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Investigation of Deposit Formation Mechanisms for Engine In-cylinder Combustion and Exhaust Systems Using Quantitative Analysis and Sustainability Study

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Abstract The formation of SI engine combustion deposits is a complex phenomenon which depends on various factors of fuel, oil, additives, and engine. The goal of this study is to examine the effects of operating conditions, gasoline, lubricating oil, and additives on deposit formation. Both an experimental investigation and theoretical analysis are conducted on a single cylinder engine. As a result, the impact of deposits on engine performance and exhaust emissions (HC, NO_x) has been indicated. Using samples from a cylinder head and exhaust pipe as well as switching gases via the dual-gas method (N_2, O_2), the deposit formation mechanism is thoroughly investigated via the thermogravity analysis approach, where the roles of organic, inorganic, and volatile components of fuel, additives, and oil on deposit formation are identified from thermogravity curves. Sustainable feedback control design is then proposed for potential emission control and performance optimization

Keywords Engine deposits · Quantitative analysis · Sustainability · Thermal gravity curve

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1 Introduction

Combustion deposits are unavoidable byproducts of spark ignition engines, independent of what type of the injection system is selected, such as carburetor metering, port fuel injection, and gasoline direct injection. Deposits accumulate directly on the combustion chamber, piston top, intake valves, and ports as well as the exhaust valves. Deposits also condense indirectly on the exhaust pipe and three-way catalyst. These deposits can lower the fueling rate, restrict air flow, increase compression ratio, alter spray patterns, induce knock, degrade thermal conductivity, and reduce catalyst reactivity. Moreover, deposit formation corresponds to the ORI (octane requirement increase). It is obvious that combustion deposits have a substantial impact on engine performance, fuel economy, cold-start and warm-up driveability, and exhaust emissions. Consequently, it is necessary to examine mechanisms of deposit formation.

The earliest survey on deposit formation mechanisms was presented in 1925, where the relationship between knock and deposits was examined. It is pointed out by Orelup [1] that in comparison with unleaded fuel, the lubricating oil introduced into the cylinder is more significant in deposit formation. Dumont [2] sets forth assumptions later on what could give rise to deposit formation, whether thermal insulation and deposit volume are major factors. Typical single-cylinder engines and four-cylinder engines are generally selected for investigating deposit formation by means of engine bench tests. Some valuable results and relevant phenomena have been obtained, especially after 1990. An intensive study of the combustion deposit formation mechanism and its actual effects on various engine performances was examined by Meng [3] based on both types of engines. For any fixed surface area, the deposit mass is heaviest on the piston top and thinnest on the exhaust valve, while deposits contain high inorganic and low organic contents on exhaust valves. As for emissions, the HC level is highly sensitive to deposits, followed by the NO_x level while the deposit has little effect on the CO level. Roughly, the specific heat and thermal conductivity of the deposit are proportional to the surface temperature. In a single-cylinder case, the surface temperature is understood to be a prevalent factor of deposit formation processes. Due to the insulating action of deposits, the combustion flame temperature and exhaust gas temperature increase, which can result in up to 30% of extra NO_x. Fuel absorption into the deposits plays an important role on the HC level. On a four-cylinder engine, the fuel storage in deposits is the major mechanism, similar to crevices on the piston top and cylinder head. In addition, the extra HC level due to deposit accumulation accounts for 10–20% of the total HC emissions [7]. Furthermore, different fuels respond to deposits in different manners in terms of knock limit and spark advance [4–7]. From most studies, the influence of lubricant oil and additives on deposit formation is greater than that of the fuel, while fuel, oil, and engine wear contribute to deposit formation collectively. For both water-cooled and air-cooled engines, the combustion deposit is a major cause of deteriorating emissions [8–10].

