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RESEARCH ARTICLE

## ANALYZING THE EFFECT OF HEATED WALL SURFACE TEMPERATURES COMBUSTION CHAMBER DEPOSIT FORMATION

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### ARTICLE DETAILS

### ABSTRACT

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One of the most important studies on using diesel fuel is the basic study of combustion chamber deposits in engines. These studies were conducted to investigate the effects of deposits on the engine and how deposits are formed in engines. Deposits in the combustion chamber are proven to be formed through three different stages: (1) the condensation of components in incomplete combustion process on the combustion chamber walls; (2) the interaction of unburned fuel droplets; (3) fuel flow (intake valve and nozzle). This paper aim is establishing a correlation between deposits formation on the wall surface when fuel droplets interact with heated wall surfaces and surface temperatures. The changes of heated surface temperature impacted on the interaction of fuel elements with the surface, the evaporation and the dryness or wetness of fuel. In addition, in this study, zones of temperature with greater or lesser deposition formation were also identified. This helps to clarify the complex fluctuations in the deposits combustion chamber in real diesel engines.

#### KEYWORDS

Emissions deposits combustion chamber, deposits formation, deposits development, heated wall

### 1. INTRODUCTION

'Deposits' can include various materials and residues which are gradually grown or accumulated on critical parts of an internal combustion engine such as in a combustion chamber, piston top, an intake and exhaust valves [1]. The thickness of the deposits on engine in-cylinder wall surfaces is closely related to the wall surface temperature and also fuel impingement area [2,3]. The combination of low wall temperature and unburned fuel causes greater deposit formation in the combustion chamber.

The combustion chamber deposit (CCD) formation in diesel engines is a complex phenomenon that causes various problems for the engine, such as reduced efficiency, increased emissions, and possible damage to diesel engines [1,4-6]. There are many causes of deposits in combustion chamber of diesel engines, mainly due to incomplete combustion of diesel fuel, and some studies indicate that lubricants are the main cause of combustion chamber deposits [2,3]. The presence of lubricant components and factors such as ash residues, inorganic residues and hydrocarbons with high boiling points found in studies have demonstrated the contribution of lubricating oils in the deposit formation [7-9]. Therefore, research on the mechanism for the formation and development of deposits in the combustion chamber of diesel engines using conventional diesel fuel or biodiesel is essential, due to it helps to find appropriate measures to prevent the formation of deposits, to ensure the use of long-term engine [10,11].

Some studies on diesel engines are conducted to understand the effects of deposits on engines and how it is formed. Most of the current research on deposits is done using statistical data from surveys and tests on real

engines [11,12]. Testing on real engines can be done in two ways: engine bench tests and vehicle tests [4,13,14]. Either way requires a long time and long distances lead to very high test costs and often damage the engine during deposits surveys. Therefore, it is difficult to observe the formation mechanism of deposits and also its development in a real engine. Researching and finding a simpler, cost-effective experimental model that meets the requirements of the surveys, evaluates the influence factors and tests for deposits formation, it is necessary [12,15]. Thus, to avoid the complexity of a deposition test in an engine, we proposed a new, simplified research method called a heated surface deposition test [7,9,16]. It was considered a substitute procedure to investigate fuel deposits in an engine. The tendencies of fuel spray impingement with a heated wall surface increase due to following reasons: (1) higher injection pressure that increased spray penetration and also as design consideration to promote spray atomization, (2) engine operation with longer ignition delay compare to the injection period, (3) engines that have short distance between the injection nozzle and the piston head such as for small and high-speed engine and (4) unburned fuel droplets resulted from incomplete combustion [17,18]. Hence, the understanding of continuous droplet deposition on the heated surface is significant to conclude the whole process of deposits formation.

The formation and development of deposits on the heated surface wall depends on the distance between fuel drops and surface wall, surface temperature, type of fuel, the initial stage of the deposition, overlapping conditions and other competitive phenomena during formation process of deposits, such as cooling effect, heat transfer effect and chemical reaction effect. These factors determine the existence of the fuel liquid film and the

amount of accumulated deposits. Different heated surface temperatures change the interaction of surface molecules, evaporation, and dry or wet conditions [19,20]. Changes in the surface temperature of the heated wall surface could be a major contributor to the deposits formed on a heated wall in a combustion chamber of diesel engine [21-23]. Therefore, the study of the effects of surface temperature on the formation and development of combustion chamber deposits through experimental modeling to determine a level of deposits formed on the heated wall surface is necessary.

