Quantifying engine valve deposits with machine vision

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Inlet valve deposits in petrol engines have a significant effect on engine operation with particular reference to cold starting and driveability. Present methods of quantifying these deposits by weighing them or rating them with the aid of a visual rating scale are recognised as not being reliable indices of the detrimental effect of these deposits. A valve deposit quantification system was developed that relied on the use of machine vision. Algorithms were formulated to track the silhouetted edge profile of a backlit valve from which a valve volume was determined. The valve deposit volume was calculated as the difference in volume between the valve in its clean and coked states. The system was able to detect a minimum coke deposit level of 0.06 g at the 95% confidence limit, the accuracy being based on the correlation between the volume as determined by the vision system and the mass of the deposit.

Introduction

Inlet valve deposits in petrol engines are becoming of increasing concern to engine and fuels producers alike. Ray & Such [1] stated that inlet valve deposits were one of the most serious problems facing the automotive industry. Intake valve deposits reduced engine performance by interfering with the swirl effect designed to improve charge mixing and combustion. Cold starting is also adversely affected by deposits absorbing fuel.[1]

Performance and cold starting have always been recognized as being affected by inlet valve deposits. The situation has now become more critical for two main reasons. The first reason is the introduction of inlet manifold fuel injection. The injectors spray fuel directly on to the valves speeding up the deposit process. This problem resulted in a large amount of research on inlet valve deposits being done by BMW culminating in the introduction of a 16 000km test to quantify driveability.[2] Driveability takes into account factors such as cold starting and performance which are difficult to quantify. The second reason is the tightening of emissions standards. United States emissions standards are becoming so stringent that in some cases inlet valve deposits can cause the engine to produce emissions above the accepted level within 15 000km.[1]

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Quantification of valve deposits is very important in determining the effect engine design and fuel quality have in preventing harmful deposit buildups. However, there are only two main physical methods used to quantify deposits. Either the valve is cleaned and the actual deposit is weighed or the valve is rated on a visual scale from 0 to 10 based on a visual rating scale such as the one from Opel Kadett. In both methods of quantification the valve head is cleaned first as deposit on the head has negligible effect on the performance or driveability. Neither of these methods is very sophisticated and their accuracy in quantifying the harmfulness of valve deposits has been questioned. In the weighing method, the valve is initially rinsed with hexane for 1 minute followed by baking in an oven for 5 minutes after which it is placed in a desiccator for 1 h and then weighed.[3] Intuitively, quantification based on volume would be a better method than that based on mass. The visual rating scale method represents a form of quantification based on volume but it is subjective and not of a high precision. Reid, Hansen & Goering [4] showed that machine vision was a sufficiently accurate tool for measuring injector coking. Their system found the difference in cross-sectional area of injector silhouettes in the clean and subsequently coked state.

The overall objective of this project was therefore to develop a system using machine vision technology that could provide an accurate quantitative description of engine valve deposits based on the deposit volume.

Equipment and instrumentation

The computer vision hardware for this project was of a standard format comprising a colour frame grabber card, frame processor, red-green-blue (RGB) monitor, charge-coupled device (CCD) camera and IBM 286 compatible host computer. A valve mounting system was designed and built specifically for this project. A schematic of the system is shown in Figure 1.

The frame grabber board captures colour images from an RGB color video source for image processing. Colour information was not specifically required for valve analysis, but yielded accurate measurements. In addition to real-time capture and display, the frame grabber performed real-time RGB/HSI (hue-saturation-intensity) and HSI/RGB colour space conversion for processing captured images in either the HSI or RGB domains. Each of the three domain components used were stored in 256 kb buffers, and an extra buffer was used as an overlay for text or graphics. Each buffer had a 512 × 512 resolution with

256 different colour intensity levels possible. The output was in the RGB format and thus an RGB monitor was required to display the images from the frame grabber.