2 Engine Specification and Test Bench

The engine bench test setup is shown in Fig. 1, and specifications of the 165F engine are shown in Table 1, where various sensing elements are used to measure performances

Table 1 165F Engine Specifications

NO.	Engine parameter	Specifications
1	Engine	165F spark ignition
2	Cooling	Air cooled
3	Chamber	L-Type
4	Bore	65.0 mm
5	Stroke	65.0 mm
6	Displacement	0.216 L
7	Spark advance	20 °CA
8	Nominal power	2.94 kW
9	Nominal speed	3000 RPM

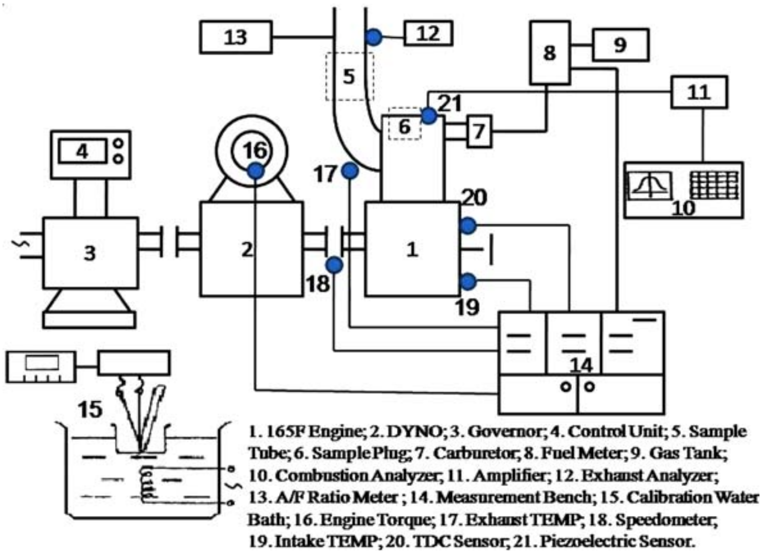


Fig. 1 Sketch of 165F engine bench test setup

of the 165F engine, hydraulic dynamometer, and exhaust system. Combustion deposits are collected using a sample tube assembled to the exhaust pipe (Fig. 2) with thermocouples and cooling devices plus a removable sample plug on the cylinder head.

All sensory elements for pressure, temperature, speed, torque, exhaust gas rates, TDC (top dead center), etc., should be calibrated. For example, thermocouples are calibrated using the water bath method, from which satisfactory results have been demonstrated over a broad temperature range. Other sensors are calibrated similarly prior to engine bench tests.

3 Bench Test Results Analysis

Based on empirical information available for the carburetor metering 165F spark ignition engine, the amount of deposit accumulation increases at a rate that is approximately

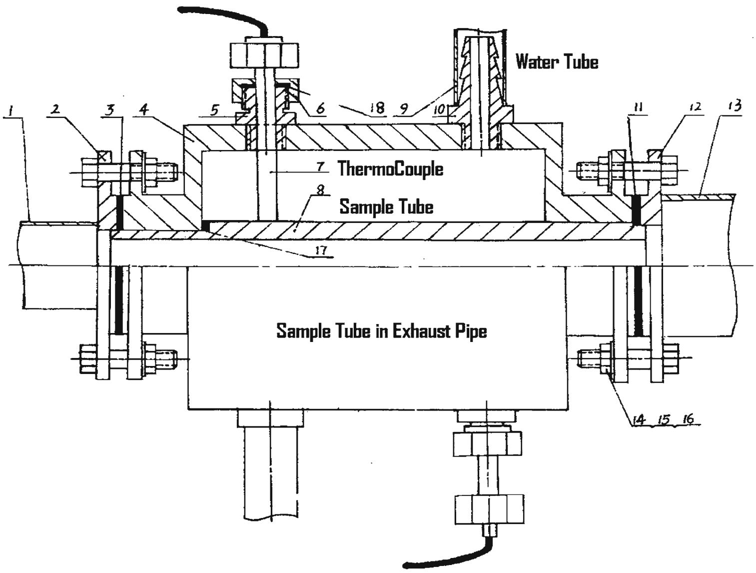


Fig. 2 Sketch of sample tube connected to engine exhaust pipe

proportional to time until it saturates after 8–10 h. This amount remains at the same level thereafter. Thus, this saturation time is used as the engine bench test duration.