This research focuses on the mechanism of deposits formation and development in a combustion chamber of diesel engines through

deposition experiments on a heated wall model designed to assess the effect of surface temperature on accumulation of deposits on the wall surface and a mathematical model to predict the trend of deposits formation and development over time.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The model is illustrated in Figure 1, which will carry out three experiments: droplet experiments, evaporative tests and deposition experiments on a heated surface.



Figure 1: Test diagram about deposits formation on the heated wall surface

A heated plate is made by aluminum alloy (AC9A). This plate is electrically heated and its surface temperature is controlled by a temperature controller. The surface temperature is measured by a thermocouple, which is mounted at the center and below the plate. However, the thermometer temperature cannot accurately reflect the surface temperature due to heat loss from its surface. So, an additional infrared thermometer is used to measure the surface temperature more accurately. The fuel injection nozzle is placed about 80 mm from the plate surface to avoid fuel heating prior to the experiment and to minimize errors due to a large drop in droplets during the interaction. The duration of the

interaction ( $\tau_{imp}$ ) is controlled by adjusting the throttle valve. The number of droplets ( $N_D$ ) is calculated using an infrared laser detector and counting device.

For the single droplet repetition apparatus, two types of tests were involved: (1) evaporation test and (2) heated surface deposition test. Both tests used the same diesel as a test fuel. Diesel fuels tested were Vietnam standard (DO): QCVN 1:2015/BKHCN. The compositions and properties of test fuels are mentioned in Table 1.

Table 1: Fuel properties

Properties	Unit	ASTM standard	Result
Density @ 15°C	g/cm <sup>3</sup>	D1298	0.850
Distillation T90	°C	D86	320
Kinematic viscosity	mm <sup>2</sup> /s	D445	3.2
Surface tension	mN/m	D971	25.8
Flash point	°C	D 93	71
Final boiling point	°C	D7500	350
Cetane number		D 976	45
Higher heating value	MJ/kg	D 240	46
Carbon residue (10% distillation)	%mass	D524-15	0.2
Carbon mass percentage	%	ASTM E777 - 17a	83.5 - 87
Hydrogen mass percentage	%	ASTM E777 - 17a	11.5 - 14

## 2.2 Methods

### 2.2.1 Evaporation test

The number of fuel droplets to be considered in this test is 100 drops for each fuel. The mass of each fuel droplet ( $m_D$ ) and its diameter ( $D_d$ ) is calculated and estimated relative to the specific mass of each fuel ( $\rho$ ).

The temperature range of the evaporation test depends on the type of fuel being tested and the heat capacity of the heater on the wall surface. The maximum temperature of the equipment during the test is approximately 125°C to 410°C. Maximum temperature fluctuation at one point is 5°C due to the impact of fuel droplets and the latency of the heater. For each level of heat, at least three tests conducted to ensure the reliability of the data. In order to understand the vaporization behavior of the droplets on the surface of the wall, the interaction between the droplets on the surface was observed and recorded by the camera.

### 2.2.2 Test for the deposits formation on heated surface

Droplets flow from the tank and continuous interaction with the wall during different interaction periods. For every 1000 drops, the mass of deposits is measured and the deposits image is taken. The presence of deposits on the wall surface and heat on the wall surface may affect the results of the data that obtained at subsequent tests so the wall surface should be cooled and cleaned before proceeding next experiment. The total number of fuel droplets in each deposition test is 19000 drops for each fuel.

Data for the maximum and minimum surface temperatures of deposits ( $t_d$ ) during the interaction were collected by using an infrared thermometer (Beta 1760/IR1600 with the emissivity of 0.90) to control the effect of heat change during deposition. While the surface temperature of the metal wall relative to the indication temperature ( $T_i$ ) is obtained by thermocouple and surface temperature ( $T_s$ ) measured through an infrared thermometer. The correlation between  $t_i$  and  $t_s$  is the basis for determining the

temperature of the wall surface. The test conditions for the deposits formation on heated surfaces are shown in Table 2. In this test, the heated surface temperature was set at 270°C to 367°C. This temperature is within the surface temperature of the combustion chamber wall.

