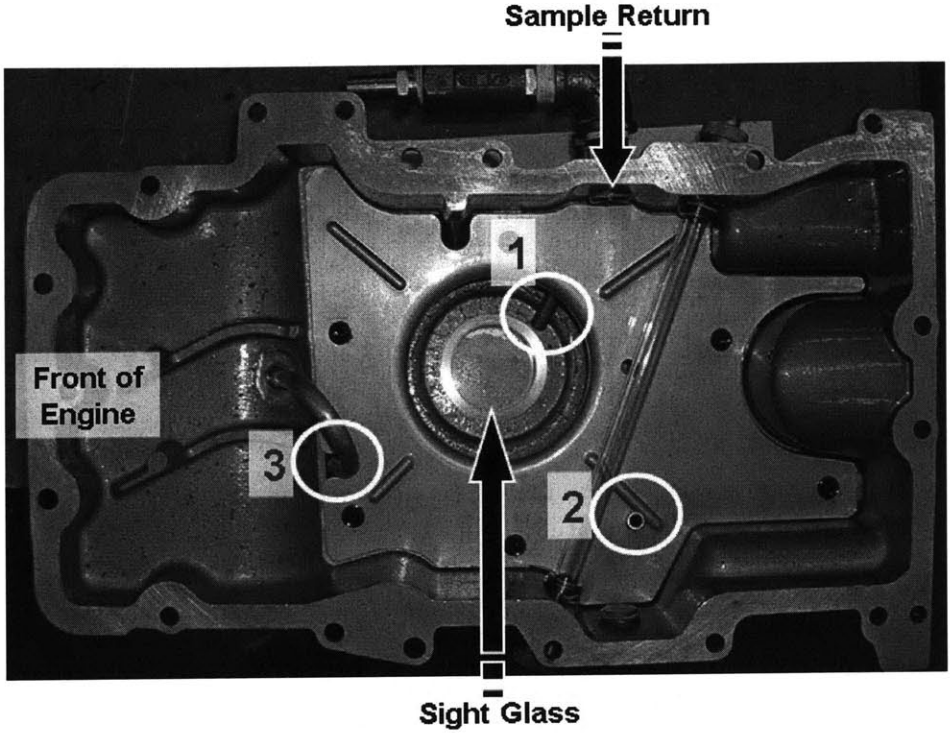


Figure 2-3 Interior view of the oil pan modifications: 1 is the pick-up sampling location, 2 is the left head return sampling location, and 3 is the chain return sampling location

The exterior of the modified oil pan is shown attached to the engine in Figure 2-4; view is from the front of the engine looking up at the oil pan from below the engine. Pneumatically actuated ball valves were used to control the oil sampling.

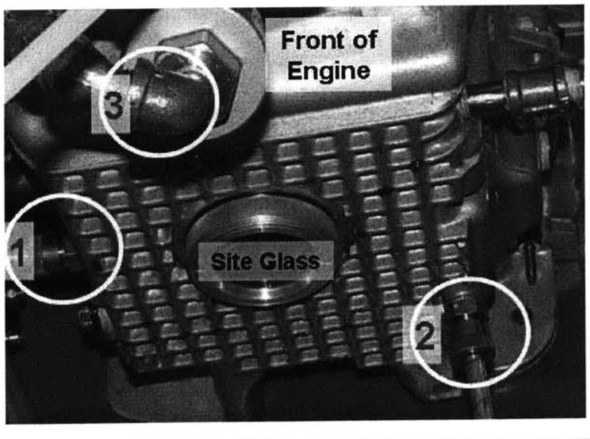


Figure 2-4 Exterior view of the oil pan modifications (labels corresponds to those in Figure 2-3)

Filtered building water was used as the engine coolant. A flow meter was installed to control the flow of the cooling water and thus control the oil temperature. Four thermocouples were installed in various locations to monitor the temperature of the oil and the engine. The temperature of the oil in the sump is continuously recorded from a thermocouple located directly in the oil sump. It accesses the sump through the dip stick tube (the dip stick was removed). The other thermocouples monitor the temperature in the oil gallery, combustion chamber, and engine block. Two pressure gauges monitor the inlet cooling water pressure and the oil gallery pressure. A labeled picture showing the location of these thermocouples and pressure gauges is seen in Figure 2-5.

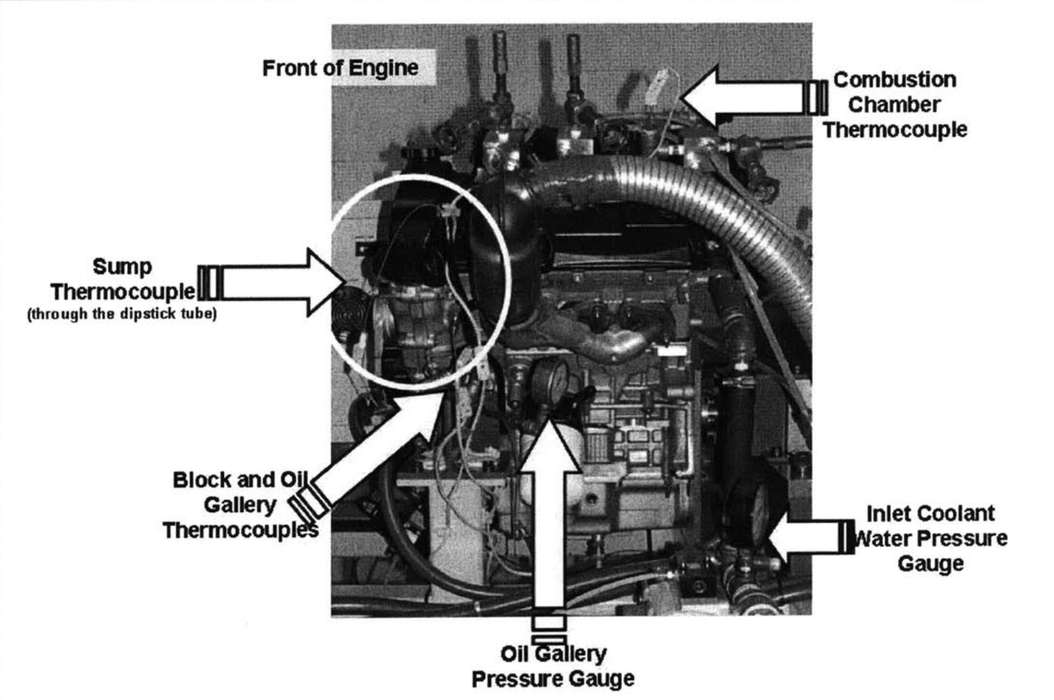


Figure 2-5 Location of thermocouples and pressures for the test engine

To ensure a smooth start-up and shut-down the spark plugs were replaces with valves which will be referred to as spark plug valves. If the valves are closed at cranking, the motor would not have sufficient torque to start the engine; if they are left open there will be significant pumping loss and the motor will stall out at high speeds. Small filters were attached to the valve openings to prevent dirt particles from entering the engine. During operation small amounts of oil reach these valves due to scraping of the cylinder wall with the piston. At speeds above 5000 rpm the spark plug valves get hot enough that the residual oil burns off. The valves were not rated to handle the pressure caused by this burning so burnt oil fumes were escaping and causing potential hazard. Since testing for this study required operating at speeds above 5000 rpm a cooling system was designed to prevent the oil from burning. A 2x2x2 inch aluminum block was adding in series to each spark plug valve. A drawing of this design is shown in Figure 2-6. Building water was siphoned off the main line, split between the two engine heads and sent in series through each aluminum block to cool the aluminum blocks. Hot air from the cylinders was allowed to flow through the aluminum blocks perpendicular to the flow of the cooling water. Thus the air from the cylinders was cooled down before it reached the valves so the valves did not over heat and burn oil.

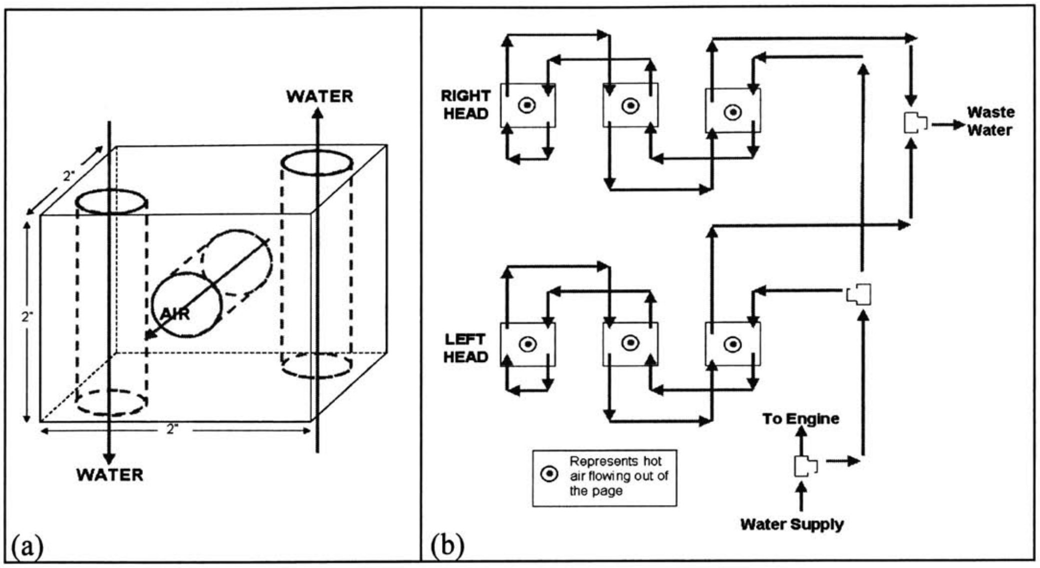


Figure 2-6 (a) Aluminum blocks used in spark plug valve cooling system (b) Drawing of the spark plug valve cooling system design

Figure 2-7 shows a picture of the right engine head spark plug valve cooling system. In this picture water flow is vertical and air flow is out of the page.

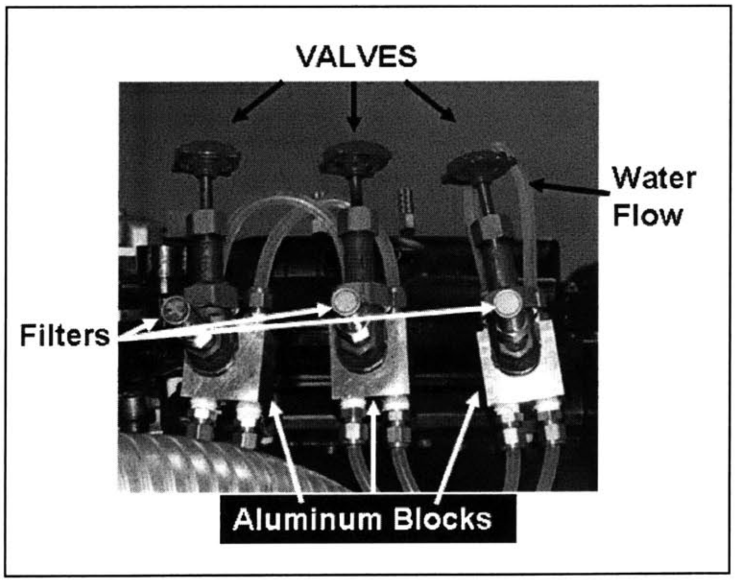


Figure 2-7 Right engine head spark plug valve cooling system

In order to be certain what volume of oil is circulating through the engine a site tube was installed in the oil pan and a ruler was secured next to it, this can be seen in Figure 2-8.

When a known amount of oil was put in the engine the oil level could be read from the site tube, this level was maintained and check in between runs to ensure that the volume of circulating oil remained constant.