When the engine is running at a low power range, the exhaust temperature is normally too low to oxidize the halfway combustion products among the exhaust emissions, which gives rise to a larger amount of deposits on the exhaust pipe as well as on its interconnected sample tube. In general, the temperature of the sample plug reflects the actual temperature of the combustion chamber, and in most cases, it is high enough to oxidize some halfway products. Meanwhile, volatile deposit substances are susceptible to evaporation at high temperature. As a result, the unit surface deposit amount on the sample plug is less than that on the sample tube at the low power range. When the engine is running at the high power range, the formation mechanism of sample plug deposits relies on the cylinder wall temperature and combustion flame temperature. Both the wider throttle opening and higher engine speed result in a larger volumetric efficiency and more rapid combustion flame propagation as well as the high temperature of the flame and combustion chamber. The high temperature makes severe carbonization of deposits occur easily and thereby excessive combustion soot is produced, so the deposit amount on the sample plug increases rapidly at the high power range. The formation of sample tube deposits mainly depends on the engine exhaust temperature. Whenever the exhaust temperature reaches a high level of 500–600 °C, the amount of sample tube deposits decreases significantly due to oxidization and reactions on the exhaust manifold and tailpipe. Consequently, the unit surface deposit amount on the sample plug is higher than that on the sample tube in the high power range (Fig. 3a).