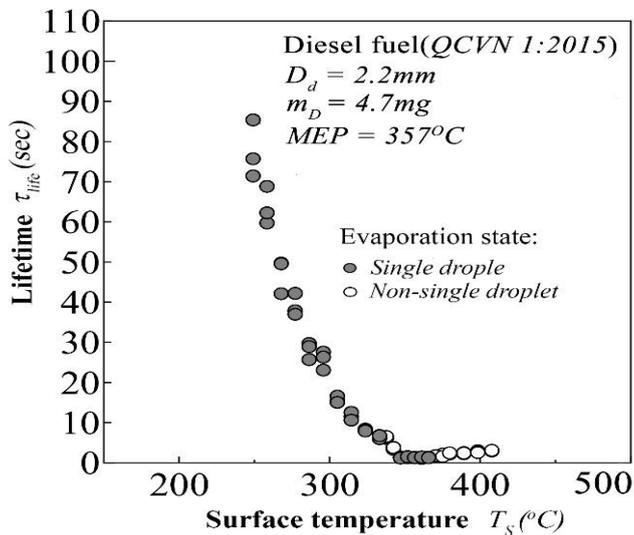
**Table 2:** Test conditions in heated surface deposits test

Name of test	Fuel	Interaction time $\tau_{imp}$ (s)	Surface temperature $T_s$ (°C)
Effect of surface temperature on the deposits formation on heated wall	DO	5	270; 306; 327; 352; 367

### 3. RESULTS

#### 3.1 Evaporation characteristics of fuels

The evaporation characteristics of diesel fuel are shown in Figure 2. The MEP (maximum evaporation point) temperature is  $T_s = 357^\circ\text{C}$  and higher than the final boiling point of diesel fuel.



**Figure 2:** Evaporation characteristic of diesel fuel

The Leidenfrost points for the diesel fuel cannot be determined because of the multiple component fuel having a higher boiling point, this is far to the right of the graph. Expanded MEP temperature have short droplet's lifetime. Experimental results show that the thin deposits layer on the wall surface is formed by different fuel compositions at the final stage of evaporation.

Wet or dry surface conditions are related to the physical interaction of fuel droplets with the wall surface. The evaporation characteristics of the fuel are an important basis for determining deposition conditions on the model of a combustion chamber wall surface.

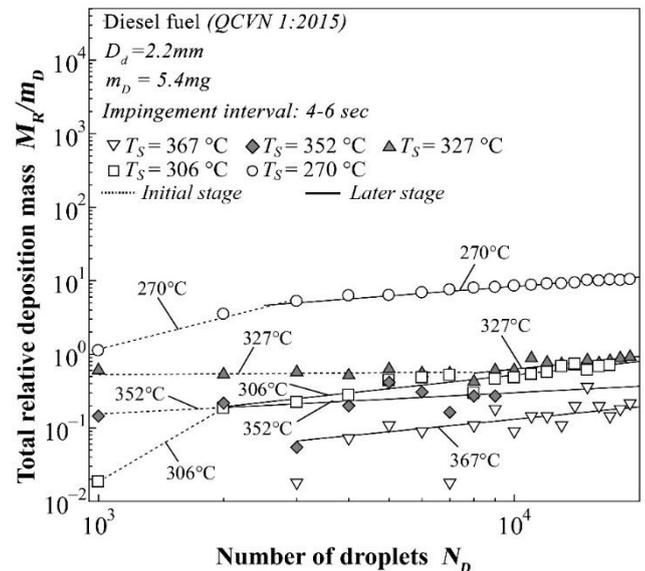
Due to the multi-component fuel used in this study, the secondary cooling temperature was calculated by equation (1) [15]:

$$\Delta T_{sub} = T_s - T_{MEP} \quad (1)$$

The secondary cooling temperature relates to the temperature difference between the test surface temperature and the MEP temperature.

#### 3.2 The deposits formation and development on heated wall surface

##### 3.2.1 Mass of accumulated deposits



**Figure 3:** Accumulated deposits in heated wall surface test

Figure 3, when the droplet is less than 1000 drops, has no basis to conclude at higher surface temperatures that less deposits formation occurs. In addition, when droplets are less than 3000 drops, data on the deposits generated at 367°C are not obtained. As the frequency increases, higher surface temperatures tend to produce less deposits than the low temperature surface. At 19000 drops,  $T_s = 270^\circ\text{C}$ , the accumulation of deposits is  $M_R = 54.8\text{mg}$ , 45 times higher than the accumulation at  $T_s = 367^\circ\text{C}$  with  $M_R = 1.2\text{mg}$ . At 9000 drops,  $T_s = 327^\circ\text{C}$  (30°C lower than MEP),  $M_R = 3.3\text{mg}$ . When  $T_s = 352^\circ\text{C}$  (5°C lower than MEP),  $M_R = 1.5\text{mg}$ , down 55%. When  $T_s = 367^\circ\text{C}$  (higher than MEP 10°C)  $M_R = 1.0\text{mg}$ , 70% less than 327°C. Initially, when the number of droplets was less than 1000 drops, the amount of deposits accumulated less than the deposits would form at 327°C and 352°C. Then, with the number of droplets greater than 1000 drops, the surface temperature at 270°C for the largest and followed by deposits at 327°C, 352°C, 367°C and 306°C, respectively.