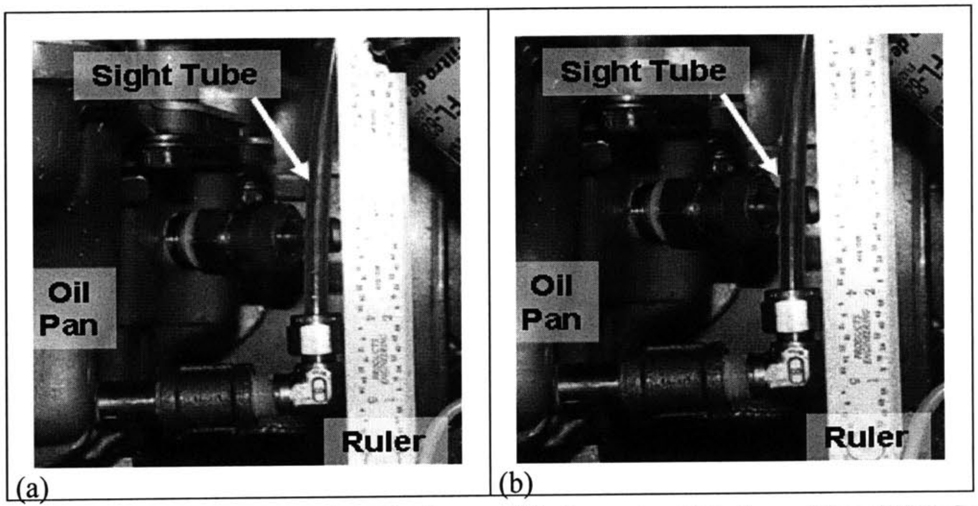


Figure 2-8 Sight tube for measuring oil volume within the engine (a) before adding oil (b) after adding 6 L of oil

The throttle plate was removed from the engine to ensure that wide-open throttle (WOT) conditions were observed in all tests. A full view picture of the test engine can be seen in Figure 2-9.

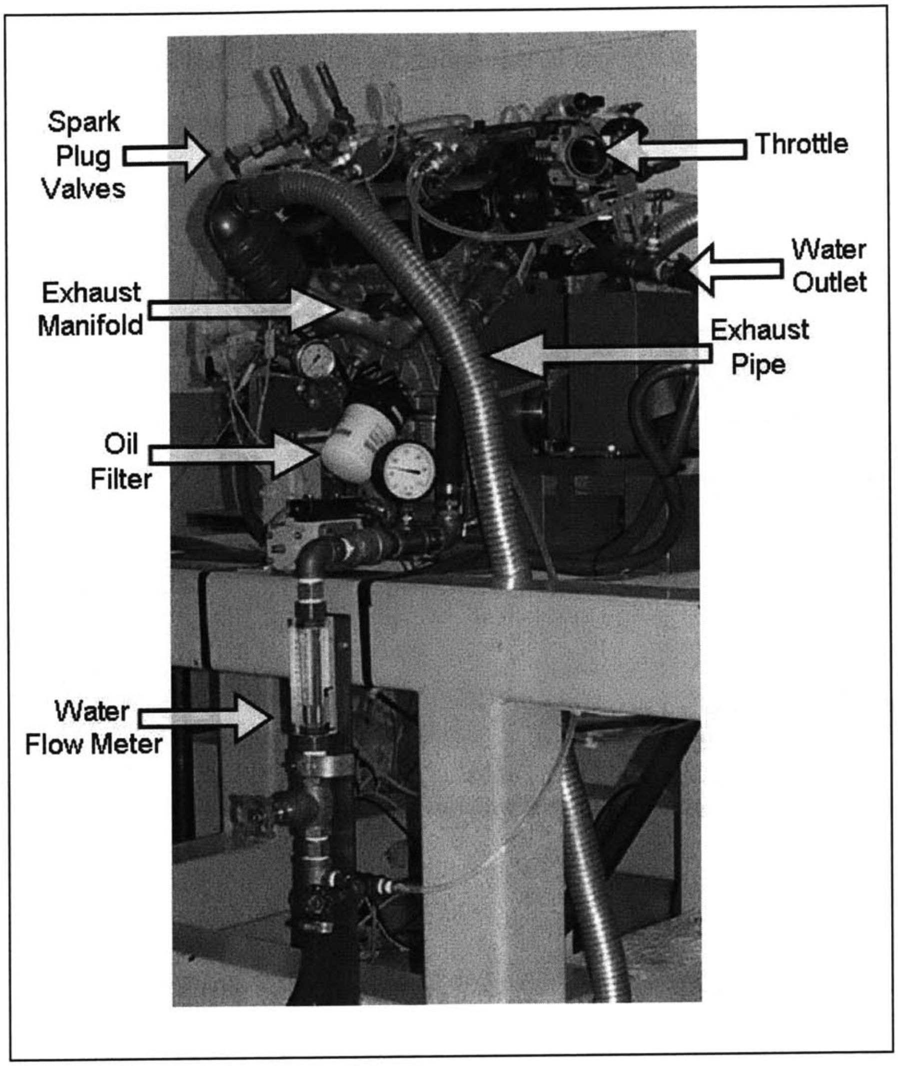


Figure 2-9 2003 Ford 3.0 L V6 DOHC test engine

All tests in study were conducted using Motorcraft SAE 5W20 engine oil, the properties of which are given in Table 2-1.

SAE Grade	5W-20
API Service	SJ / EC
Gravity	35 °API
Density, @ 15.5°C	851 kg/m^3
Flash Point, COC	185 °C
Kinematic Viscosity at 40°C	4.9 x10^{-5} m^2/s
Kinematic Viscosity at 100°C	8.8 x10^{-6} m^2/s
Viscosity Index	161
HT/HS Viscosity @ 150°C	2.65 cP
Pour Point	-45 °C
Sulfated Ash	0.94 Wt. %
Total Base Number	7.5 TBN
ASTM Color	4

Table 2-1 Motorcraft SAE 5W20 engine oil properties [18]

2.2 Aeration Measurement Apparatus: Air-X

ASTM tests relating to foaming of lubricating oils do exits (D892 and D6982) but do not apply to running engines [8]. Several laboratory methods for measuring aeration on a running engine have been developed. However, most of these methods are tedious and unreliable. Delta Services Industriel (DSI) Deltabeam developed an instrument for on-line monitoring of lubricant aeration in mechanical systems such as IC engines. The instrument is called "Air-X" and will be referred to as such. All measurements in this study were obtained using Air-X.

2.2.1 Equipment

Air-X is capable of connecting to the engine via a pressurized line but it is also equipped with an internal pump so it can be connected at atmospheric pressure. In this study all samples are drawn from the engine sump which is at atmospheric pressure, therefore the Air-X pump was utilized to continuously draw oil from the sump into the Air-X. Air-X can be seen in Figure 2-10, connected to the engine.

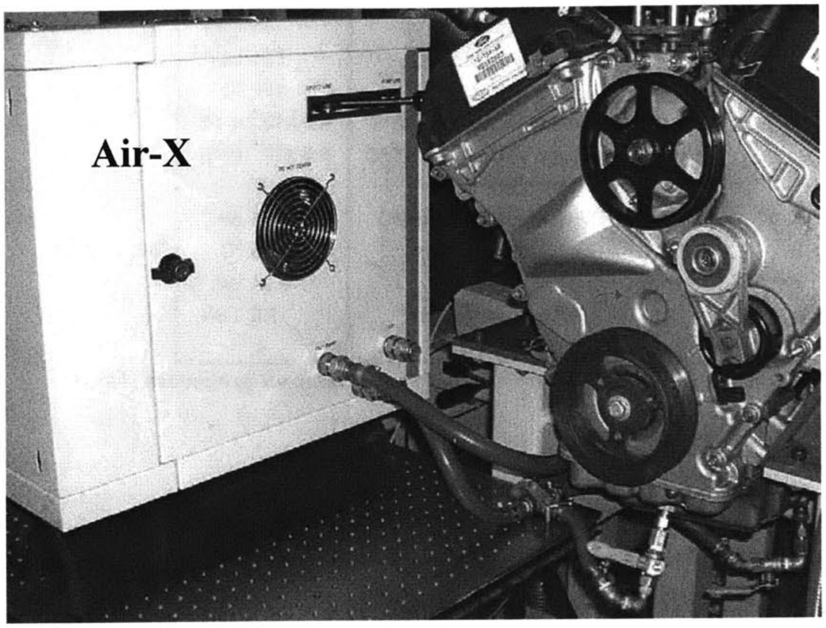


Figure 2-10 Air-X connected to the test engine

The sample volume is small (less than 500 mL) and the sampling rate, which is set by the user, cannot be larger than 5 L/min to ensure minimal impact on engine operation. Table 2-2 summarizes the specifications for Air-X.

Dimensions (W x H x D)	600mm x 520mm x 483mm
Mass	50kg
Viscosity range	3.8mm²/s to 3500mm²/s
Temperature range	0 to 150°C
Pressure range	0 to 10bar
Oil flow	0 to 5L/min
Measurement range	0 to 100% aeration
Accuracy	At 10s acquisition time: 0.5% At 100s acquisition time: 0.2%
Sample oil volume	less than 500mL
Aeration data	0% of oil aeration: 0V 100% of oil aeration: 4V

Table 2-2 Air-X specifications [4]

Upon entering Air-X the oil enters the viewing chamber where a camera captures a visual image of the sample. The oil then enters a measuring chamber where a low energy x-ray passes through the sample and the resulting intensity of the beam is measured. The x-ray comes from a sealed radioisotope source of Cadmium 109 which has and activity of 950 kBq and a half-life of 1.3 years [4]. A picture of the chambers can be seen in Figure 2-11.

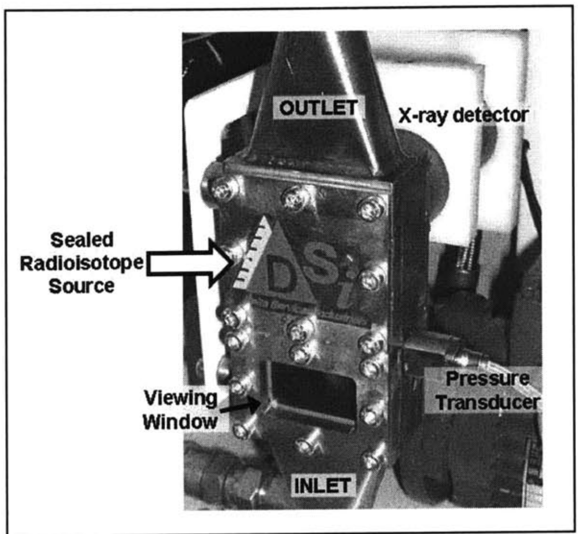
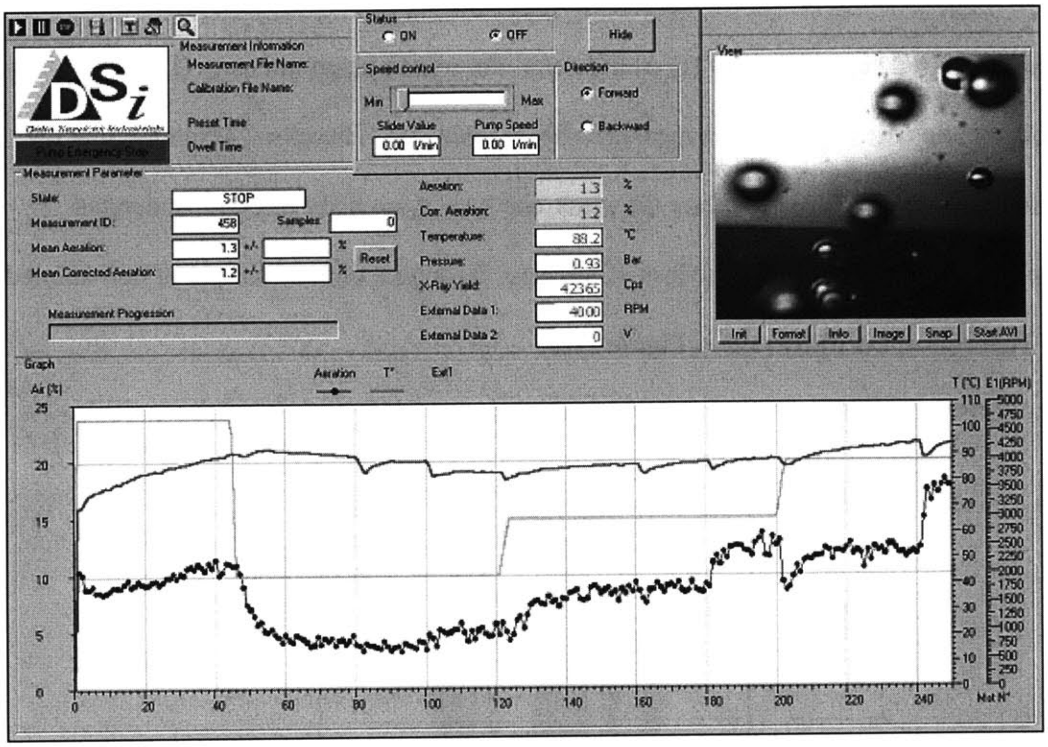


Figure 2-11 Air-X measuring and viewing chambers

A thermocouple is located in the outlet to record the sample temperature. Air-X also outfitted with a pressure transducer to record sample pressure in the measuring chamber. Air-X is equipped with two external analog inputs (-10 V to +10 V). Signals are converted (DAC) and data results are logged simultaneously by Air-X during aeration measurement [19]. For this study the two external analog inputs were used to record engine speed and sump temperature.