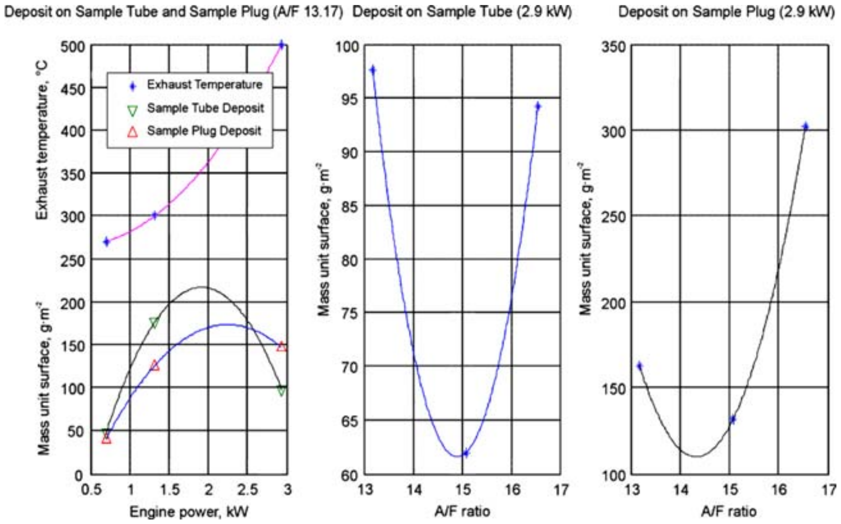


Fig. 3 Engine experimental results

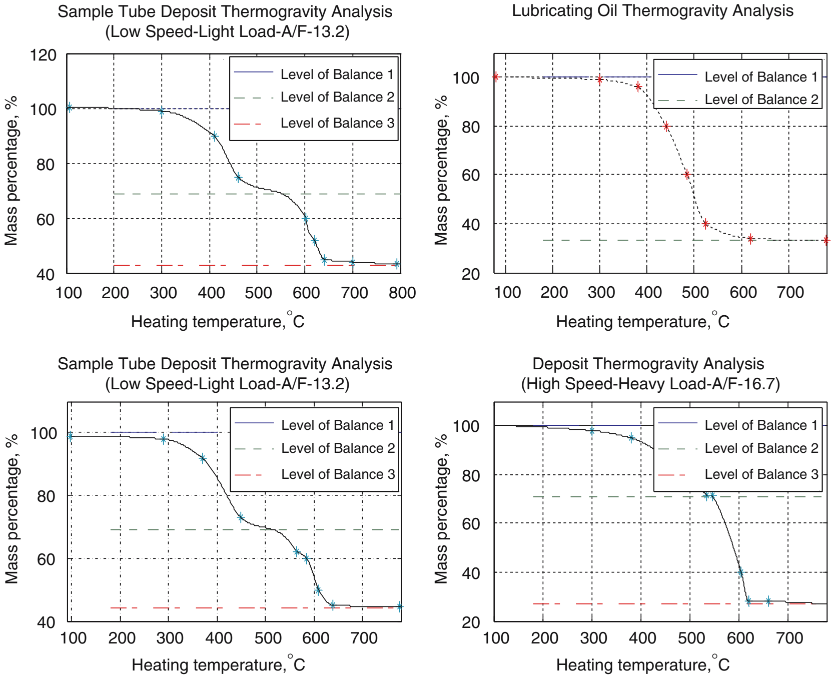
The deposit accumulation is closely related to the completeness of the engine combustion process. The minimal possible amount of combustion deposits occurs at the stochiometric A/F (air/fuel) ratio, which corresponds to complete combustion. At high speeds and in the heavy-load region, under various A/F ratio testing conditions, the ultimate combustion deposit amount decreases when the A/F mixture changes from a rich condition to the stochiometric A/F ratio and its amount starts to go up again if the A/F mixture reaches a much leaner condition. Particularly, when the A/F ratio is about 12–13, the combustion flame propagation is the fastest at a high flame temperature. In this range, the rich mixture has a low oxygen concentration leading to incomplete combustion. Accordingly, halfway products accumulate on the cylinder wall. Due to the high temperature, the carbonizing effect is remarkable where large amounts of combustion deposits accumulate on the sample plug. In addition, under rich conditions, the combustion deposit on the chamber wall grows with an increase of the engine power. To make a comparison at high speeds and in the heavy-load region, the sample tube contains more unit surface deposits than the sample plug does due to the presence of halfway products. When the A/F ratio is around 15–16, complete combustion takes place under enriched-oxygen and high-temperature conditions, so carbon turns into CO_2 and a high level of NO_x shows up. In this region, the amount of deposit is minimal on both the sample plug and sample tube. If the A/F ratio continues to go up, an excessively lean mixture is present. Halfway products cannot react fully because of the low flame and reaction temperature. Hence, some significant amounts of reaction products accumulate on the combustion chamber surface; other amounts emit out of the cylinder into the exhaust system and accumulate on the exhaust pipe and sample tube. For this reason, the amount of deposits increases on both the sample plug and sample tube (Fig. 3b, c). Combustion deposits foul spark plugs and result in rough engine operations. Therefore, it is detrimental to engine durability. Hence, the concept of sustainable design needs to be considered together with the investigation of deposit formation.

4 Quantitative Thermogravity Analysis

Thermal analysis is widely used to determine fractional components of deposits. Among assorted approaches of thermal analysis, such as TGA (thermogravity analysis), DMA (dynamic thermal analysis), DSC (differential scanning calorimetry), etc., TGA instrumentation has a much broader application base. As an example, the superiority of TGA to DSC is that thermal properties and mass changes can be qualitatively measured when being heated. In general, combustion deposits consist of organic and inorganic substances and the rates of organic and inorganic substance formation can be determined by calculating the change in mass when shifting atmospheric gases.