Generally, during non-overlapping state, the surface temperature of deposits was maintained almost constant due to less amount of deposit accumulated. Thus, no changes were occurred in droplet evaporation rate and in deposit formation rate even if the droplet impingements were continued. Maximum amount of deposit after evaporation of each droplet depends on surface temperature and deposit formation increment was low. During a dry up period after the evaporation of every impingement, part of carbonaceous deposits was reduced due to oxidation. Longer non-overlapping period causes more amount of deposits reduction.

Amount of deposit accumulated increases with the repetition of impingement. It depends on the overlapping period between two continuous droplet impingements. For each new droplet impingement, amount of volatile and non-volatile fuel components that remains on the heated surface are increasing due to incomplete evaporation and deposit formation processes of the previous fuel droplet. Thus, greater amount of deposits is accumulated. The surface temperature of deposits reduces below the heated surface temperature due to a low thermal conductivity of deposits. Thus, deposit formation rate at the later stage of repetition is somewhat reduced through large amount of deposits is accumulated.

##### 3.2.2 Development of deposits

Figures 3 and Figure 4 show that there are two types of deposits development: the two-stage form and the one-stage form. When the surface temperature is about 270°C, 306°C and 327°C, respectively (lower than the MEP temperature), the deposits development consists of two stages, the initial stage (dotted line) and the later stage (continuous line). However, when surface temperature is under 352°C and 367°C (very close to the MEP temperature), the deposits development is only in a single stage [24].

At surface temperatures of 352°C and 367°C, the one-stage form of deposition development is absolute dominance. Elements such as secondary temperatures are small, the short existence of fuel droplets (about one second) and non-overlapping conditions ( $\tau_{\text{life}} < \tau_{\text{imp}}$ ) are achieved. At the initial stage, it causes the entire non-volatile constituents remaining on the surface to transform completely dry deposits.

Figure 3 shows that although the accumulated deposits at 270°C is the highest, the growth rate of the deposits at the later stage is lower than the temperature of 306°C. Thus, at a lower temperature (270°C), the slow formation rate of deposit prefixes, although deposits formation is higher because of non-volatile fuel at the initial stage.

A cooling effect by liquid fuel was dominant at the beginning of deposition. It reduced the surface temperature of deposits. Chemical reactions such as polymerization and oxidation took place after the repetition number increased. Due to oxidation, heat was released and the surface temperature of deposit increased. After more deposits accumulated, the surface temperature of deposits was slightly decreasing due to the effect of low thermal conductivity of deposits. It was clearly observed at the later stage of 270 °C.

The surface temperatures that far lower than the MEP temperature, the maximum deposit surface temperature decreases at the later stage of deposition. However, for the surface temperature that closes to the MEP temperature, the maximum deposit surface temperature increases due to the exothermic process during the repetition.

As for the surface temperatures of 270 and 306°C, their droplet lifetimes were far longer than the impingement interval. Due to this long droplet lifetime, some of the liquid fuel of previous impingement droplet was remained at the time of next impingement. Then, overlapping impingement condition maintained throughout the repetition. However, when the surface temperature was changed to 327°C, droplet lifetime was close to the impingement interval. Due to the maximum deposit surface temperature being exceeded the heated surface temperature, the droplet lifetime was sometimes reduced from the original and became shorter than the impingement interval. At the later stage (drop number greater than 10000) when the thickness of the deposit layer increased, the droplet lifetime also increased and overlapping condition resulted.

As for deposit developments at surface temperatures of 352 and 367°C, the surface temperatures of deposits tended to be maintained close to the heated surface temperatures. Thus, the estimated lifetime of the droplet was always less than the impingement interval and non-overlapping condition was completely maintained.