2.2.2 User Interface

The Air-X interface allows the user to set the pump sampling rate and direction of flow. A window in the upper right hand corner shows the image being captured by the internal camera in the viewing chamber. Air-X outputs are displayed on the screen and can be tracked graphically if desired. These outputs include aeration, corrected aeration, sample pressure, sample temperature, x-ray yield, engine speed (external data 1), and sump temperature (external data 2). The average aeration and corrected aeration are continuously calculated and displayed but can be reset at any time. The Air-X user interface can be seen in Figure 2-12.



Slider Value: 0.00 l/min
Pump Speed: 0.00 l/min
State: STOP
Measurement ID: 458
Samples: 0
Mean Aeration: 1.3 +/- %
Mean Corrected Aeration: 1.2 +/- %
Aeration: 1.3 %
Corr. Aeration: 1.2 %
Temperature: 88.2 °C
Pressure: 0.93 Bar
X-Ray Yield: 42365 Cps
External Data 1: 4000 RPM
External Data 2: 0 V

Figure 2-12 Air-X user interface

2.2.3 Operating Principles

When the x-ray passes through the oil sample a portion of the x-ray is absorbed by the oil via the photoelectric and Compton effects [8]. The x-ray energy level, oil sample thickness, oil density, and composition affect how much of the x-ray is absorbed. These parameters are related to the x-ray absorption by as shown below.

$$I = I_o e^{-\mu \rho x}$$

Where: I is the intensity of the transmitted beam (number of x-rays /s)

I_o is the intensity of the source beam (number of x-rays /s)

μ is the absorption coefficient depending on x-ray energy and material (cm^2/g)

ρ is the mass density (g/cm^3)

x is the thickness of the oil sample (cm)

Due to its low density air does not affect the intensity of an x-ray, if the sample were all air the measured beam intensity (I) would equal the source beam intensity (I_o). Any air in the oil sample will not affect the measured beam intensity. Therefore, assuming that the height and width of all samples are the same, the loss of intensity through an aerated sample of oil will be equal to the loss of intensity through a thinner sample of non-aerated oil. This concept is illustrated in Figure 2-13.

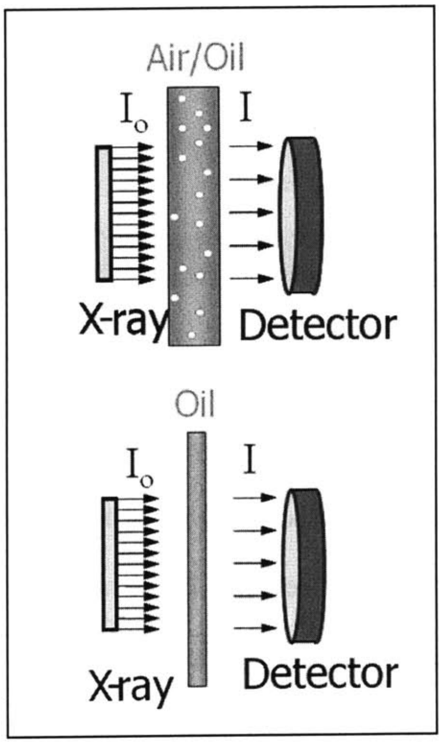


Figure 2-13 Illustration of Air-X operating principle

Air-X measures the intensity of the transmitted beam, then using the relation mentioned above ($I = I_o e^{-\mu\rho x}$), the thickness of non-aerated oil (x_{oil}) can be calculated.

$$x_{oil} = \frac{\ln\left(\frac{I}{I_o}\right)}{-\mu\rho}$$

The actual thickness of the sample corresponds to the sample chamber size (x_{total}).

Aeration is a volume ratio between air and oil in a given sample:

$$\Phi = \frac{V_{air}}{V_{air} + V_{oil}}$$

Since width and height are assumed to be equal for all samples aeration (Φ) can be thought of as a ratio of sample thickness:

$$\Phi = \frac{x_{air}}{x_{air} + x_{oil}}$$

Air thickness can be related to oil thickness and total thickness by:

$$x_{air} = x_{total} - x_{oil}$$

Therefore, aeration is

$$\Phi = \frac{x_{total} - x_{oil}}{x_{total}}$$

In actuality this calculation is based completely on x-ray intensity. An initial calibration of Air-X with the given oil type calculates the beam intensity of a non-aerated (0% aeration) sample of oil (I_1). This intensity corresponds to a sample thickness the size of the measuring chamber (x_{total}). Using just intensity measurements, aeration is calculated by (ρ and μ cancel out):

$$\Phi = \frac{\ln\left(I_1 / I_o\right) - \ln\left(I / I_o\right)}{\ln\left(I_1 / I_o\right)}$$

The measured intensity (I) is adjusted for the decay of cadmium. The 0% aeration intensity (I_1) must be adjusted to account for the thermal expansion of the oil density. By measuring the x-ray intensity over a range of temperatures a calibration second degree polynomial curve can be obtained, saved, and later used to make the density correction. This curve for SAE 5W-20 oil is show in Figure 2-14. Air-X software has built in functions to make this correction. Aeration both before and after this correction are give in the output data file.

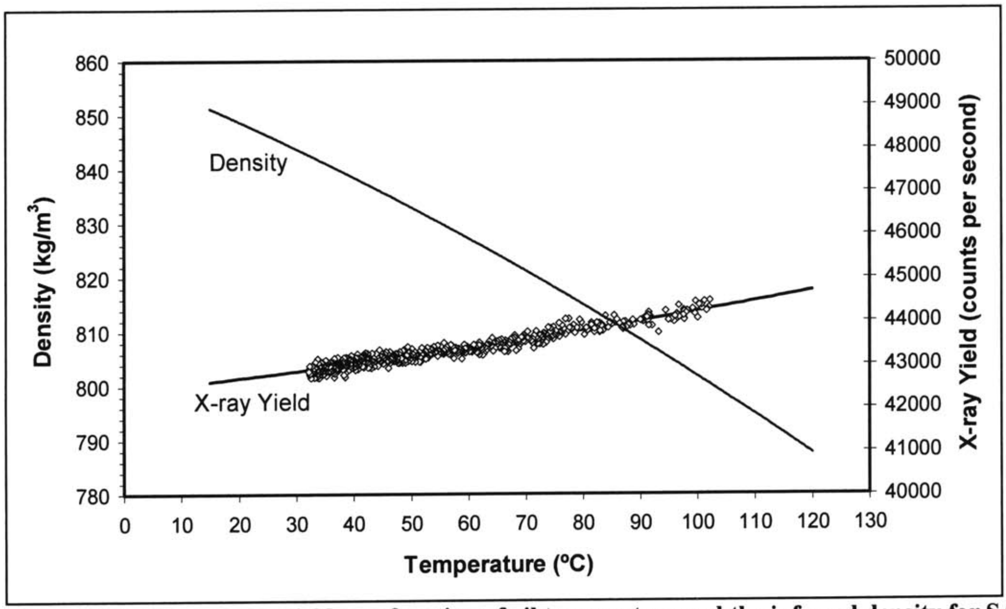


Figure 2-14 Air-X x-ray yield as a function of oil temperature and the inferred density for SAE 5W-20 oil [4]

No additional corrections were made for the temperature or pressure difference between the sump and the measuring chamber. Temperature was monitored and recorded both in the sump and in the measurement chamber. The temperature difference was never more than a few degrees Celsius. The sump was at ambient pressure (approximately 1 bar) while the measuring chamber was slightly lower (.8 bar). Calculations were performed to compensate for this differential. However, the impact on the aeration measurement was not significant enough to justify applying the calculation to all measurements and thus the differential is considered negligible.

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Chapter 3: Repeatability and Reproducibility Study

Prior to altering any hardware for parametric study on the engine, it was necessary to do a repeatability and reproducibility (R&R) study. In doing so, a measurement method was established and the uncertainty in the measurements of Air-X was determined. Therefore, when changes were made to the engine the acceptable spread in data was known. Two types of tests were preformed: a day-to-day repeatability test and a same-run repeatability test. In the day-to-day test the same test procedure was performed on separate days. This was done to establish if data collected on different days was comparable (repeatable). The same-run test involved repeating the same test point within the same test (or run). This was to assure that each test point was independent of each other. A reproducibility test was not conducted as there was only one operator for this study.

3.1 Testing Procedure

During all R&R tests building water was constantly circulating through the engine for cooling. Oil was always sampled from the pick-up (location # 1) at a rate of 1 L/min. The location was chosen because this is where the oil is taken up into the engine so it is of highest concern. The sampling rate choice was based on a previous study by Manz which was conducted on the same test engine [4]. Air-X was set to collected data every 5 seconds; that is x-ray photons are counted and averaged in consecutive 5 second intervals. This time scale is long enough to encompass noise and fluctuation, but short enough to capture any systematic changes. This decision was based on data from another study by Manz [4]. Every test was preceded by a "warm-up" during which the engine was set to run at 5000 rpm for 10 minutes. This assured that the engine was at the same conditions at the beginning of every test. The R&R study was conducted with the same windage tray in place.

3.1.1 Test Profile

The same test profile was followed for every R&R test for consistency. It includes repeatedly running at 3000 rpm and 5000 rpm for the same-run test. This same profile was run on consecutive days and multiple days apart for the day-to-day test. The test profile is shown in Figure 3-1.

