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The engine deposits and its effect on heat transfer: A review

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Abstract: Deposit, which is found in the combustion chamber of the internal combustion engines after operating hundred hours, causes many various issues such as reduce in the engine power and performance, reduce in ability of heat transfer, reduce in conduction rate but increase in toxic emissions content. Beside, deposit also causes the jam between the motive mechanical parts in engine combustion chamber, even cause the abnormal combustion. The study of deposit formation and structure is necessary in order to find out the method aiming for overcoming the negative influence on the engines. The paper presents a review of deposit, the deposit formation and structure are mentioned by many researches and aggregated in this work. Findings of paper not only enrich the knowledge about the engine deposit but also are potential to carry out an experimental set up in order to estimate, calculate the ability of forming the deposit on a same condition as in the engine combustion chamber.

Keywords: deposit, internal combustion engine, deposit formation, deposit structure, heat transfer

1. Introduction

Deposit or carbon deposit is considered as heterogeneous mixture made from carbon residue (CR), soot and resinous material that attach together like the uniform mixtures [1]. It also includes many other materials or residue grown or built up on mechanical parts of the internal combustion engine (ICE) [2].

Deposits at the various mechanical parts of the ICE cause an important matter that effect on the ICE performance, fuel consumption, start at cold temperature of ICE, and exhaust gas emission. They are lower rate of fueling, restricting air in flow progress, increasing in the ratio of the compression, changing of the spray pattern, minifying of the thermal conductivity [3]. Furthermore, a problem correlated with the deposit in the ICE combustion chamber and effected dramatically on the exhaust valve and exhaust gas temperature has been reported by [4]. This causes the difficulties in start-up of ICE, especially in low or cold temperature, and increase in hydrocarbon or toxic emissions [5, 6], and lastly it will cause a loss of pressure compression in the ICE cylinder.

Some mechanical parts of ICE, in combustion chamber, such as the head of cylinder, piston, intake and exhaust valves, and fuel injector tip are one of the most common mechanical parts accumulated deposits regularly. The influence of deposit on the mechanical parts in engines is shown in Fig.1.

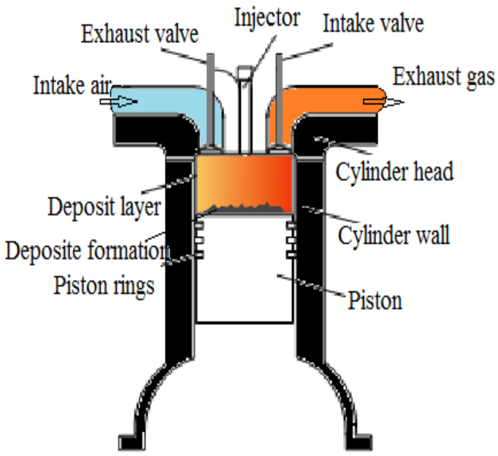

Fig.1. Deposits on engine mechanical parts

In term of engine impairment, it is seen that deposits fouls of engine mechanical parts especially they occur on piston head and cylinder surfaces [7, 8], which may cause sticking for the ring and certainly interfere with the normal operation of ICE [9]. Eilts [10] denoted that the formation of deposits in ICE leads to serious damage in direct injection diesel engine (DIDE) while DIDE is operated at low load and long time. Nowadays, due to advanced engine technology system such as for injection system, therefore deposit formation shows much complication. The different fuels will cause the difference in forming and structure of deposits.

2. Combustion chamber deposits overview

2.1 Structure of deposit

The deposit structure of ICE is depended on many parameters such as fuel characteristic, engine operating condition, and the attendance of fuel additives [13]. Physical features of deposits are considered as major causes that effect on heat transfer and HC emission resource.

Gurlap et al [2] studied the properties of the deposits coat that effects mainly on heat transfer and combustion progress. Moreover, the cavernous volumes in the deposit content shown the potential of convective and radiative heat transfer. The chemical structure of deposits is varied depending on the time and engine operating condition, therefore the thermal conductivity of deposit coat will also vary [12]. The cavernous structures of deposits work based on the mechanism of fuel storage and plays important part on formatting of HC content [3]. Furthermore, the masses and thickness of deposits are considered as well-correlating and well-relating well to HC emission and proposed in theoretical work by Eilts [10]. In the opinion of Zerda et al. [13], the microstructure of the deposit, itself, is able to directly relate to the intractability and removal from the ICE combustion chamber. A microstructure with more graphitic and condensed may be waterproof, difficult and impervious to oxidation and be burnt, and they cause the difficulty of removal from the ICE.