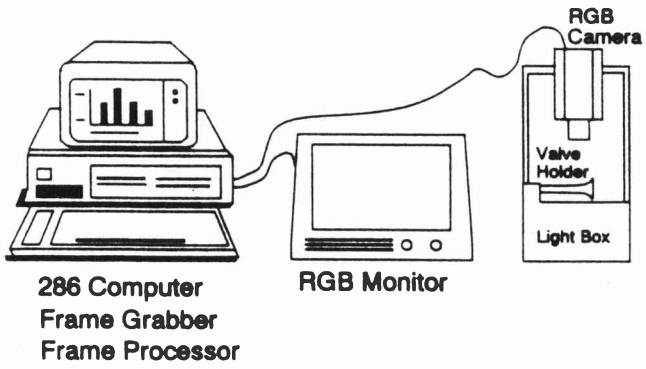

Figure 1 The colour – based valve analysis system

A stand was constructed to hold the camera and valve in position on a light box. A simple dividing head with one degree resolution was used for valve mounting and rotation. Valves were fitted into collets matched to the valve stem size. The integral system could be adjusted to capture backlit valve profile images from a position perpendicular to the principal axis of the valve. The light box consisted of a circular shaped fluorescent light enclosed in a wooden box. A rectangular section of the box above the light was made of opaque glass. A template was placed on top of the opaque glass to minimise the area of backlight viewed by the camera and to minimise the light reflected off the sides of the valve and so reduce the edge effects (see Figure 2).

Software development

The C programming language was used to develop software to quantify engine valve deposits from valve profile images acquired on the test stand. A technique was established for finding the centreline of the valve using the valve stem and then chain-coding the edge outline. Software was also developed to calibrate the system, align the valve, calculate the valve volume, and collect the data as they were measured. While colour was used for this application, a black and white system would have provided acceptable contrast between the valves and the background with additional spatial sensitivity.

Calibration routine

The test stand was constructed for collecting valve profile images perpendicular to the major axis of the valve. Pixel dimensions in the image required calibration for calculating actual deposit volumes. The calibration was based on finding the x and y dimensions of a spherical ball of known dimension. Using a ball as opposed to a flat object removed the necessity for levelling the disk in the plane of the image.

Routine for valve analysis

The routine for valve analysis determines the profile of the valve at a particular rotation. The profiles at a number of rotations were used to define the valve volume. Valve volume was determined from the valve edge profile by calculating its volume of revolution about the centreline from the valve head to a certain fixed distance along the valve stem.

The valve analysis was automated except for the selection of a window around the valve stem which established a reference point for determining the valve profile as illustrated in Figure 2. An image intensity threshold was used to segment the valve from the background. The centreline of the valve was computed from the average point of the two symmetrical edges of the valve stem within the window and the average angle of the two edges as shown in Figure 2. The valve stem is a machined part of the valve, most of which is located within the valve guide. It was therefore assumed that the stem was sufficiently clean within close proximity of the valve tulip to insure a reliable estimate of the valve location in the image. After the valve stem was windowed another image was captured by the frame grabber. This marked the beginning of a loop which was repeated for each rotation requested.

The valve centreline was found from the midpoint of the valve stem in the windowed area of the image selected by the operator. The centreline was located from the midpoint of the top and bottom edges of the valve stem. The top edge was determined by checking for object pixels from the top left hand corner of the windowing rectangle illustrated in Figure 2. A similar procedure was used for the bottom edge of the valve starting from the bottom left corner of the rectangle and then searching sequentially upwards. An edge tracing algorithm determined the profile of the valve and an 8-direction chain code was used to store the edge profile.

Chain-codes are a compact means for storing edge profile information. The chain-codes are specified from a starting point and then successively the direction from one edge point to the next. In this case with the application of eight connectivity chain-coding there are eight possible chain-coding directions. The masks in Figure 3 indicate the possible directions used for chain-coding. The shaded square represents the current pixel and the numbers represent the possible pixels to be coded next. The current point is the point on the edge profile which was last chain-coded. The two possible directions, anticlockwise and clockwise are specified when chain-coding the different directions around the valve.

The starting point for chain-coding the valve edge outlines was defined by the point where the valve centreline intersected the valve head. The starting point was therefore found by following along the valve centreline towards the valve head from the coordinate defining the centreline until a background pixel was found. The starting point was then the previous point on the centreline. The valve was always fixed in such a manner that the direction for