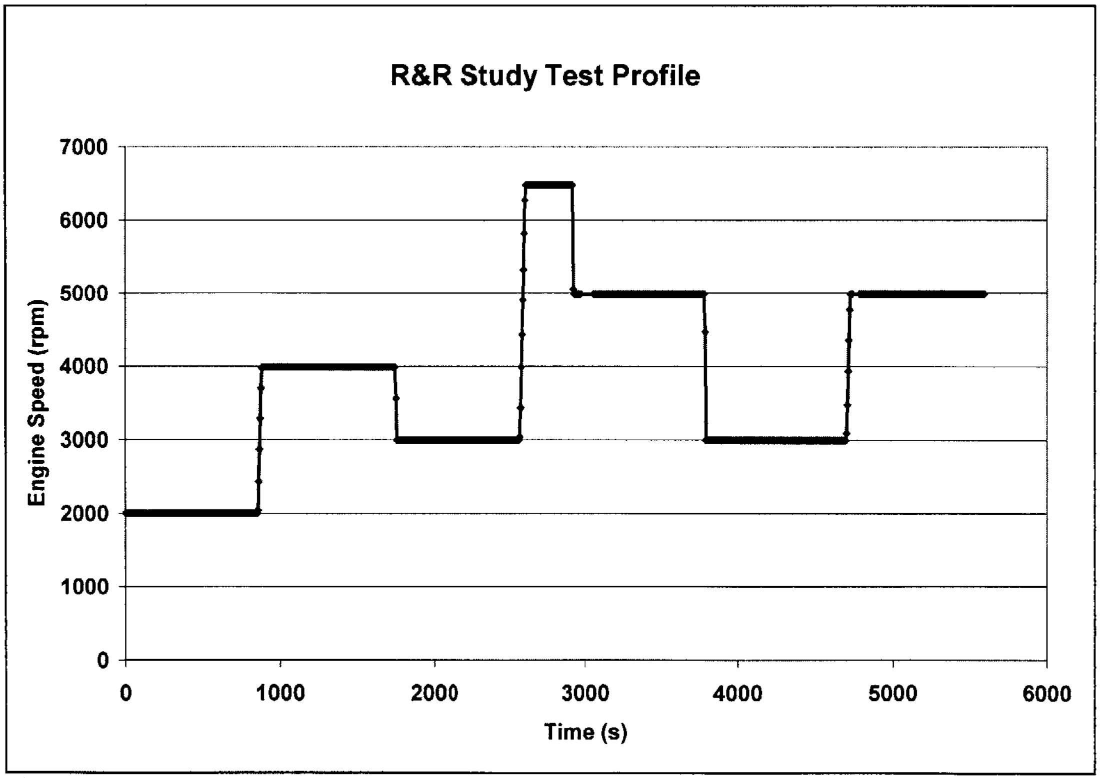

Figure 3-1 R&R study test profile

After warming up for 10 minutes by motoring at 5000 rpm, the test starts at 2000 rpm. It then goes to 4000, 3000, 6500 and 5000 rpm in that order. Immediately after this series of test points both 3000 and 5000 rpm are repeated for the same-run test. Each test point is approximately15 minutes long to allow aeration to fully stabilize with the exception of 6500 rpm. During the R&R study the aluminum cooling blocks discussed in section 2.1 and depicted in were not yet in place so the spark plug valves would over heat at 6500 rpm and burn oil. Therefore, the 6500 rpm test point only lasted approximately 7 minutes.

3.2 Data Analysis

Air-X outputs a CSV data file which can be opened and analyzed using Microsoft excel. For all cases the Air-X measurement that corrects for the thermal expansion of the oil density, referred to as "corrected aeration" is the measurement analyzed. From here on out aeration refers to this "corrected aeration" measured and calculated using Air-X. A typical R&R study aeration data trace from Air-X is shown in Figure 3-2.

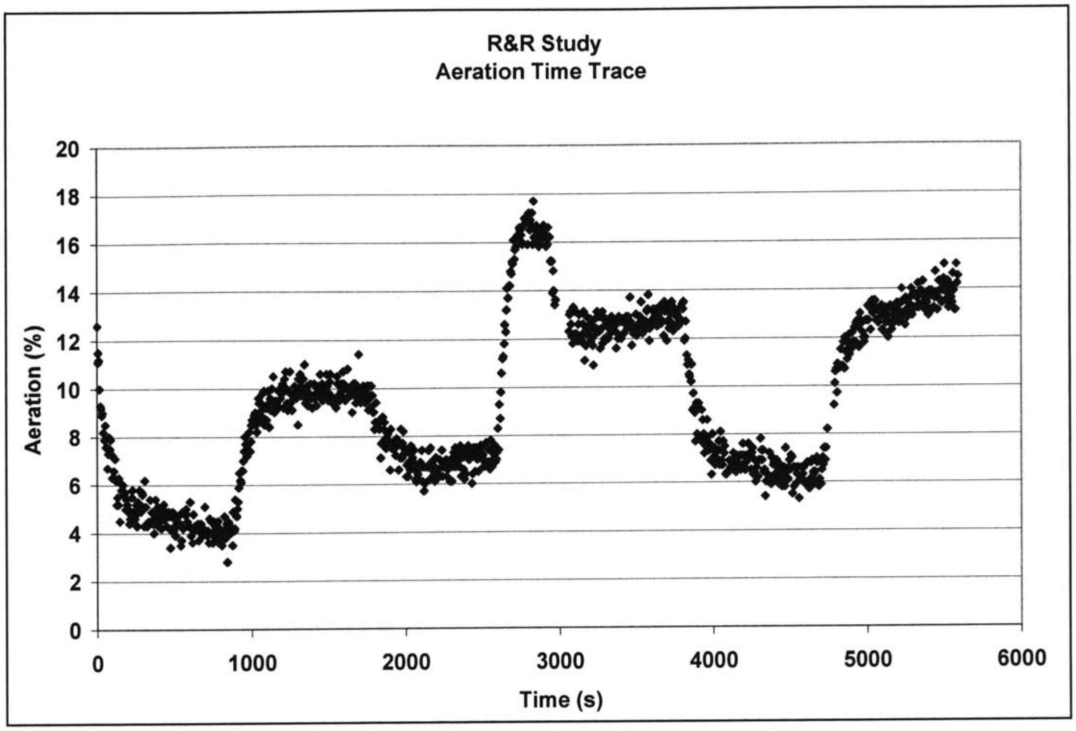

Figure 3-2 Typical R&R study aeration time trace from Air-X

At each test point (engine speed) the data was windowed to only include the measurements after the aeration had leveled off. A t-statistic test was applied to the windowed data using Matlab software [20]. The test calculates an average value and range in which a specified percentage of the data points fall. For this study a 95 % confidence interval was specified. The Matlab t-statistic test gives the data average and a delta value that correlates to the range around that average in which 95% of the data points are located. The smaller the delta value the tighter the range and the more precise the measurement.

3.3 Results

3.3.1 Day-to-Day Repeatability Test

The results of the day-to-day test are shown as a bar graph below in Figure 3-3. The delta bars (95% confidence level for the single day measurement) are not shown in the graph because the delta values were less than 0.19% for all cases and therefore the visual is so small it is barely legible. The values are however included in the Appendix.

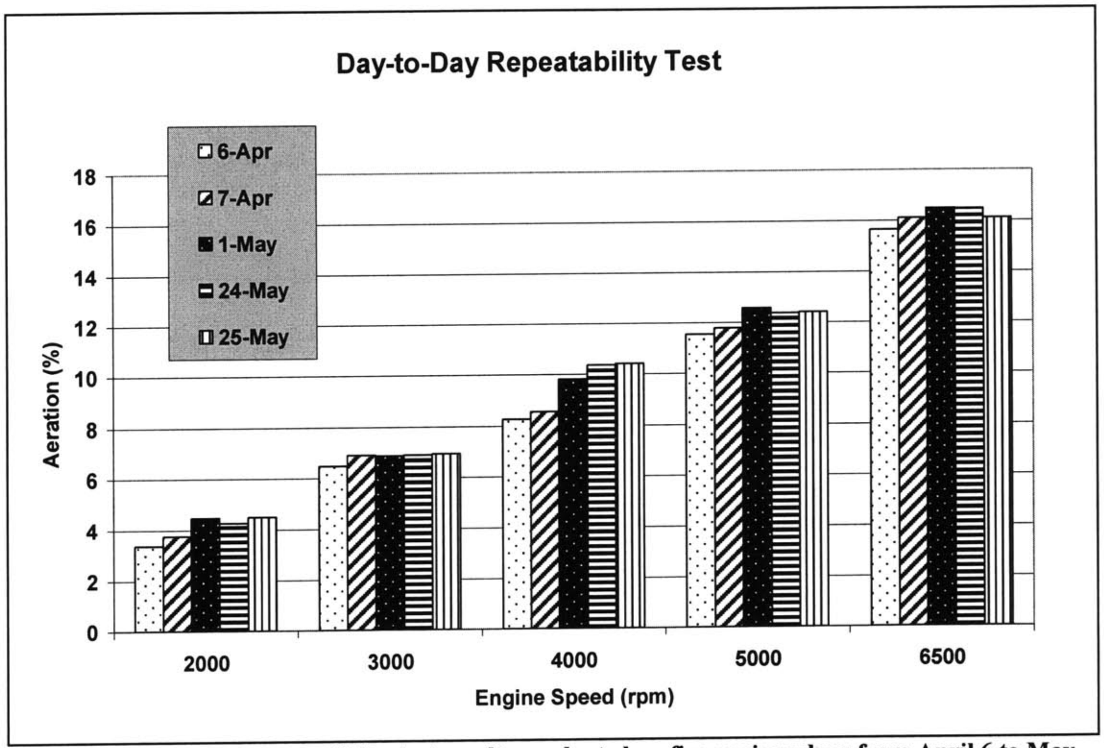

Figure 3-3 Day-to-day repeatability test results conducted on five various days from April 6 to May 25, 2006

In Figure 3-3 each type of shaded bar represents a different day of testing. The bars are grouped by engine speed which makes for easy visualization. As can be seen, at every speed the measured aeration level is very close from day to day. Figure 3-4 shows the differential between the maximum and minimum measurements over the 5 testing days at each engine speed. Since the accuracy of Air-X is approximately ±1 aeration percentage any differential significantly larger than 2% would be unacceptable. 4000 rpm shows more spread than any of the other speeds, but it is not large enough to cause concern.

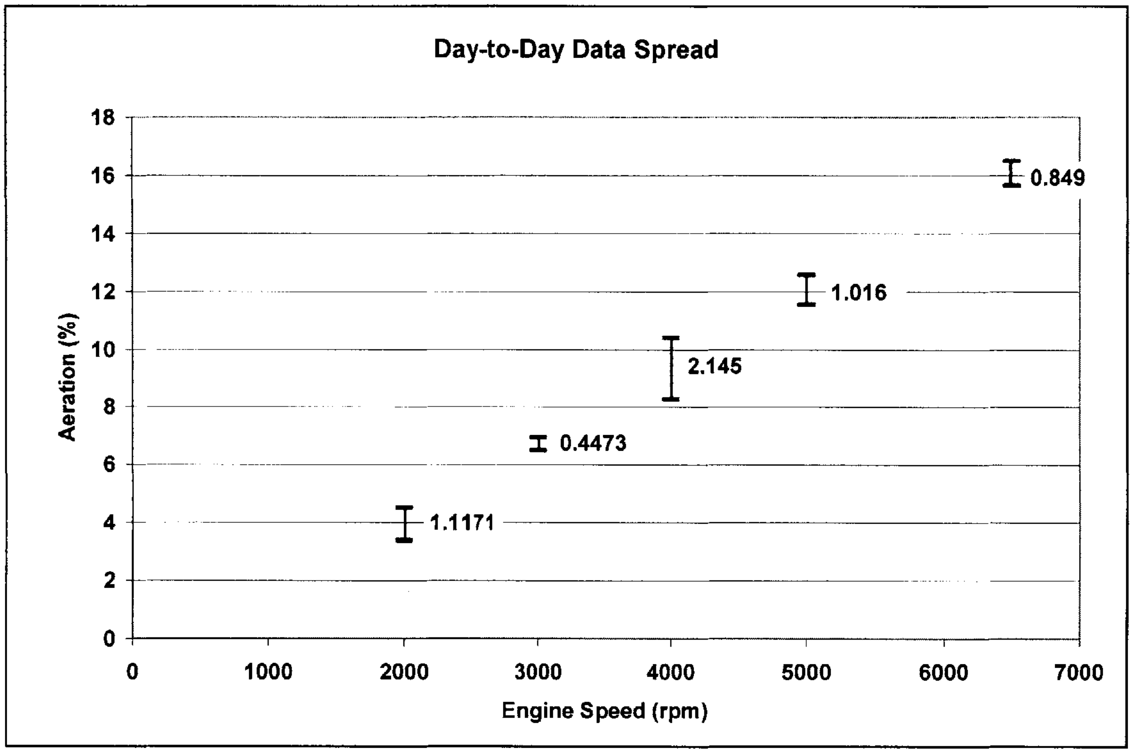

Figure 3-4 Day-to-day repeatability test data spread

3.3.2 Same Run Repeatability Test

Figure 3-5 shows the results of the same-run repeatability test in bar graph form. This test was only performed at 3000 and 5000 rpm, the two different speeds are differentiated by differently shaded bars. The test was conducted simultaneously with the day-to-day test, therefore, it was repeated on five various days. Each test is grouped together and labeled with the date of occurrence along the horizontal axis. Each day has two 3000 rpm bars and two 5000 rpm bar because that speed was repeated twice during each test run as explained in 3.1.1. As for the day-to-day repeatability test, the bars represent the number calculated by the t-statistic test. The delta bars are again not shown because they are all less than 0.12, therefore graphic visual would be very small and illegible. All delta values for the same-run repeatability test can be seen in the Appendix.