Using a dual-gas method during the heating process, tests are conducted first for an inert atmosphere where nitrogen is used instead of argon whose flow rate is set to be $40\,\mathrm{ml}\cdot\mathrm{min}^{-1}$ while the HC substance evaporates during this heating process until any solid content virtually disappears when the temperature reaches 450 °C. Under this inert environment, the amount of water vapor and volatile fuel can be neglected. To determine concentrations of the volatile substance, soot and ash among the deposits, the inert atmosphere is switched to an oxygen atmosphere by providing inflow air at the same rate while increasing the temperature. Organic substances are oxidized rapidly, while residues are merely metallic salts. The sample mass of TGA is recorded as the temperature increases at a fixed rate of $40\,^{\circ}\mathrm{C}\cdot\mathrm{min}^{-1}$. As the deposit mass decreases, the volatilization of compounds takes place and different thermal events can be distinguished from mass loss versus temperature curves as well as by spectral analysis and theoretical analysis. For a low-speed and light-load region, the lubricating oil plays a vital role on combustion deposits. The overlap between the deposit thermogravity curve and oil thermogravity curve for a temperature range below 400 °C is obtained (Fig. 4a, b). Over the range of 400–600 °C, the thermogravity curve tends to be horizontal and away from the oil thermogravity curve, which reaches an equilibrium level. Above 600 °C, nitrogen is switched to air, and the two curves vary significantly. Here, the thermogravity curve attains another equilibrium level, where residuals are metallic salts, oil additives, and ashes.

Low-speed and light-load operation corresponds to the low engine power output, where the oil content has a dominant effect on combustion deposit formulation. It has been indicated by coincidence of oil and deposit thermogravity curves at low temperatures. Now the engine power increases when the testing conditions are shifted to a low-speed and heavy-load condition or a high-speed and heavy-load condition at an A/F ratio near stoichiometry. The temperature in the combustion chamber increases such that volatile components can have further reactions inside the cylinder (Fig. 4c, d). At the same time, the carbonizing effect is significant. Thus the percentage of involatile substances (e.g., carbon, metallic salts) increases while that of volatile substances drops considerably. As a result, the residues primarily originate from oil and fuel additives.



Sample Tube Deposit Thermogravity Analysis (Low Speed-Light Load-A/F-13.2)

Lubricating Oil Thermogravity Analysis

Sample Tube Deposit Thermogravity Analysis (Low Speed-Light Load-A/F-13.2)

Deposit Thermogravity Analysis (High Speed-Heavy Load-A/F-16.7)

Fig. 4 Curves of thermogravity analysis

5 Impact of Deposits on Engine Performance

An investigation of engine deposit formation mechanisms on the combustion chamber and exhaust pipe under different engine operating conditions has been conducted. The results indicate some general consequences due to deposit accumulation. Considering various factors related to deposit formation, the temperature effect is the most significant. Both the combustion flame temperature and cylinder surface temperature are major factors to in-cylinder deposit formation. Also the exhaust temperature is a major factor to the tailpipe deposit formation. The intake air temperature has minor effects. The A/F ratio is another major factor to deposit formation. The combustion chamber deposits come from the fuel, lubricating oil, and additives, where the fuel and a small portion of the lubricating oil and additives act as reactants of combustion. A rich fuel-air mixture provides favorable conditions to accelerate deposit formation. On the other hand, a high fraction of deposit inorganic materials and the presence of ash residues imply that the lubricating oil is, in fact, a primary contributor to all combustion deposits.

A combustion deposit is associated with thermal insulation and heat release. These factors induce overheating on the cylinder wall and exhaust tailpipe: the combustion deposit layers influence the conduction rate which restricts the capability of heat release; the reduced volume inhibits the capability of convection which also hampers effective emissions, and the combustion deposit itself functions as a blackbody whose radiation rate is strongly dependent on the temperature according to Planck's radiation law, producing additional thermal insulation against outward heat release. Due to the combustion deposit, the engine compression ratio increases from 6.36 to 6.68 in the current study until the deposit accumulation reaches a steady state as does the cylinder wall temperature. Overheating degrades gasoline which, in turn, speeds up deposit formation. At high temperatures, a partial fuel-air mixture may lead to auto-ignition before the flame front reaches the mixture, causing engine knock. On the other hand, engine power performance changes slightly with the presence of the deposit. For the sake of its higher compression ratio, fuel economy shows little improvement which remains at a similar level. Compared with the drawback on emission levels and engine knock, its merit on fuel economy is trivial.