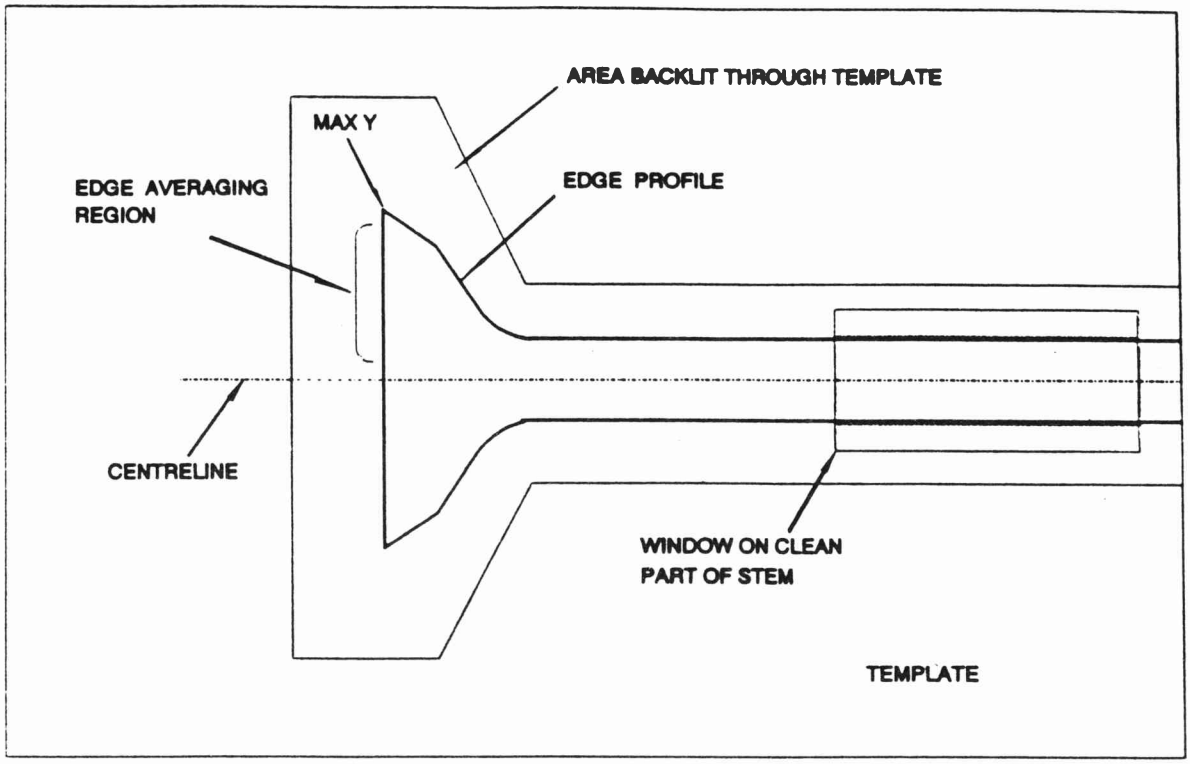

Figure 2 Illustration of valve in image

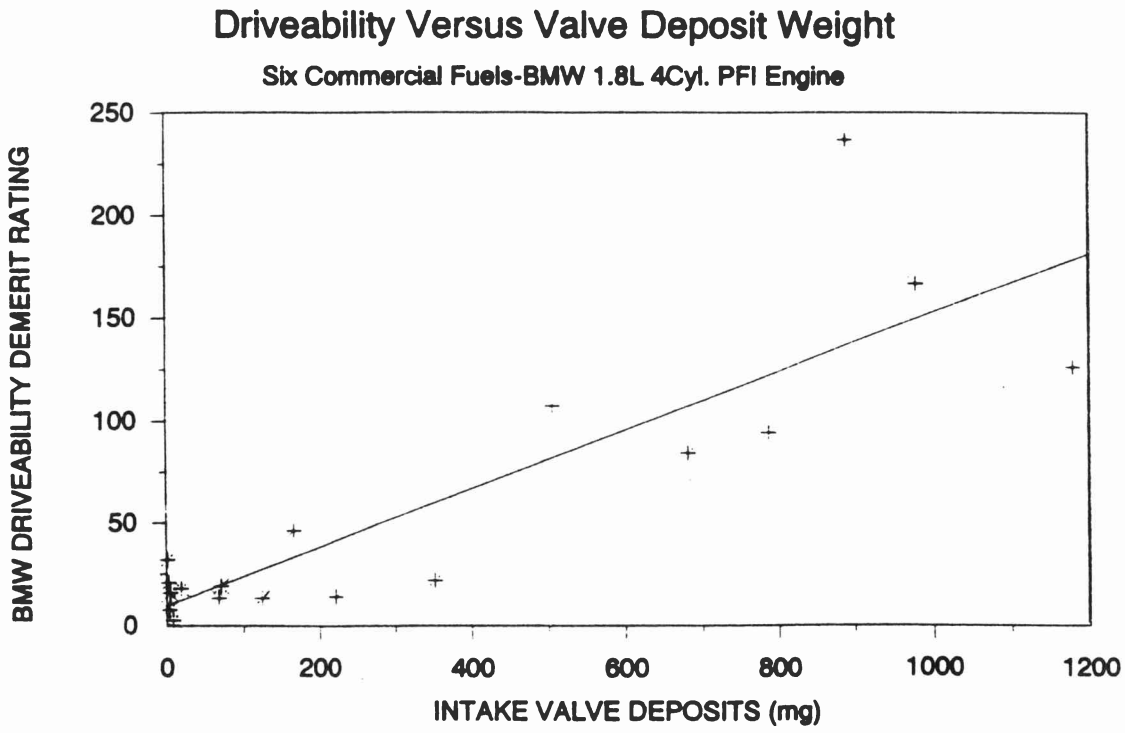

Figure 6 The correlation between deposit mass and driveability (after Bitting *et al.* [3])

following the centreline was set from right to left across the screen as shown in Figure 2.

ANTICLOCK

5	6	7
4		0
3	2	1

CLOCK

7	6	5
0		4
1	2	3

Figure 3 Masks used for eight connectivity chain-coding

For each rotation, a procedure computed the valve volume for the top and bottom valve profiles using chain codes from the starting point determined from extending the valve centreline to the head of the valve. Valve volume was calculated from the edge profile by determining the volume of revolution of the profile over a length of 30 mm extending from the valve head to a point on the valve stem. The volume of revolution was calculated as the sum of the cylindrical volumes obtained at each x coordinate, using the y coordinate as the radius and the x dimension of a pixel as the height of the cylinder. The volume of the valve as determined from a single profile is thus given by the following equation:

$$V = \sum_{S}^{S+L} \pi y^2 x_S y_S^2 \qquad (1)$$

where V = valve volume in mm^3 as determined for a single profile, S = x coordinate of valve head, L = length in pixels along valve stem for measurement, y = y coordinate corresponding to x coordinate, x_S = scale in mm/pixel of x side of pixel, and y_S = scale in mm/pixel of y side of pixel.

Once the volume was calculated, the chain-code of the edge and the calculated volume were saved to disk. This procedure was repeated for each valve rotation.

Results and discussion

The valve analysis system was used to quantify simulated and actual engine deposits on valves. The tests conducted with the simulated deposits using repeated measures formed the basis for a statistical analysis to determine the accuracy of the system. Additional tests on four different valves with simulated and with actual deposits were performed as a means of evaluating the system with respect to certain factors that were likely to influence the accuracy of the system.

Deposit mass-volume relationship with repeated measures

Tests were performed using grease deposits to simulate carbon buildup on the valves. These tests were used to determine the accuracy of the system and the number of rotations required per valve deposit measurement.

Eight different deposit levels were measured ten times for each deposit level resulting in 80 measurements. Measurements of the valve profile were made at 32 segments equally spaced around the valve determined from 16 equally spaced valve rotations. A spreadsheet was used to compute the volume using 16, 8, 4, and 2 rotations per 180° by taking the average of the profiles at these respective rotations. The mean volume for each rotation for the simulated tests is shown in Figure 4.