As can be seen in Figure 3-5 within the same test run, repeated measurements are very close. At 3000 rpm the second measurement is slightly less than the first. At 5000 rpm the second measurement is slightly greater than the first. However, the difference between the first and second measurements at both 3000 and 5000 rpm is always within the ± 1 aeration percentage accuracy of Air-X.

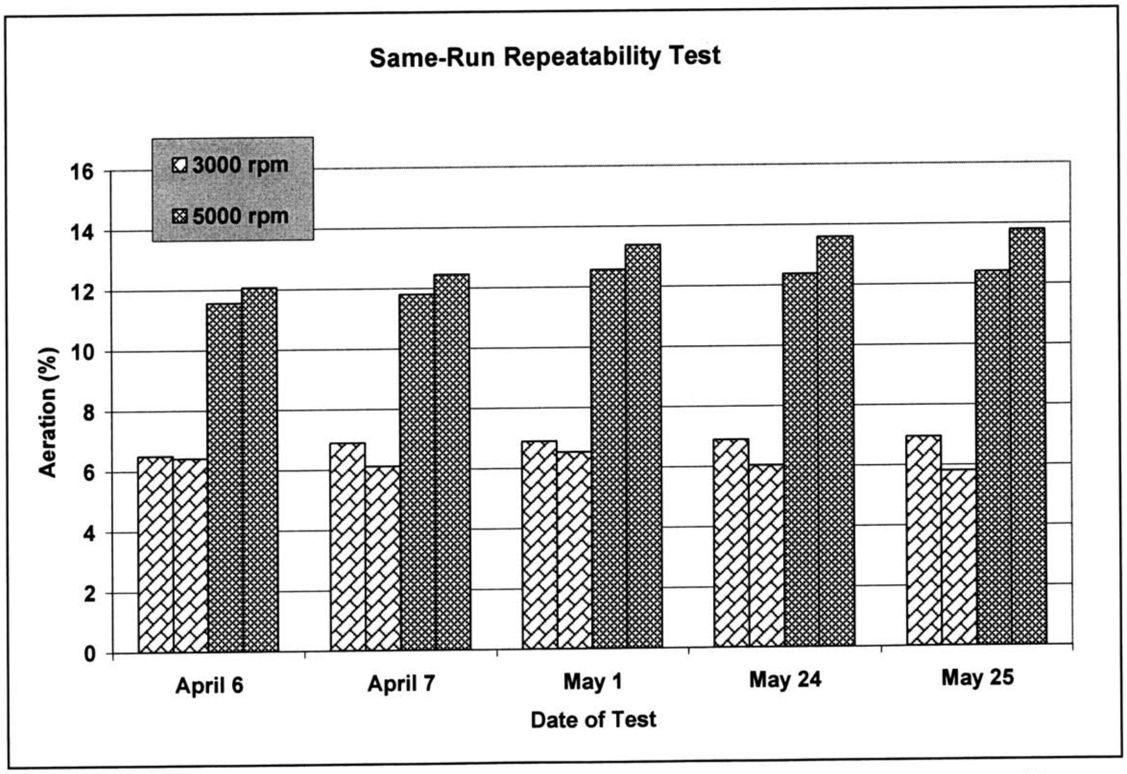

Figure 3-5 Same-run repeatability test results taken on various days between April 6 and May 25 2006

3.4 Analysis

Based on the data presented above, the testing method used in this study it considered to be sufficiently repeatable. When changes are made to the engine, the measurements can confidently be compared to each other to determine the effects of the hardware changes.

Chapter 4: Windage Tray Aeration Reduction Study

During car maneuvers, the sump oil sloshes around can come in contact with the crankshaft thereby inducing a drag force on the crankshaft and reducing engine performance. To prevent this from happening, a component, called a windage tray, is bolted to the bottom of the engine block. It is also sometimes referred to as a baffle or a scraper because it performs both of those functions. As a baffle it has gaps that allow oil flung from the rotating crankshaft to drain back to the sump. As a scraper it skims drops of oil off the counter weights as the clearance between the windage tray and counter weights is only 5 mm. This study is an examination of the windage tray design's effect on engine oil aeration. The original windage tray for the engine used in this study is shown in Figure 4-1.

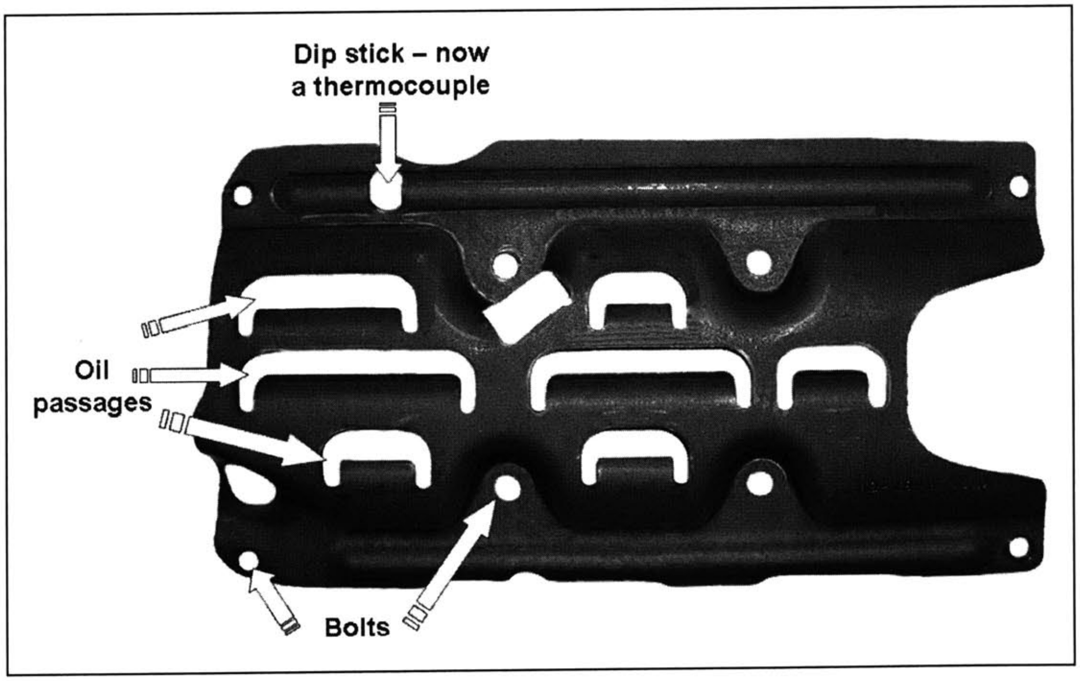

Figure 4-1 Original windage tray of Ford 3.0 L V6 DOHC engine used in this study

Figure 4-2 shows the windage tray in place bolted to the bottom of the engine block.

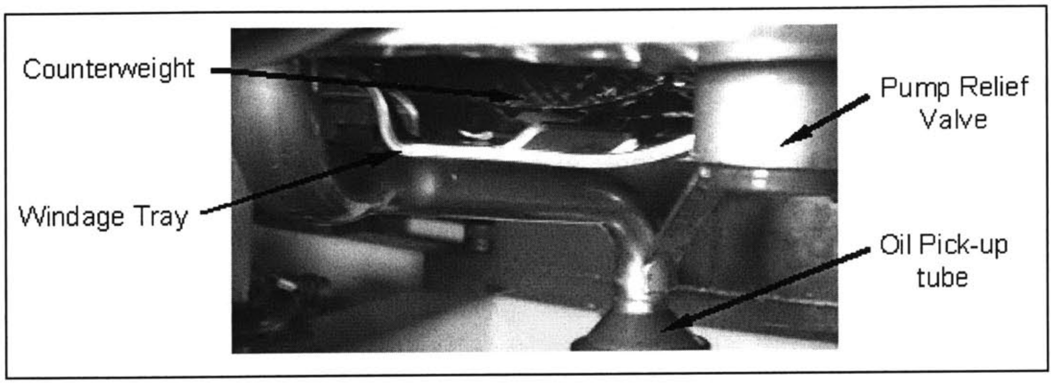

Figure 4-2 Windage tray in place bolted to the bottom of the engine block

4.1 Testing Procedure

For the windage tray study, as for the R&R study, oil was always sampled from the pick-up (location # 1) at a rate of 1 L/min. The location was chosen because this is where the oil is taken up into the engine so it is of greatest concern. The sampling rate choice was based on a previous study by Manz which was conducted on the same test engine [4]. Air-X was set to collected data every 5 seconds; that is x-rays are counted and averaged in consecutive 5 second intervals. This time scale is long enough to encompass slight variation but short enough to capture any significant deviations. This decision was based on data from another study by Manz [4]. Coolant water was circulated through the engine, but at a controlled rate and will be discussed below.

4.1.1 Temperature Control

Initially, for the windage tray study, a constant sump oil temperature was desired. To do this without affecting the oil aeration level a flowmeter was installed as show in Figure 4-3 to control the building cooling water through the engine. Tests were performed to determine the necessary water flowrate at every engine speed to keep a constant oil sump temperature. However, results of this testing, proved it impossible to maintain a constant oil sump temperature over the range of operating speeds. As can be seen from the graphical representation of the results in Figure 4-4 every operating speed has a sump oil temperature window of less than 20 °C. Air-X is only calibrated up to 110 °C; therefore no testing was performed beyond that temperature.

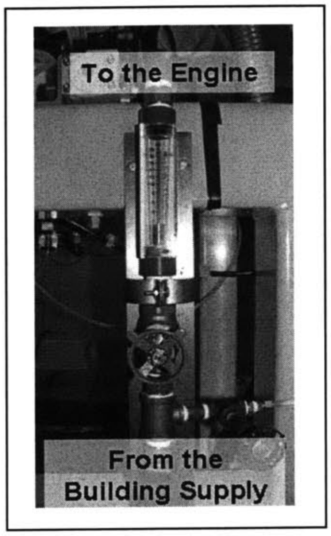

Figure 4-3 Flowmeter that controls the flow of building coolant water to the engine

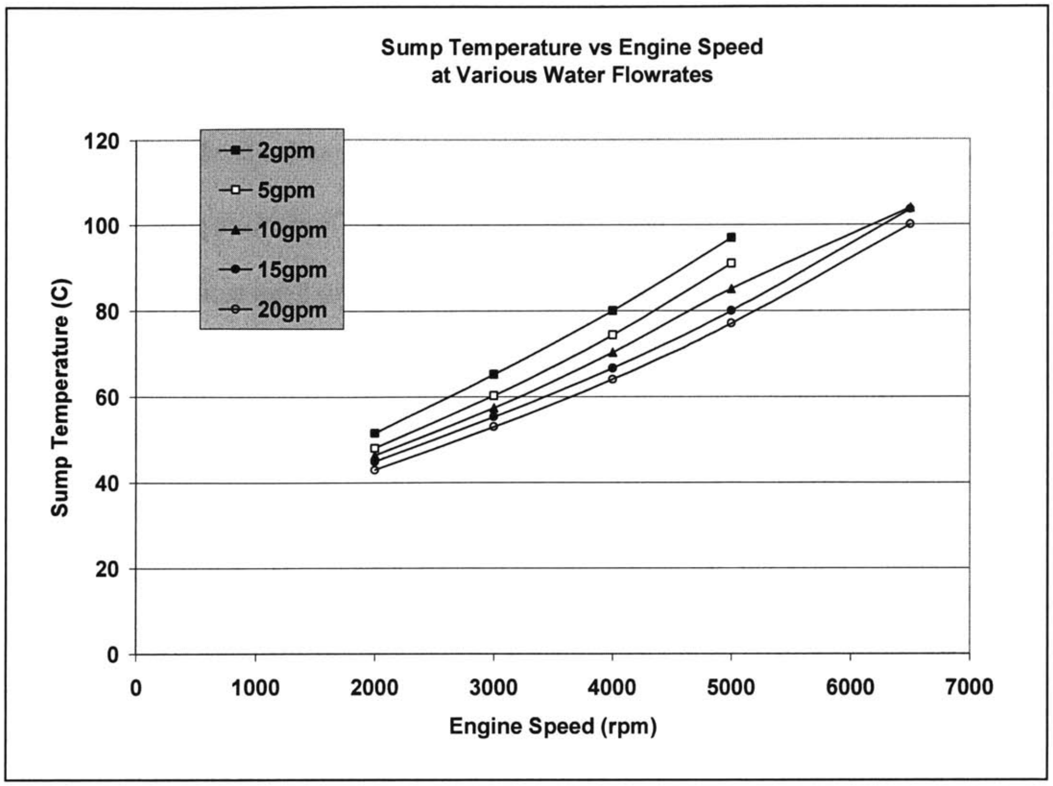

Figure 4-4 Test results to determine water flowrate for oil sump temperature control