The deposit microstructure is porous such that the deposit pores activate fuel storage mechanisms. In most cases, exhaust emissions deteriorate from the effect of deposits by momentarily absorbing fuel and then releasing fuel. This reduces the efficiency of a three-way catalytic converter and increases the emission levels. In general, the effect of deposits under a low cylinder pressure condition is greater than that under a high-cylinder pressure condition. HC deposit formation is activated when the oxidized HC species formed in the premix flame region are adsorbed on a relatively cold surface. Porous deposit storage stimulates additional HC emission as the fuel absorption into deposits plays a critical role in HC formulation. Consequently, the rate of HC emissions increases along with the rate of combustion deposit formation. On the contrary, an increase of the cylinder wall temperature has a negative effect on HC formulation but a positive effect on NO_x formation. Due to thermal insulation, a long duration under overheating yields a suitable situation for NO_x formation. The NO_x emission level increases as the engine deposits accumulate. Unlike HC and NO_x, the CO emission rate varies only a little. It is because a fresh mixture is heated by engine deposits during intake and compression strokes. At the same time, the compression ratio increases with deposit formation. The CO concentration thus keeps at a constant level for a certain A/F ratio. From curves in the final stage of quantitative analysis, it is concluded that metallic salts act as the leading component. Some metallic salts serve as combustion catalysts as well (e.g., lead salt). Metallic detergent forms a larger amount of deposit than ash dispersants.

Emission levels deteriorate as a result of combustion deposits, and they have a negative influence on engine operations at cranking, warm-up, cold-start, idling, and steady-state operations. Sustainable technology thus can be introduced to suppress these adverse effects. The sustainability design is capable of minimizing environmental impact and delivering better performance at a fairly low cost. Sustainable methodology with optimization is a promising solution for both energy restoration and waste disposal which give rise to enhanced environmental preservation and efficient energy usage (Fig. 5).

6 Sustainability Study of Engine Deposits

Limited global resources demand sustainable energy usage for the automotive industry. Sustainability means satisfying the needs of the present without compromising the

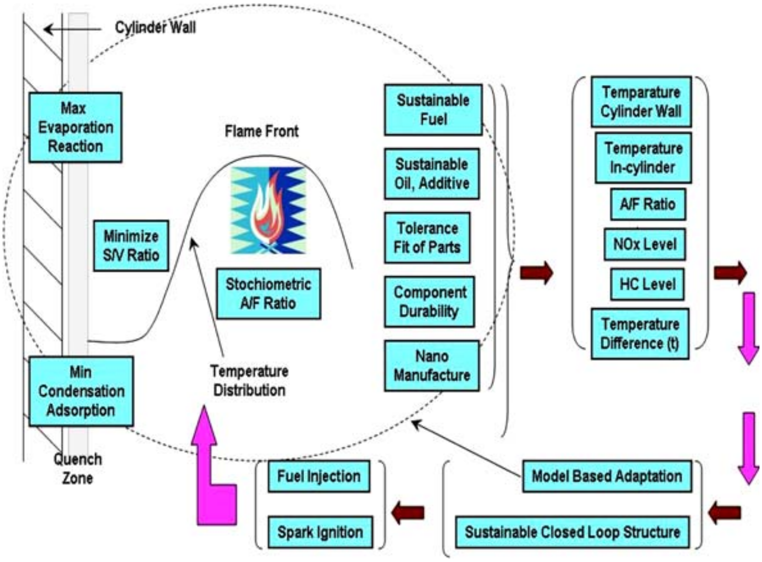


Fig. 5 Sustainability analysis and concept of feedback control

ability for future needs. Speaking of sustainability, there are diversified alternative energy resources that could provide sustainable outcomes, such as natural gas (e.g., methane), solar power, and hydrogen as well as hybrid fuel cells. For whole-scale technical applications, vehicles powered by an internal combustion engine are still unique and unbeatable. In order to reduce greenhouse and toxic gases so as to preserve the natural environment, sustainable feedback control is a shortcut method to preserve and restore the natural environment.