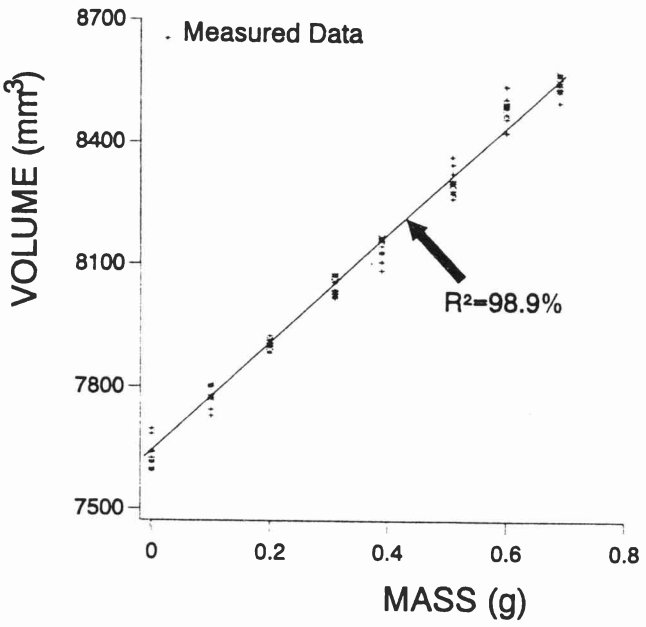

Figure 4 Mass vs volume of the simulated deposits for 8 deposit levels

A correlation exists between mass of deposit measured with the Mettler scale and the volume as determined by the machine vision system. The correlation for a linear fit provided an R^2 value of 98.9%. Regression analysis was used to account for the variation between rotations. The linear regression above was the determination of volume in terms of mass as volume was the dependent variable. From standard regression statistics it would be possible to determine the accuracy of volume in terms of mass. However, it was preferable to determine the accuracy of mass in terms of volume. It was not possible to perform a regression of mass on volume as the repeated measures were of mass. It was therefore necessary to perform a reverse interpolation of the results from the regression of volume in terms of mass. As the regression was for a linear correlation the following formula was used to obtain an

estimate of the confidence limits:[5]

$$C_L = \pm \frac{(tS_{x.y}/b)\sqrt{((n+1)/n)(1-c^2)+\hat{x}^2/\sum x^2}}{1-c^2} \quad (2)$$

where $c^2 = \frac{1}{\sum x^2}\left(\frac{tS_{x.y}}{b}\right)$, $t = t$ statistic for the required confidence level, b = slope from regression, S_{xy} = sum of products from regression, n = number of measurements, $\sum x^2$ = sum of squares mass data, and $\hat{x}$ = predicted value at which estimate is required.

The above equation gave an estimate of the accuracy of the machine vision valve analysis system to predict mass of deposit. The resulting estimate indicated an accuracy of 0.04 g of grease at the 95% confidence level.

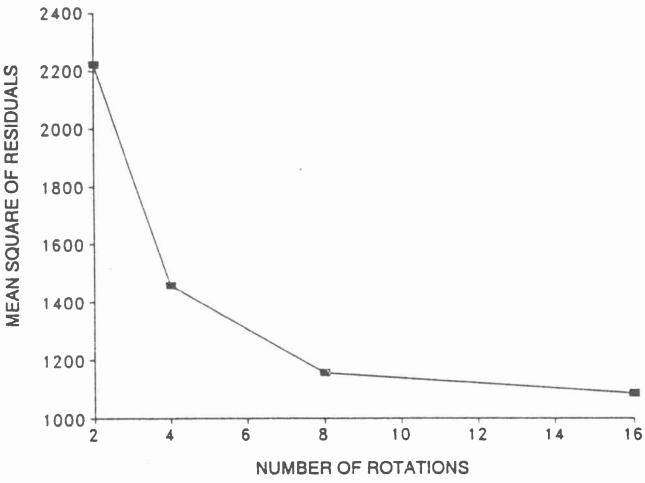

Figure 5 The number of rotations vs the mean square of the residuals for each rotation

The analysis of the data from the repeated measures was also used to determine the minimum number of rotations necessary without sacrificing accuracy. The mean of the squares of the residual for each rotation versus the number of rotations used to compute valve volume is given in Figure 5. The difference in the mean of the residuals between 16 and 8 rotations was not significant, whereas the differences between 8 and 4 and 4 and 2 were significant and increasing. On this basis it was concluded that the minimum number of rotations per 180° required was eight.

The regression assumptions were based on a relationship between volume and mass. As there was no accurate way of measuring the deposit volume physically the only means by which the device could be tested was to use a variable which was highly correlated with volume as an estimate of the actual volume. In the regressions above the accuracy of the system was based on its ability to predict the mass of deposit on a valve. However, mass may not be an ideal indicator of volume. Two factors which affect the correlation are the deposit density and the surface texture of the deposit. Changes in density affect the deposit mass to volume relationship. In the simulated deposits the variations in density could have been caused by possible air entrapment in the grease which was not quantified. Surface texture also plays a role as sharp surface dents result in surface holes being counted as volume. A better correlation between mass and volume could be expected in practice with actual carbon buildup because of a more uniform deposit density and porosity, however, surface irregularities or indentations in the deposits may be more prevalent in actual deposits.