Based on these results it was determined that with the current configuration, controlling the oil sump temperature at a single fixed value was not possible for the zero to 6000 rpm range. Therefore, it was decided that for the windage tray study water flow would be controlled to maintain a particular temperate at every operating speed. 6000 rpm was chosen as a test point rather than 6500 rpm to ensure that the sump oil remained within the acceptable temperature range. Water flowrates and oil sump temperature targets were chosen for the windage tray testing procedure based on the results in Figure 4-4. The values are shown below in Table 4-1.

Engine Speed (rpm)	Water Flowrate (gpm)	Oil Sump Temperature Target (°C)
2000	2	50
3000	5	60
4000	5	75
5000	12	85
6000	15	95

Table 4-1 Water flowrate and sump oil temperature targets used in the windage tray study

4.1.2 Test Matrix

The windage tray study examines four different tray designs plus the effect of no windage tray at five operating speeds. The entire study is completed with two different volumes of oil circulating through the engine, 5 L and 6 L. A summary of the metrics tested in this study is included in Table 4-2.

Tray Designs	Engine Speeds	Oil Volumes
Original	2000	5 L
Design 1	3000	6 L
Design 2	4000	
Design 3	5000	
No Tray	6000	

Table 4-2 Summary of metrics tested in the windage tray study

4.1.3 Test Profile

Each test in the windage tray study was preceded by a "warm-up" during which the engine was set to run at 5000 rpm and building water circulated at a rate of 10 gpm for 10 minutes. This assured that the engine was at the same conditions at the beginning of every test, sump oil temperature was approximately 80 °C. The test profile for the windage tray study is very similar to that of the R&R study and is show in Figure 4-5.

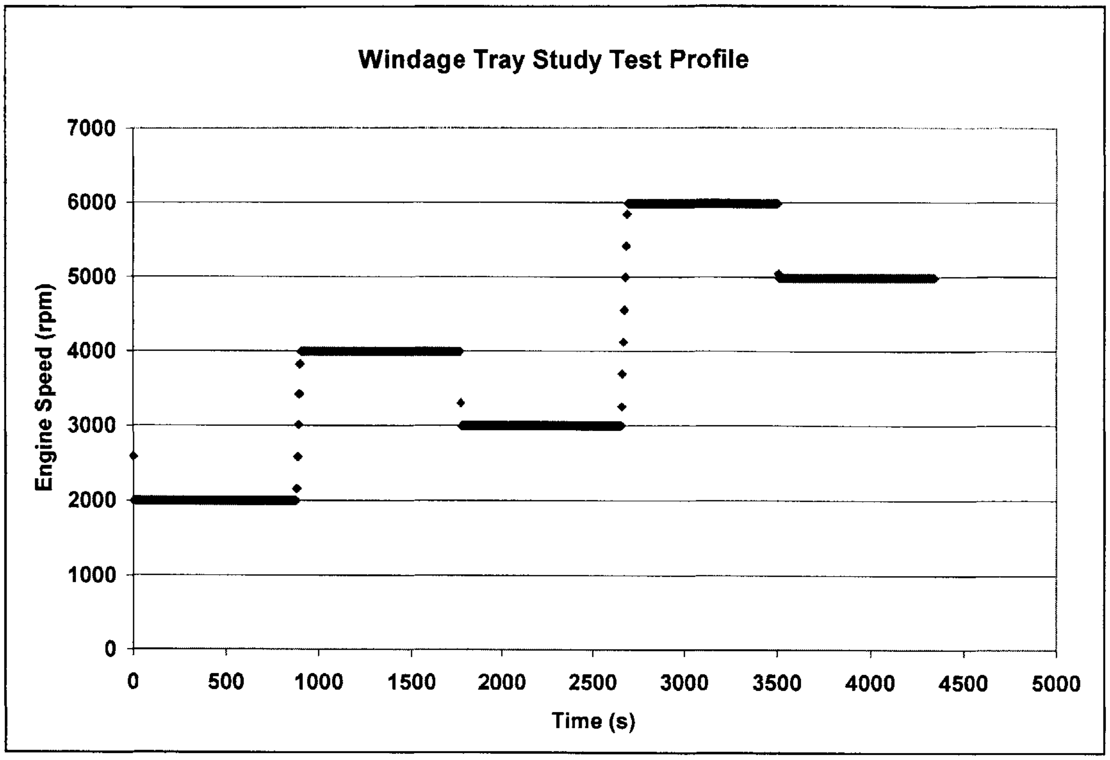

Figure 4-5 Windage tray study test profile

As mentioned earlier, the maximum engine speed in the windage tray study is 6000 rpm to ensure oil temperature does not exceed Air-X limitations. Since the aluminum cooling blocks were installed prior to this testing the 6000 rpm test point lasts just as long as all other test points, approximately 15 minutes. The test starts at 2000 rpm after the warm-up then goes to 4000, 3000, 6000, and 5000 rpm in that order.

4.2 Windage Tray Design

It was thought that perhaps a thin layer of oil was building up on the surface of the original windage tray (shown in Figure 4-1) like a puddle. Then oil droplets from the rotating crankshaft were impinging on the windage tray, splashing into this layer of oil and causing aeration. Based on this hypothesis, the new tray design aimed to create a faster drainage system for the oil that collects on the windage tray surface. The windage tray design is very specific to the engine. No addition can be made to the tray in thickness as there is only a 5 mm clearance between the windage tray and the counter weights of the rotating crankshaft. The tray is specifically molded to ensure this clearance is met. To modify the tray for this study the center area of the tray was cut out as shown in Figure 4-6.

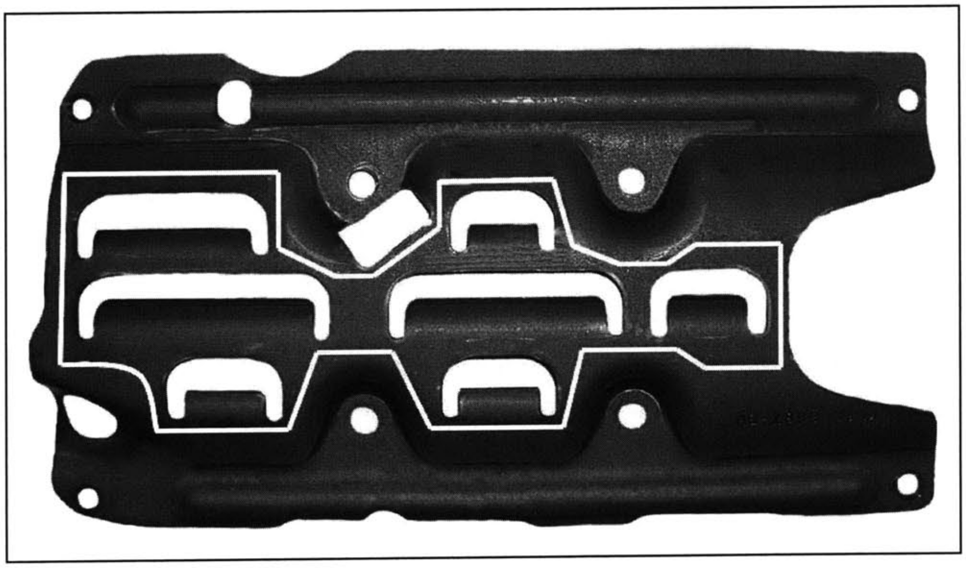

Figure 4-6 Original windage tray showing where the center was cut out

This cut out area was replaced with a wire mesh which was secured to the tray via screws and small threaded holes that were tapped along the cut out area. Three different size wire meshes were tested. The wire meshes are referred to by the number of mesh per inch horizontally and vertically. As an example, the 6x6 wire mesh has six meshes every inch horizontally and six meshes every inch vertically. A pictorial schematic of the 6x6 wire mesh is shown in Figure 4-7.

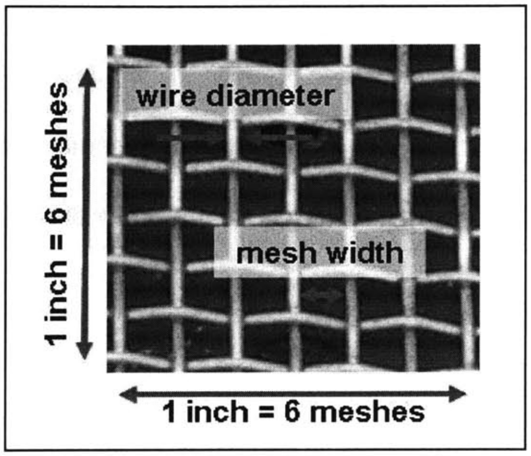

Figure 4-7 6x6 wire mesh schematic showing wire diameter, mesh width, and number of mesh per inch

The specifications for the 3 different wire meshes used in this study are summarized in Table 4-3.

Mesh	Number of Mesh per Inch	Wire Diameter (mm)	Mesh Width (mm)	% Open Area
2x2	2	1.68	11	76
6x6	6	0.9	3.4	62
14x14	14	0.55	1.35	51

Table 4-3 Wire mesh specifications

The wire meshes has to be cut to size to cover the cut out area of the windage tray. The design allowed for the different meshes to be interchangeable on the single windage tray with the center cut out. Figure 4-8 shows the 2x2 wire mesh attached to the windage tray along with the 6x6 and 14x14 wire meshes.