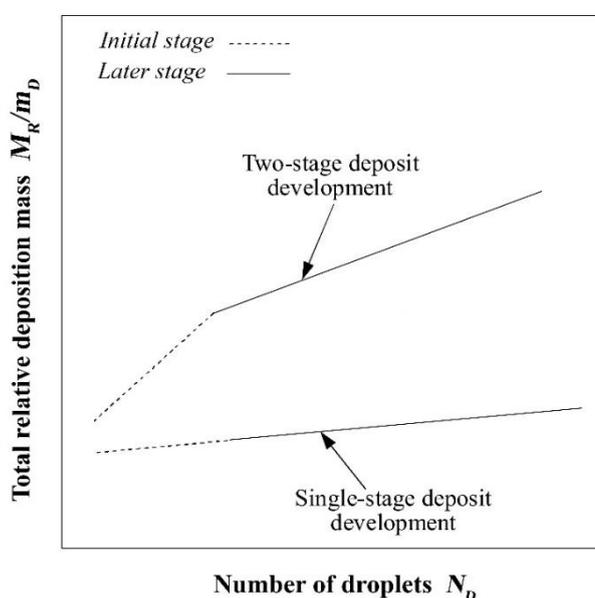


Figure 4: Types of deposits development

### 3.2.3 Regression of deposits accumulation and development

Data analysis and experimental planning by linear regression showed that the total relative deposition mass ( $M_R/m_D$ ) increased linearly with the logarithm of the number of droplets. To describe the development of deposits on the surface of the heated wall, the appropriate regression model was selected similarly to formula (2).

$$\frac{M_R}{m_D} = aN^b \quad (2)$$

$M_R$ : total mass of deposits on the heated wall surface [g];

$m_D$  = mass of a single fuel drop [g];

$N_D$  = number of interactive drops;

$a$  = coefficient of initial deposition formation [-];

$b$  = coefficient of deposition development [-].

The values of  $a$  and  $b$  for each stage of deposits development are shown in Table 3. The values of  $a$  and  $b$  in the gray area of the table show that the deposits formed in the non-overlapping and dry deposition condition, with a low value of  $b$  ( $b < 0.60$ ), indicates slow growth of the deposits [25]. The non-overlapping condition means that the droplet's lifetime is shorter than the interactive time, while the dry deposition condition means that the non-volatile fuel can be completely transformed into dry deposits.

Table 3. The coefficients  $a$  and  $b$  for different wall surface temperatures

Surface temperature $T_s$ (°C)	$a_1$	$b_1$	$a_2$	$b_2$
270	$6.10^{-5}$	1.43	0.17	0.42
306	$2.10^{-12}$	3.32	0.0018	0.62
327	0.41	0.04	0.0032	0.57
352	0.021	0.29	0.021	0.29
367	-	-	0.00075	0.56

Experimental planning results show that deposits formation is strongly correlated with the coefficient of deposition development, where  $b < 0.7$  is the slow rate of deposits formation, whereas rapid deposits formation when  $b \geq 0.7$ . At 270°C and 306°C, the value of  $a$  at the initial stage is very small. In fact, the amount of deposits at the beginning depends on the interaction of the droplet with the surface. At the same surface temperature, any location that has a large contact area between the fuel droplets and the surface will have a large amount of deposits [26-28]. The interaction of fuel droplets and the formation rate of the deposition prefixes are the main factors that make the very small coefficient of initial deposition formation at an early stage. Besides, low temperatures cause much of the fuel to be deposited, resulting in a higher rate of  $b$  at higher initial stages.

## 4 CONCLUSION

From the experimental results above, some conclusions can be drawn as follows: The temperature of the heated wall surface in the experimental model has a great influence on the interaction of the fuel droplet and the wall surface, evaporation time, wet/dry deposition conditions and the ability of liquid formation. These effects change the rate of deposits formation and development on the heated wall surface. Experimental results show that the mass of deposits is larger when the surface temperature of the heated wall is lower. At 270°C, the accumulated deposits mass is the largest, while at 367°C, the deposits mass is the smallest. Thermal analysis of the heated wall surface shows two types of deposits development: if the surface temperature of the wall is lower than the MEP temperature, the deposition development in two stages, whereas if the temperature is higher than the MEP temperature, the deposition development process is only one stage. The tendency for deposits formation on heated wall surface can decrease as the surface temperature is near the MEP temperature. The heated surface temperatures that located near MEP temperature have the potential to reduce the deposit formation on the heated surface. Lesser non-volatile fuel remains, the existence of non-overlapping and dry deposit condition,

higher deposit surface temperature and higher oxidation rate of carbonaceous deposit were the factors that contributed to the deposit formation reduction within this temperature regime.

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