In view of the fact that mass cannot be correlated perfectly with volume it was concluded that the accuracy of the system was somewhat higher than that determined above, as part of the estimated error of the system would have been due to the natural non-correlation of mass with volume. Furthermore the estimate of the accuracy of the system was based on the precision of the system to measure mass. For research purposes what is really required when quantifying valve deposits is the propensity of the deposit to affect the engine adversely or a measure of the driveability index.

Bitting *et al.* [3] described a driveability test performed by BMW which specifically evaluates the driveability during the critical early warm-up phase, which in turn is affected by inlet valve deposits. Figure 6 is a graph of the correlation between deposit mass and driveability as found using the BMW test. The correlation has an R^2 of 0.78 which Bitting *et al.* [3] regarded as 'excellent'.

It is likely that correlation of deposit volume versus driveability would be better than the above correlation as volume provides a more valid description of the deposit on the valve. Moreover porosity of the deposit plays a major role on the effect the deposit has on driveability. An indication of the porosity could be found from the density which can be calculated once the volume and mass of the deposit are known.

Actual vs simulated deposits and sources of error

In order to evaluate the system when used to analyse actual valve deposits and to highlight the effects various factors had on the deposit estimates, two sets of additional tests were carried out. The first set included four different valves with actual coke deposits and the second set comprised 4 different valves with simulated deposits.

The tests with the actual deposits were performed to assess how actual deposit measurements compared with those of simulated deposits. It was not possible to perform a regression on the data from the four valves with actual deposits. Valves with actual deposits in the range required for this project were difficult to acquire for the following reasons. The levels of deposit being measured were levels which would be reached after approximately 50 h of engine operation. The valves were thus only available from a company which ran controlled engine tests. The deposit masses available were in two groups separated at each end of a wide range and essentially only two data points were available and no statistically valid line fitting could be done. With reference to the Opel Kadett rating

scale in which a rating of 10 represents the cleanest valve and one, the most coked, the two groups of deposit would have been equivalent to deposit levels nine and one. The reason for the limited range was the lack of an adequate selection of valves with actual deposits. However, by fitting the data for these actual deposits to the graph in Figure 4, which provided the regression of mass on volume of the simulated data it was determined that actual coke deposit was approximately $\frac{2}{3}$ the density of the grease simulated deposits. The estimated accuracy of 0.04 g simulated deposit was thus equivalent to an accuracy of about 0.06 g of actual deposit.

A fuel manufacturer in South Africa indicated that accuracies of approximately 0.01 g would be desirable so that deposits resulting from short duration engine tests could be measured. The accuracy of 0.06 g fell somewhat short of this requirement. However, when compared to the range of deposit masses typicallyy measured in practice, for example in Figure 6, this accuracy was regarded as adequate. It must also be noted that 0.06 g is a very small deposit which would take about one to two thousand kilometres of travel to accumulate in the average car engine depending on the fuel used. In tests involving quantification of valve deposits the duration of the tests would normally be much longer than 1 000 km as the deposit must exceed a minimum thickness before its specific characteristics will emerge.

Figure 7 illustrates the profiles of a valve with no deposit and with an actual deposit of 1.5 g. This level of deposit would be regarded as heavy. The gap of approximately 10 pixels between the origin and the valve head on the x-axis is the result of an offset of 10 pixels added to the x coordinate values for the purpose of displaying the valve outline on the computer screen. The axes are given in pixels, but conversion to millimetres was achieved by the x and y scales for the x and y axis, respectively. For the tests the x and y scales were approximately 0.15 and 0.11 mm/pixel, respectively.