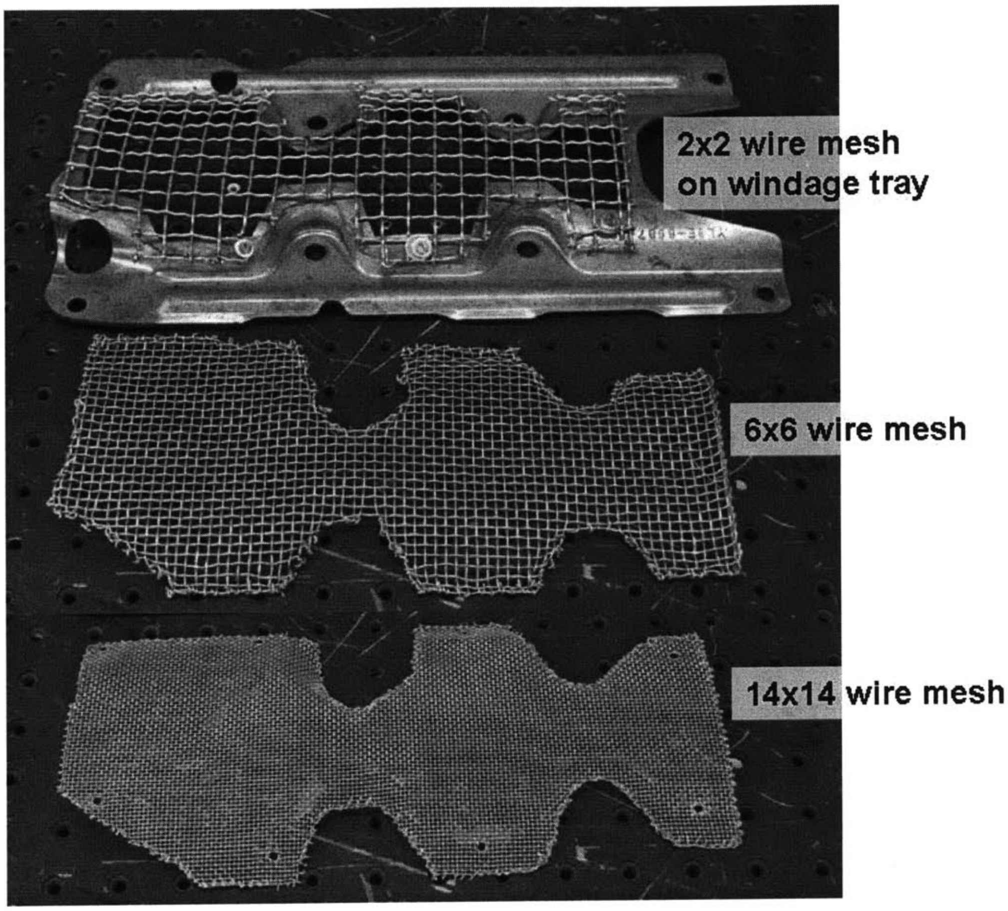

Figure 4-8 Cut to size wire meshes used in the windage tray study: 2x2 wire mesh attached to the windage tray, 6x6 wire mesh, and 14x14 wire mesh

The three new windage tray designs consist of replacing the cut out area of the tray with one of these three wire meshes. The windage tray study also tested the original tray and no tray for a baseline.

4.3 Data Analysis

The data analysis for the windage tray study is very similar to that of the R&R study. Figure 4-9 is a typical aeration time trace from Air-X, it also shows sump temperature. Note that, with the exception of 2000 rpm, at all speeds the sump temperature stabilizes n each speed window in testing.

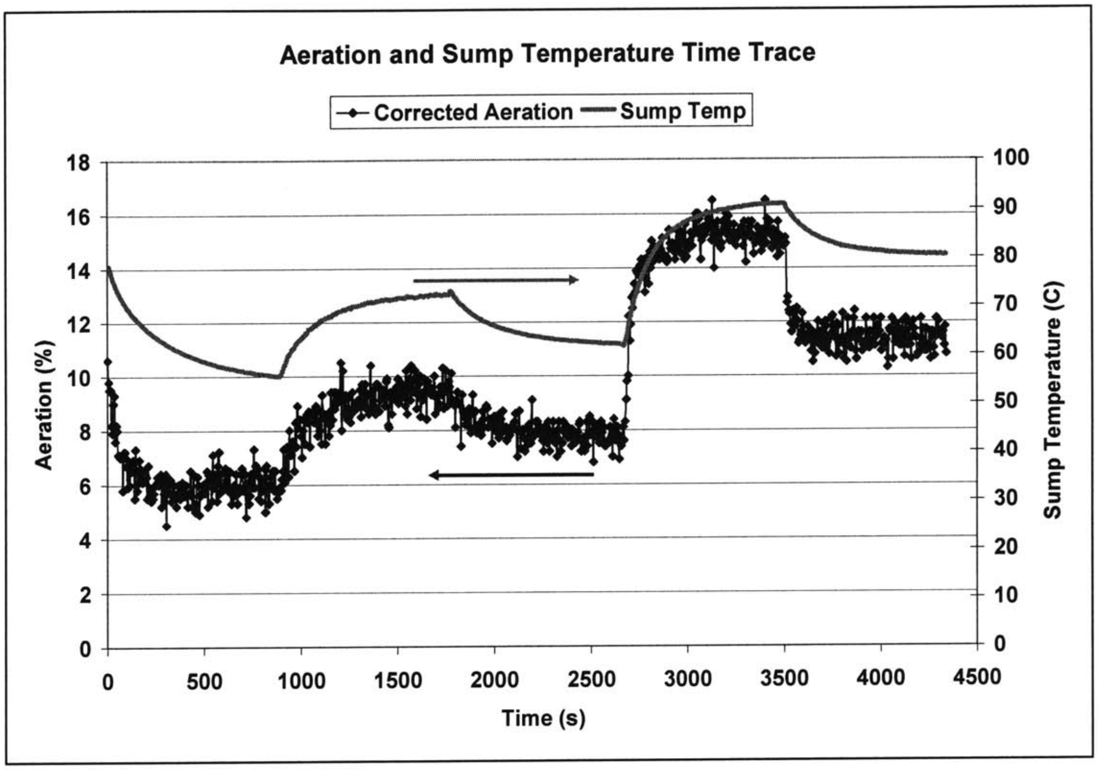

Figure 4-9 Typical aeration and sump temperature time trace

As for the R&R study, at each test point (engine speed) the data was truncated to only include the measurements after the aeration had leveled off and the t-statistic test was applied to the truncated data using the Matlab statistics toolbox. Again, a 95 % confidence interval was specified.

4.4 Results

4.4.1 Windage Tray Study with 5 Liters of Oil

Results from the windage tray study with 5 L of oil are shown in Figure 4-10. The three new windage tray designs using the different size meshes are shown along with the original windage tray and no windage tray.

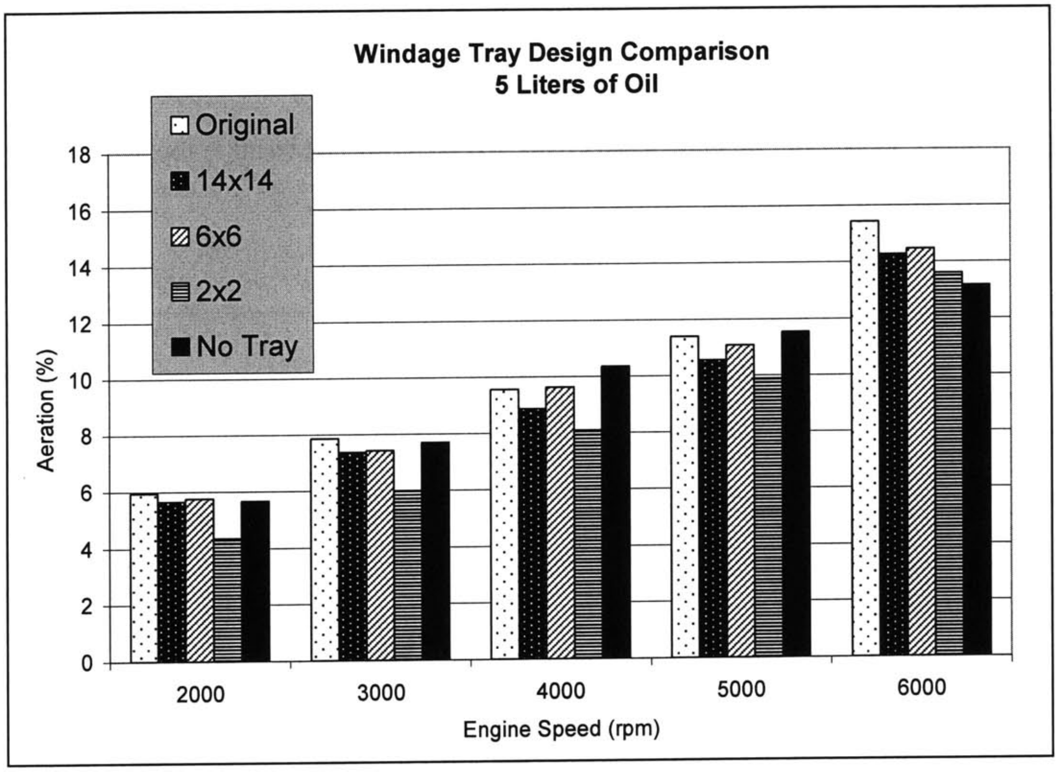

Figure 4-10 Results of the windage tray study with 5 liters of oil

Each type of shaded bar represents a different windage tray and the bars are grouped by engine speed. The delta values are not included in Figure 4-10 because they are so small that they are graphically illegible. However, they are tabulated in the Appendix along with the aeration values. Clearly aeration increases with engine speed; this is a commonly known phenomenon. No pattern is apparently obvious for the dependence on the windage tray design.

4.4.2 Windage Tray Study with 6 Liters of Oil

The windage tray study was also conducted with 6 liters of oil circulating through the engine. The data results are shown in Figure 4-11. Again, the delta values are not included graphically as they are illegible because they are so small. They are however tabulated in the Appendix. As with 5 liters of oil, there is no clear trend in the data.

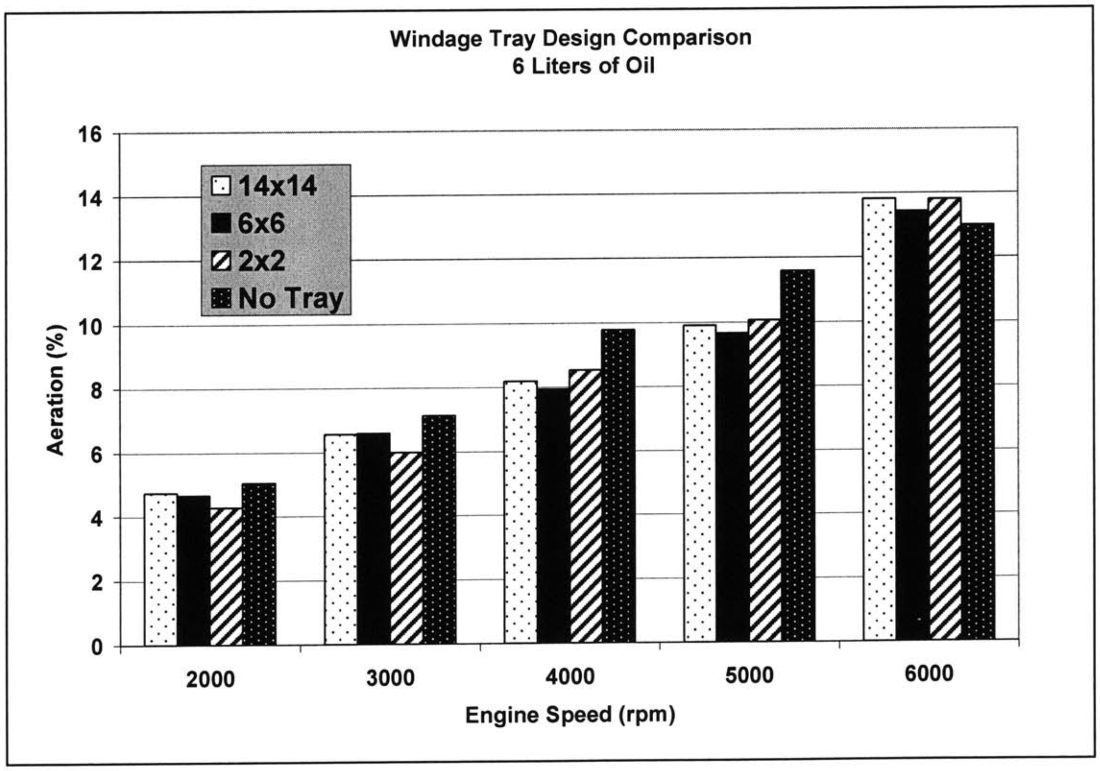

Figure 4-11 Results of the windage tray study with 6 liters of oil

4.5 Analysis

In an attempt to find a correlation between the different windage tray designs and aeration Figure 4-12 plots aeration against percent of windage tray that is open area. The windage tray open area percentage is based on the percent open area of the wire mesh used. No windage tray is considered 100 % open area. Although there appears to be a dip at 75%, the difference is actually relatively small and is therefore, not considered significant. The trend at 6000 rpm is a bit different with 100 % open area. But again, the difference is so small it is not considered significant.