From a chemical point of view, the temperature inside the cylinder varies with the distance to the cylinder wall as the flame approaches. The temperature is highest where complete combustion proceeds. Inside the cylinder, halfway combustion products are formed from a partially burned fuel-air mixture. The flow and propagation of the fuel-air mixture convey some halfway products toward the cylinder wall, and then these species condense and evaporate to and from the surface of the engine deposits. Chemical reactions occur continuously inside the combustion deposits. Some condensed species become part of the deposit structure and the others are removed by evaporation, oxidation, and reaction processes, until this in-cylinder system reaches dynamic chemical equilibrium. Fuels with light-weight molecules are highly volatile which are susceptible to evaporation, and do not easily condense on surfaces. Thus, fuels with higher volatility should be considered.

From a mechanical point of view, the tolerance fit and durability of components must be improved to reduce the chance of introducing lubricating oil into the engine cylinder and to enhance the fuel injection efficiency. For instance, due to improper sealing of valves, flaking of deposits results in a low compression pressure. A small compression ratio is appropriate to minimize the temperature-induced problems and to decrease deposit formation. Fuel additives and catalysts can help to keep the engine internal surfaces clean so that the flow pattern of the mixture and the spray pattern will not be restricted. At the same time, pollutant levels (NO_x) will be reduced as a result of chemical reactions that limit possible rising temperatures, and the requirement of the ORI is also alleviated.

In order to minimize the deposit accumulation in general, there are three basic approaches. The first is to minimize the portion of partially burned mixtures and halfway products. The second is to minimize the surface-to-volume ratio so as to reduce the surface area subject to engine deposits. The third is to maximize the ratio of the deposit releasing rate (evaporation, reaction) to the condensing rate among the engine deposits (e.g., high volatility). If the rate of deposit being depleted is faster than that being created, deposits diminish gradually. For this objective, a model-based structure needs to be developed to handle the concern with sustainability. The in-cylinder temperature, A/F ratio, emission levels of NO_x and HC, etc., will be taken into account simultaneously. Complete combustion under stoichiometry without combustion deposits can be used as an ideal model. The goal is to minimize the amount of deposits to improve emissions, durability, engine performance, and fuel economy.

7 Conclusions

A single-cylinder spark ignition engine has been analyzed to study the formation mechanisms of combustion deposits on the combustion chamber and exhaust pipe. The accumulation of deposits is a complex procedure that involves multiple factors derived from the fuel, oil, and additives under various engine-operating conditions. This work focuses on investigating the impact of these factors on the early stages of deposit formation, where a sample plug and sample tube are used for deposit collection from a cylinder head and exhaust pipe, respectively. Typical engine operating parameters are selected to represent various working conditions for bench tests. Accordingly, a quantitative analysis is carried out to identify the effects of fuel and oil, as well as additives on deposit formation. In particular, a thermogravity analysis is employed so that mass changes of combustion deposits can be measured qualitatively when being heated. This dual-gas method has been shown to be effective in calculating the differences in deposit mass when changing atmospheric gas from nitrogen to oxygen during a heating process, by which the amount of organic and inorganic substances can be identified. Volatilization of deposits is justified by the fact of the mass loss process, which makes it easy to distinguish different thermal events via the actual two-dimensional curves about mass loss versus temperature. In addition, a theoretical analysis is performed to determine the impact of combustion deposits on emissions, fuel economy, and engine power. The sustainability issue is then discussed on both chemical and mechanical bases. A sustainable structure is proposed via feedback control for enhancing engine performance with the presence of combustion deposits.

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