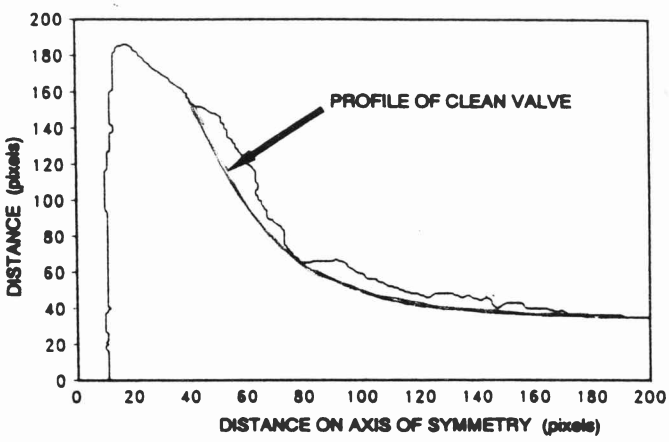

Figure 7 Valve profile with no deposit and with 1.5 g of actual deposit

A second set of tests involving four separate valves was used to identify possible sources of error in the measuring system. Deposits were simulated to represent typical deposit levels found in short duration engine testing. Deposit levels of 0.05, 0.12, 0.15, and 0.20 g were used. Two measures of eight rotations were performed at each deposit level resulting in eight valve measures. Initial deposit volume data are illustrated in Figure 8 with a graph of valve volume vs mass. The line in the graph was obtained using a simple least squares linear fit. The higher three deposit levels had an adequate fit whereas the lowest deposit level had a poor fit for both of its measures. The results were still encouraging as the lower deposit level of 0.05 g of grease was approximately the same as the level of accuracy that would be expected from the system.

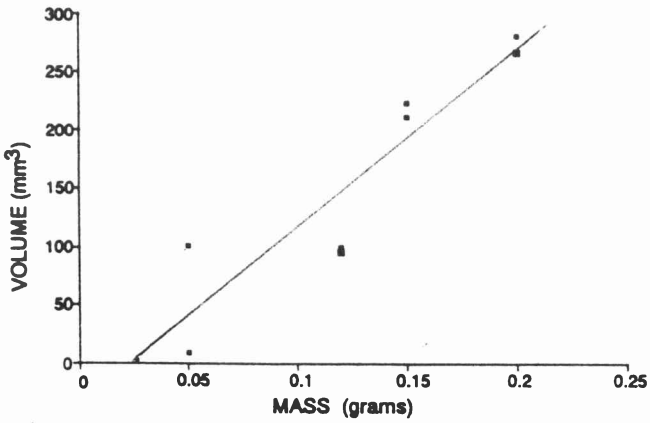

Figure 8 Variations of simulated deposit volume with mass for four typical deposit levels

A modification was made to the volume calculation routine such that equation (1) was changed so that fractions of a coordinate could be used as the starting point. The integer value of the average x coordinate was taken as the starting point and the volume was calculated in the normal way. The fractional part of the average x coordinate multiplied by the volume of rotation of the starting point was then subtracted from the volume while the fractional part of the average x coordinate multiplied by the end plus one x coordinate was added to the volume. This new method of calculating the volume is given in equation (3) and, as for the case of the original volume calculation routine, the volume of the valve was taken as the average of all the volumes of rotation found from each profile at each rotation.

$$V = \sum_{x_s}^{x_f} \pi y^2 s_x s_y^2 + \pi \left(y_{f+1} - y_s\right) s_x s_y^2 f \qquad (3)$$

where V = calculated volume, y = maximum y coordinate for a given x coordinate, $S_x = x$ scale of the pixels, $S_y = y$ scale of the pixels, x_s = starting x coordinate, x_f = finishing x coordinate, y_{f+1} = maximum y coordinate at the next x coordinate after x_f, y_s = maximum y coordinate at the starting x coordinate, and f = fractional part of the average x coordinate.

Table 1 Volume data for a valve before and after modification of the volume calculation procedure (Volume units in mm^3)

VALVE	ca-before		cb-before		da-before		db-before	
SIDE	A	B	A	B	A	B	A	B
ROTATIONS 1-8	8162	8398	8311	8267	7990	8445	8208	8400
	8159	8402	8263	8266	8039	8337	8179	8365
	8277	8254	8279	8258	8066	8399	8298	8410
	8269	8199	8285	8204	8054	8425	8302	8452
	8237	8249	8267	8253	8149	8398	8449	8310
	8151	8315	8133	8322	8213	8414	8377	8273
	8043	8343	8065	8355	8243	8318	8378	8348
	8044	8342	8035	8371	8261	8269	8372	8385
STANDARD DEVIATION		106		91		147		75
MEAN VOLUME		8240		8246		8251		8344
AVERAGE CLEAN				8243				
DEPOSIT VOLUME						8		101