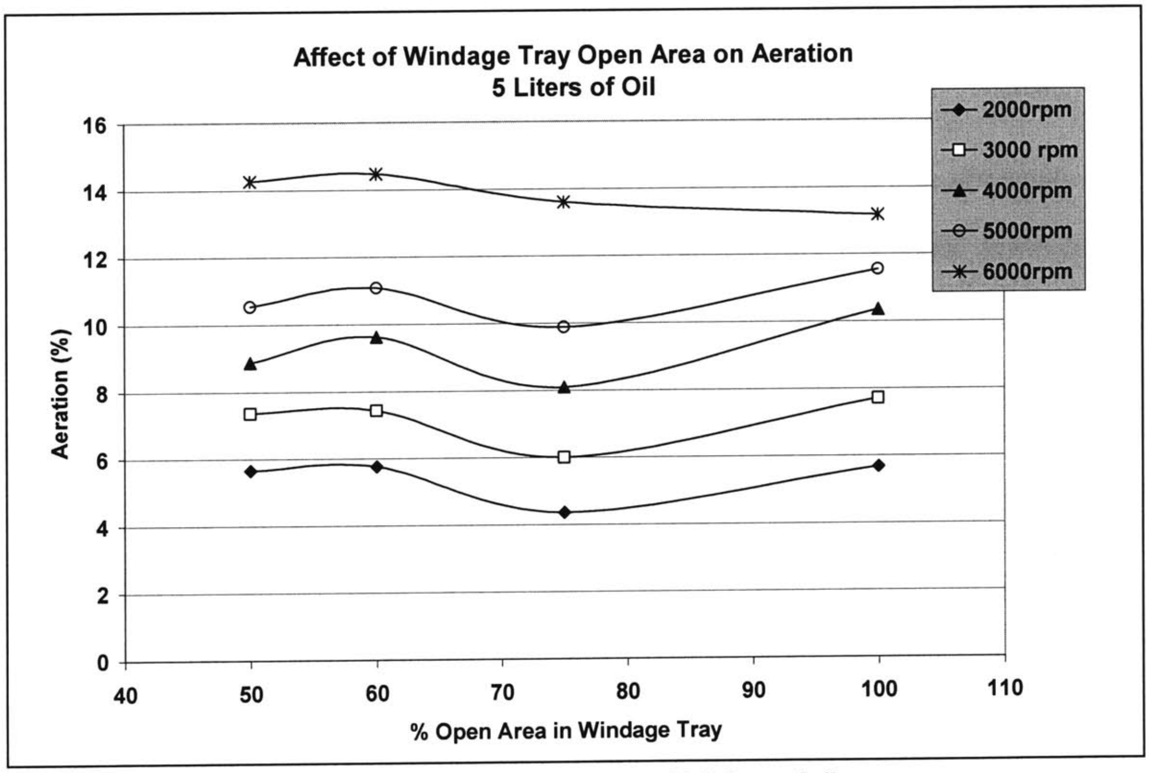

Figure 4-12 Affect of windage tray open area on aeration with 5 liters of oil

Since Air-X has a tolerance of ± 1 aeration percentage, changes in aeration are only considered significant if they are greater than 2 aeration percentages. Therefore, Figure 4-12 suggests that the percent of open area does not have a significant impact on the aeration level.

The goal in modifying the windage tray is to reduce aeration. The original windage tray design is, therefore, considered the baseline in this analysis. As can be seen in both Figure 4-10 and Figure 4-11 the new windage tray designs did not have a significant impact on the aeration level.

Oil volume was also considered a parameter in this study, hence why the study was repeated with both 5 and 6 liters of oil. Although the same aeration trends are seen with both oil volumes there is a difference when the two volumes are compared directly. Figure 4-13 compares the aeration level of the 6x6 wire mesh windage tray with 5 and 6 liters of oil. Over the entire operating speed range the aeration level is higher with 5 liters of oil. This phenomenon has been observed previously by others [4]. Results from this study further confirm those observations. This is believed to occur because a greater oil volume results in a longer resident time which gives the oil more time to de-aerate.

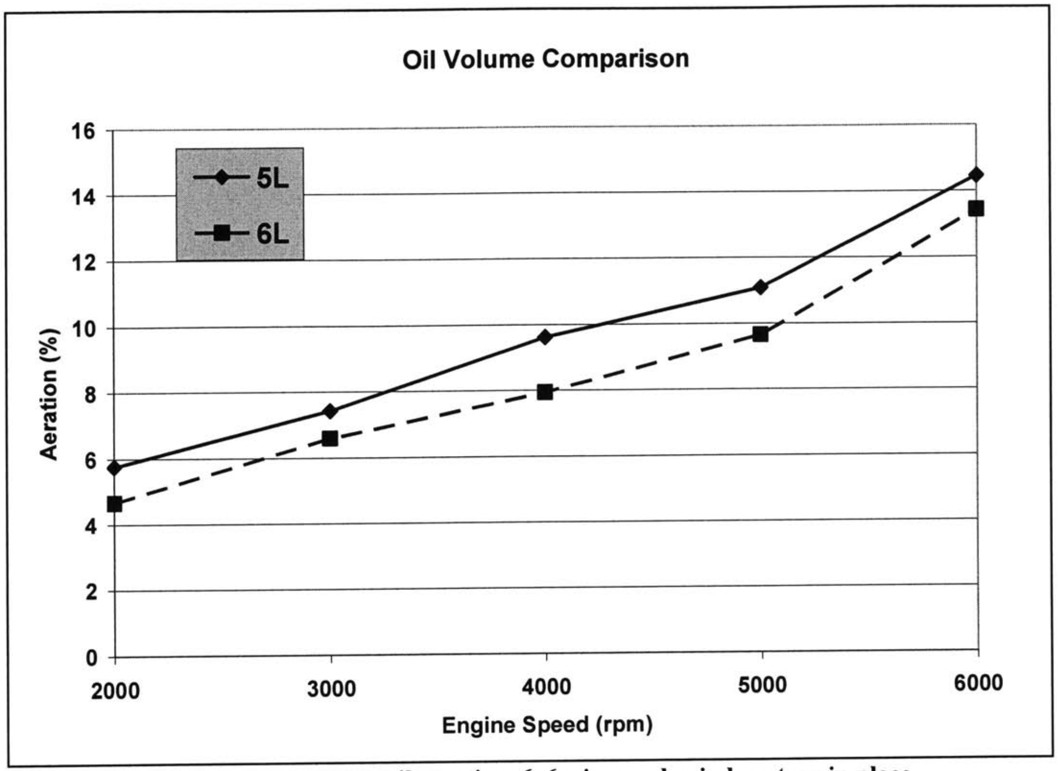

Figure 4-13 Affect of oil volume on oil aeration, 6x6 wire mesh windage tray in place

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Chapter 5: Summary and Conclusions

Oil aeration is the entrainment of air in lubricating oil. It can occur in three different forms; dissolved air, air bubbles, and foam. Dissolved air is not detrimental to an internal combustion engine. However, dissolved air can come out of solution if there is a drop in pressure or an increase in temperature, both of which could occur and lead to oil aeration in the lubrication path. Air bubbles and foam are detrimental to IC engines. They can cause failure of hydraulic components as well as reduce the oils ability to cool the engine and increase oil aging. Therefore, aeration is of great concern for IC engines. Many parameters effect aeration such as oil additives, oil pressure and oil temperature. Other parameters also affect aeration and were observed in this study.

It is common and accepted knowledge that aeration increases with engine speed. This phenomenon was seen during this study with both 5 and 6 liters of oil (Figure 4-10 and Figure 4-11). The faster the engine rotates the faster the oil circulates through it. That means the oil spends less time in the sump de-aerating.

Oil volume is another parameter that affects oil aeration. Figure 4-13 shows this affect. Aeration decreases with an increase in the oil volume in circulation. The more oil that is in circulation the longer the oil will sit in the sump and de-aerate.

Engine component design is also believed to affect aeration. This study focused on the affect of the windage tray on aeration and design changes to reduce aeration. The windage tray is a specifically molded sheet of metal that separates the oil sump from the rotating crankshaft. An initial repeatability study was conducted and found the testing method to be repeatable. Then a windage tray aeration reduction study was performed. Three alternative tray designs were tested. Results showed the design changes to have no significant affect on the aeration level.

Based on this study it can be concluded that changing the extent of the open area of the windage tray has no significant effect on the aeration level. Some mechanism other than the processes occurring in the oil layer on the windage tray must be the cause of the aeration and should be further investigated.

APPENDIX

Aeration and delta values from the day-to-day repeatability study:

	April 6		April 7		May 1		May 24		May 25	
speed	aeration	delta	aeration	delta	aeration	delta	aeration	delta	aeration	delta
2000	3.3789	0.0934	3.763	0.0995	4.4638	0.0964	4.2657	0.0855	4.496	0.1104
3000	6.4876	0.0713	6.8886	0.0767	6.8796	0.0931	6.8825	0.0757	6.9349	0.0847
4000	8.2622	0.0787	8.5522	0.0796	9.8153	0.0799	10.374	0.0867	10.4072	0.0806
5000	11.5517	0.0731	11.7876	0.0784	12.5677	0.0832	12.3654	0.0837	12.4102	0.111
6500	15.6362	0.1099	16.1	0.1405	16.4852	0.1839	16.4775	0.1711	16.1	0.2392
3000	6.4074	0.0907	6.1116	0.1004	6.5254	0.0888	6.024	0.0818	5.8099	0.1032
5000	12.0545	0.1048	12.4425	0.0878	13.3783	0.1094	13.5892	0.1084	13.7948	0.1098

Aeration and delta values form the same-run repeatability study:

	April 6		April 7		May 1		May 24		May 25	
speed	aeration	delta	aeration	delta	aeration	delta	aeration	delta	aeration	delta
3000	6.4876	0.0713	6.8886	0.0767	6.8796	0.0931	6.8825	0.0757	6.9349	0.0847
3000	6.4074	0.0907	6.1116	0.1004	6.5254	0.0888	6.024	0.0818	5.8099	0.1032
5000	11.5517	0.0731	11.7876	0.0784	12.5677	0.0832	12.3654	0.0837	12.4102	0.111
5000	12.0545	0.1048	12.4425	0.0878	13.3783	0.1094	13.5892	0.1084	13.7948	0.1098

Aeration and delta values from the windage tray study with 5L of oil:

	Original Tray		14x14 Mesh		6x6 Mesh		2x2 Mesh		No Tray	
Engine Speed	aeration	delta	aeration	delta	aeration	delta	aeration	delta	aeration	delta
2000	5.9411	0.0885	5.6438	0.1126	5.7516	0.1142	4.3502	0.1053	5.6654	0.1241
3000	7.8588	0.0826	7.3570	0.0898	7.4221	0.1080	5.9914	0.0993	7.6975	0.1114
4000	9.5619	0.0906	8.8613	0.1007	9.6124	0.1133	8.0905	0.1010	10.3472	0.1223
5000	11.3841	0.0786	10.5392	0.0766	11.0762	0.0910	9.8769	0.0777	11.5370	0.0900
6000	15.4207	0.1027	14.2569	0.1005	14.4602	0.1042	13.5914	0.1112	13.1591	0.1087

Aeration and delta values from the windage tray study with 6L of oil:

	14x14 Mesh		6x6 Mesh		2x2 Mesh		No Tray	
Engine Speed	aeration	delta	aeration	delta	aeration	delta	aeration	delta
2000	4.7396	0.1385	4.6552	0.2316	4.2721	0.1016	5.0339	0.1066
3000	6.5515	0.0970	6.5852	0.3228	5.9764	0.0940	7.1339	0.0816
4000	8.1859	0.1011	7.9365	0.2572	8.5275	0.1235	9.7698	0.1245
5000	9.8879	0.0848	9.6485	0.6008	10.0528	0.0795	11.5757	0.095
6000	13.8036	0.0926	13.4291	0.7812	13.7964	0.0989	12.9831	0.1147

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