2.2 Properties of deposit

Internal structure of deposits in the ICE combustion chamber may be the primary factor in order to determine the thermal conductivity and diffusivity, heat capacity and leading to the reduce in thermal insulation of the metal walls and parts, the heat dissipation such as cylinder wall [13]. Jonkers et al. [12] has denoted that, the more expanded and evolved the deposit formation is, the more decreased the deposit conductivity is. This is probably explained that, due to the increase in concentration of aliphatic content and a reduction of polyaromatics in the nigritude of carbon. However, soot is considered as a structure of polyaromatic with high thermal conductive and cause the increase in thermal conductivity during the start-up of the ICE.

The aliphatic contents and components from the fuel has likely contributed dramatically to the deposit formation and reduction of thermal conductivity. Therefore, many researches show that, the deposits of higher viscosity, density fuel such as biodiesels, vegetable oils are higher than that of diesel fuel. Results gained from Guralp et al. [2] prove a strong correlation between the thickness, volumes and the thermal diffusivity of deposits in the ICE combustion chamber. It is clearly-known that, the thicker the deposite layers of material are, the lower the effective thermal diffusivity is. Besides, the deposit is forming continuously but its constantly changed morphology is also occurred depending on the rate of injected fuel mass and gas, engine operating conditions and temperature of combustion.

The porosity and uniformity degree, the types of HC molecules creating out different coats are continuously changing. Anderson and Prakash [14] proposed that, the material porosity is a substantial characteristic in order to control the heat transfer rates on the surface, thermal conduction is the major factor of heat transfer progress involved to deposits.

Tree et al [15] studied and proved that the cavernous characteristic of the deposits coat and layer in the combustion chamber strongly connects and interacts with the characteristic of fuel spray, especially in diesel engine, because the diesel engine is a direct injection engine. Besides, [2] shows an increase in the porous deposits in the duration of heat release. Woschni [16] denoted that, the capacity in thermal storage for the deposits layer on the wall cylinder in ICE will appear the burning flame, which is closer to the thermal boundary layer, hence the increase in the heat transfer to the wall cylinder.

2.3 Origin of deposits

Generally, the main factors contributing to form the deposits in ICE combustion chamber may be raised and derived from the characteristics of fuel, the lubricant oil or both. The fuel with high viscosity, low cetane number may cause the non-clean-combustion. Besides, the influence of fuel and lubricant oil on contributing the deposits in ICE combustion chamber also depends on many various factors such as the type of engine (high or low speed engine; gasoline or diesel engine) and the location of the mechanical parts in engine combustion chamber.

Lepperhoff et al. [11] proposed that, the formation of the deposit at the high temperature locations occurs primarily due to the residuals from incompleted evaporating or burning the fuel, specially from lubricating oil.

Different studies suggested different influence of fuel and lubricating oil on formatting the deposits. Some studies and researches has found that, lubricant oil is the main contributor of deposits in the ICE

combustion chamber [11, 17]. The appearance of the elements such as the ash, the inorganic materials, hydrocarbon content are the proofs, which prove the participation of lubricating oil.
Other studies [18,19] have found that fuel components are the primary component in combustion chamber deposits. The reason is able to explain that, the fuel containing high sulphur and aromatics promote CCD formation. However, some type of small diesel engines lubricated by the diesel fuel, thus the lubricating oil is not a resource supplying metal ions to form the deposits.

Leedham et al. [30] suggested that, the metal trace appearing on the surface may be implicated and related to the mechanism of the deposit formation in ICE. The experimental test on engine was carried out and shown that, the traditional fuels have not important levels of deposits. However, in the trace appearance of zinc may play a substantial level in forming the generated deposits. This is understood due to the lubricity additives play an important part in the zinc uptake into the fuels. However, the type of ester lubricity additives do not affect the zinc content in the fuel, on the contrary the acid content in the lubricity additives is implicated in the zinc uptake.

3. Deposit effect

3.1 The effect of CCD on combustion

As studied in previous researches, deposits have a significant effect on combustion in the chamber. Because of the thermal effect of CCD on combustion, an additional physical influence as well due to absorption of fuel or gases may occur, etc. This is especially true in diesel engines where there is a potential for fuel spray plumes to impact deposits on the piston and walls. Additionally, just the long-term accumulation of deposits in the engine is enough to have a significant effect on compression ratio, regardless of combustion type.

It has been clearly recognized that the CCD forming on the piston tops and the cylinder heads could unfavorably effect on the engine operation. The CCDs affect ignition because of the alterations in heat transfer during the stroke of the air intake or the air compression in the engines, but also create an extra effect on burning because of an altered conditions of near-wall boundary [2].