VALVE	ca-after		cb-after		da-after		db-after	
SIDE	A	B	A	B	A	B	A	B
ROTATIONS 1-8	8141	8341	8268	8211	7976	8369	8131	8340
	8140	8350	8247	8213	8022	8301	8153	8315
	8260	8210	8258	8221	8054	8358	8263	8327
	8230	8148	8249	8155	8037	8394	8275	8416
	8213	8212	8244	8212	8149	8398	8428	8310
	8066	8286	8054	8293	8154	8372	8356	8226
	8036	8306	8056	8324	8165	8262	8343	8290
	8036	8294	8017	8311	8246	8226	8349	8346
STANDARD DEVIATION		99		90		139		79
MEAN		8204		8208		8218		8304
AVERAGE CLEAN				8206				
DEPOSIT VOLUME						11		98

side A = top profile of valve

side b = bottom profile of valve

ca = measure 1 of clean valve

cb = measure 2 of clean valve

da = measure 1 of dirty valve

db = measure 2 of dirty valve

Table 1 gives the results of the volume calculation for the individual rotations of the valve at the 0.05 g deposit level. These results represent the output before and after modification to allow for fractional starting points. As would be expected the mean volume of the data fell slightly after the modification as in the case of 'ca' the mean volume fell by 36 mm^3. This may be compared to the total volume of 11 mm^3 on 'a'. However, the volume of both the dirty and clean valves dropped by approximately the same amounts. For example the deposit on 'a' was measured at 9 mm^3 before the modification and 11 mm^3 after the modification, a change of only 2 mm^3. It would appear that while the modification made significant changes to the individual readings, the effect of the changes tended to cancel out over 16 readings.

Possible errors resulting from misalignment of the valve centreline were found to be insignificant as the combination of the profiles of each half of the valve tended to have a cancelling effect on misalignment errors. Another possible source of error that will have to be addressed further in future work is the effect the valve head has in obscuring the valve head profile. The valve head is slightly offset with reference to the image. That part of the valve head closest to the camera can thus obscure the valve profile at its horizontal axis. With reference to Figure 7 it can be seen that there is a slight curvature in the valve head profile. This curvature is likely to have been caused by the obscuring of the valve head. It is necessary to have the valve head slightly offset in order to make maximum use of the system's resolution by protruding into the image as far as possible.

Conclusions

A prototype for quantifying engine valve deposits was able to predict the mass of deposits simulated by grease with an accuracy of 0.04 g. This represented an accuracy of approximately 0.06 g of actual coke deposit, which was based on the correlation between the volume, as measured by the system, and the mass of the deposit. This accuracy did not meet the initial stringent requirement of the project of 0.01 g. However, it was adequate for more common valve deposit measurements. In addition the density of the deposit can be determined relatively easily and can be used to characterize the deposit.

The accuracy of the system was based on its ability to predict the mass of the deposit. Mass is used to quantify engine valve deposits at present. What engine and fuels researchers actually need to quantify is a driveability index which would describe the adverse effect that the deposit has on driveability and performance. The correlation between mass and the BMW driveability index had an R^2 value of 0.78. It is thus difficult to predict the accuracy of the valve analysis system in terms of the driveability index by determining the accuracy of the system to measure mass which is correlated with the driveability index with an R^2 of only 0.78. It must therefore be recommended that to evaluate this system for deposit quantification further tests must be undertaken. These tests would need to be performed in conjunction with a large fuel or engine manufacturer which could supply not only valves with deposits in a suitable range but also valves which had previously been quantified in a driveability test such as that used by BMW. Volume-driveability and mass-driveability correlations would then give an indication of the relative precision of the two quantification methods. It may also be of benefit to examine the correlation between deposit volume and emissions as deposits are known to cause problems in terms of emissions.

It was determined that a minimum of eight rotations per 180° of valve rotation or a measure of the valve every 22.5° was sufficient to achieve an optimum trade off between measurement time and the accuracy of the final result.

It can be concluded that machine vision as a valve deposit quantification system would provide an effective tool for determining the volume of valve deposits. Machine vision also has the advantage of being able to store a database of valve profiles for later reference and comparison. In comparison to the visual rating system of Opel Kadett it provides a far more objective technique that can detect relatively low levels of deposit accurately. With the increasing pressure that is being placed on engine and fuel manufacturers to reduce engine emissions, this system for quantifying engine valve deposits could form an important tool in assisting the manufacturers with their research.

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