Mixture of gas and fuel is heated by the engine deposits during the stroke of the air intake or the air compression [3]. Ishii et al. [20] have made many efforts to better understand heat transfer mechanisms in ICE so it is natural for them to perform a study on deposits. They confirmed that, through the using of fast response combustion chamber surface heat fluctuation probes that peak temperature levels to the metal below a decreases in the layer of deposit material. Thus there is a gradual decrease in the cycle average temperature with the formation of CCD. Additionally, peak heat flux levels also decrease with deposit layers but the cycle net heat transfer out of the chamber does not change much for the cycle. Woschni [21] also shows a trend countering the expected for a diesel engine. Woschni suggested that, the capacity of the thermal storage of soot and deposit on the wall in the chamber combustion causes the increase in heat transfer to the wall, though this finding still remains controversial.

La Vigne et al. [22] shows that, it is simplified to consider CCD as a homogenous layer of insulating quality. La Vigne et al. considered the effective porosity of the material as a principal characteristic, which controls the heat transfer rates on the surface, the indeed transmission is the major mode of heat transfer related to deposits.

Tree, Wiczynski, and Yonushonis [23] augmented the reasoning line by claiming that the porous characteristics of the CCD layer actually interacted with the characteristic of the fuel spray in a diesel engine. This was causing the duration of release in heat to increase and indicated specific fuel consumption (ISFC) suffered as a result. Additionally, they pointed out that surface roughness inherent in the material affected local air flow and mixing. They then tested these hypotheses by studying the changes in combustion with pistons coated with various materials like zirconia, which is a ceramic with similar thermal properties of deposit material [24]. By varying other physical properties such as surface roughness and porosity, they showed that a change in heat transfer was not the only factor influencing combustion.

3.2. The effect of CCD on heat transfer

Regardless of the different forms of influence that combustion chamber deposits have on engine operation, its thermal effect is most dominant. In order to ultimately quantify and assess the impact of CCD on engine parameters, there must be a thorough understanding of the heat transfer processes involved, and in accordance a significant effort has been put forth by the fuel and engine community to accomplish this, at least in the context of conventional engines.

3.2.1 Thermal and physical properties of CCD

The specific properties of deposit material in the chamber are important for their effects on in-cylinder processes. Whether they are thermal or some other physical properties, it is worthwhile trying to experimentally determine the CCD properties as a function of different operating modes and conditions. There have been a number of attempts in conventional engines, as documented below, but none have so far been performed in a marine diesel engine.

Probably the most popular method for trying to determine the thermal properties of deposits is through the using of chamber surface thermocouples. Overbye et al. [25] performed one of the first in-depth studies regarding experimental in-cylinder crank angle resolved surface temperature measurements in a spark ignited engine. The work was split among general in-cylinder heat transfer and heat transfer affected by combustion chamber deposits, with the latter subject matter providing the most useful insight. They tracked parameters such as cycle temperature swing, temperature gradients, and cycle averaged temperature trends, with different degrees of CCD formation. They also devised methods for estimating the thermal properties of CCD as well as the effective surface temperature of the deposit layer itself, though many approximations were required.

Anderson [26] focused on radiometric measurements to determine the thermal conductivity and diffusivity of CCD. He used a two strokes SI engine with optical access and surface mounted fast response thermocouples to measure the steady heat flux through the deposit layer and determine a conductivity range. The ignition was cut and the temperature decay at the surface of the deposit layer was tracked in order to determine the effective thermal diffusivity. These values were then related to the cycle temperature swing and deposit layer thickness at the sampled chamber location. In addition to temperature measurements.

Nishiwaki and Hafnan [27] also used infrared radiometry on investigate with deposit growth after removing from the engine. Not only did they calculate values of the same relevant properties, but also tracked the changes of the properties considered as a function of different operating conditions, such as equality ratio, engine load, engine speed, and fuel oil content.

Anderson et al. [28] used the method of the measurements of below temperature and on the deposit layer surface in order to indirectly determine the quantitative values of thermal conductivity, thermal diffusivity, and heat capacity. They found that, the deposits change not only the properties such as the thickness, but also it occurs with a non-linear manner, therefore their effect on the unsteady heat transfer progress is quite dramatically. Furthermore, the porous volumes found in the studied material has shown the heat transfer in the intra-material through the convection and the radiation, which is different for understanding fully the mechanisms of the heat transfer.

Hopwood et al. [29] invented one of the most practical methods in order to estimate the thermal properties of the deposits in the chamber. Similar to others, they used the instant measurements for the surface temperature in chamber. They tracked the changes of the signal phasing such as the formation of the deposits material on the surface. Therefore, the effective thermal diffusivity is calculated by combining this with the measurements of the deposits material thickness. In the fact that, this procedure is very practical for the experimental setup and will be discussed in more detail later.

3.2.2 Deposits effect on heat transfer

The condition of the surface on the combustion chamber wall is considered an important factor for controlling the rate of deposit formation. Unburned fuels adhering on the surface of the wall in the ICE combustion chamber play an important part in forming of the deposits on the heating surface.

The deposit layers will act as a thermal insulator, which affects the ability of the heat release in the combustion chamber. Yamada, et. al. and Ishii, et. al. [20] shown that, the amount of deposit adhering on a wall surface is a factor to alter the instantaneous temperature at the surface. Low thermal conductivity of deposits is certain in reducing the conduction rate reduction and retarding the heat release capability from the combustion chamber. Because of the thermal isolation characteristic of the deposit, the temperature of deposits (TDe) on the surface wall is higher than that of the non-deposit-wall (Tw) and shown in Figure 2.

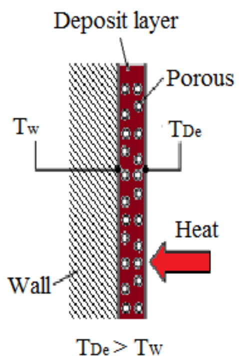

Fig.2. Model of heat transfer

The heat release content and the difference between TDe and Tw rely on the thermal properties of the deposits. The porous structure and non-volatile matter such as ash are the main factor leading to the low thermal conductivity of the deposit adhering on the surface of the wall in the ICE combustion chamber [16].

The more increasing the temperature on the surface of the deposits is, the more reducing the gradient temperature in the gas is. Therefore, an overheating cylinder wall occurs in the ICE combustion chamber, which can cause the knock of the engine and the degradation of fuel. And the ever-increasing fuel degradation cause more deposits, increase in combustion flame and exhaust gas temperature as mentioned by Ye, et. al. [3]. As shown in Figure 3, it was demonstrated how crank-angle resolved temperature and heat flux measurements from the head and piston surfaces can be used to gain insight into combustion chamber deposit formation.

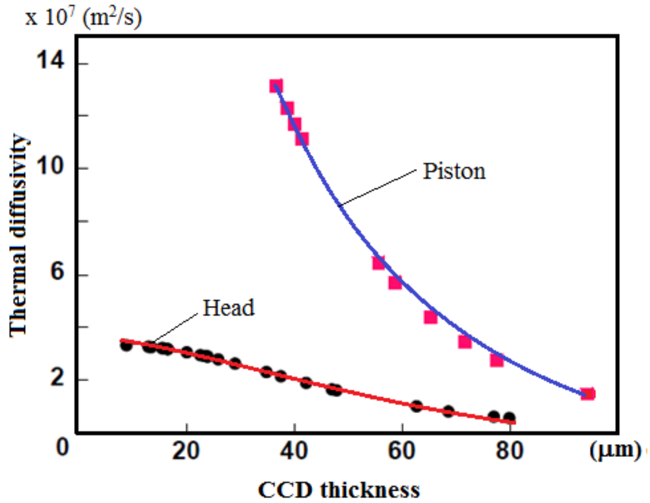

Fig.3. Relationship between thermal diffusivity and thickness of deposit layer on head and piston

The general characteristics of the change in temperature profiles as a function of deposit layer thickness were shown, as well as a method for estimating the thickness of local deposit layers in-situ. The most important outcome is that CCD in either case produces a significant effect on small marine diesel engine's combustion and that surface temperature measurements can provide insight about the nature of this effect. The fact that these materials are likely different is not really important. The goal is to understand the effects on wall heat transfer that any given material could have and what is the mechanism of its effect on combustion of small marine diesel engine.

Heat loss during compression was reduced with a deposit layer present. This resulted in higher layer surface temperature swings and an advance in combustion ignition timing and phasing. It was shown that heat stored up in the deposit layer leading up to combustion did eventually diffuse out of the chamber later in the expansion stroke. The effects of deposit coverage on bulk burning and hydrocarbon emissions can be attributed to this.

4. Conclusions

The effect of CCD on heat transfer in small marine diesel engine is much significant: A decrease in heat loss during compression results in advanced ignition timing and overall combustion phasing. Heat stored in the deposit layer leading up to ignition causes the periphery of the air/fuel charge to burn faster in the last half of the heat release event, also causing a reduction in unburned hydrocarbon emissions.

Combustion chamber deposits only have a transient effect on heat loss from the combustion chamber of small marine diesel engine. The insulating properties of CCD are offset by higher combustion rates associated with advanced phasing. Cycle net heat loss does not change with a conditioned combustion chamber so the only increase in thermal efficiency is due to the advanced phasing of combustion. In next research, the influence of other alternative fuels to the hardness, the strength of steel and alloys will be carried out.

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