COMBUSTION GRAPHOLOGY USED TO IMPROVE EMULSIONS OF WATER IN HEAVY FUEL OIL

Corneliu MOROIANU¹, Gheorghe POPESCU²,
Gheorghe SAMOILESCU³, Victor GHA

¹NAVAL ACADEMY OF CONSTANTA, ²POLITEHNICA UNIVERSITY OF BUCHAREST

Abstract. The vaporization and combustion characteristics of a heavy oil-water emulsion droplet are investigated with a graphological method. The combustion graphology of fuel oils is defined as a new technical and scientific field which deals with the graphic transposition of the processes of fuels combustion development in a simulator. Thus, it is easy to establish the ignition-combustion characteristics, including the laws that govern their changes depending on the combustion conditions and fuel specifications.

Keywords: oil-water emulsion, vaporization, graphological method.

1. INTRODUCTION

In the actual process of development of technologies for obtaining liquid fuels we can mark out two main classes: the class of liquid fuels with cenosphere and the class of liquid fuels without cenosphere. In the former class, the so-called intermediate and heavy fuels which resulted from the mixture in different proportions between the residues obtained from the oil processing (air distillation, vacuum distillation, analytic cracking, thermal cracking, etc.) and light products. According to the combustion particularities, they have a similar behavior, both of them belonging to the class of fuels with cenosphere. In the latter class, they are included Diesel oil, lamp oil, methanol, etc. The reduction of distillates in the mixture makes worse their quality by appearing in their composition a high content of Conradson coke and asphaltenes, by increasing the viscosity, the content of ash, sulphur and suspended mechanical particles.

Oxides of nitrogen (NOₓ) emissions from ship engines and boilers are significant on a global level. NOₓ emissions participate in the formation of photochemical smog and acid rain. Marine sourced emissions have significant impact on air quality on land. The challenge is to control NOₓ emissions without increasing fuel consumption and smoke. The slow speed diesel engines and boilers tend to produce higher NOₓ emissions than the medium speed ones. The ship engines are very fuel efficient but have a relatively high output of NOₓ emissions. They use very poor quality fuel for economical reasons (heavy fuel oil). The introduction of water into the combustion chamber for engines and boilers ships reduces the combustion temperature due to the absorption of energy for evaporation and it increases the specific heat capacity of the cylinder gases. The water can be introduced in the charge air (humidification) by direct injection into the cylinder or by water/fuel emulsion. The water/fuel emulsion can reduce smoke while humidification can increase smoke. The water/fuel emulsions place the water more directly in the combustion area where it has the maximum effect on NOₓ generation.

2. THE THEORETICAL CRITERIA ON THE VAPORIZATION AND COMBUSTION RATES OF LIQUID FUEL DROPLET

The accurate combustion test for gas oil determines the economic improvement of their quality. Although, in the early, it had a large field of application, the combustion graphology of fuel was defined as the scientific branch concerned with the graphic transposition of these fuel combustion processes, establishing the ignition-combustion characteristics including the laws which govern their change, depending on the combustion conditions and the chemical structure of the liquid fuels. The graphological ignition-combustion characteristics of the liquid fuel result from the interpretation of the combustion oscillogram which is experimentally obtained. The need for increasing the degree of marine fuel combustion with and without cenosphere, imply the water emulsification of fuel for obtaining the secondary atomization. This paper deals with finding new methods and means for improving the combustion processes of marine liquid fuel. It tries to make evident the effects of water emulsion on the marine liquid fuel during combustion. The assessment of emulsification influence was made by comparing the combustion performance and the results with those obtained in the absence of emulsification under the same test conditions. The laboratory researches developed on the isolated droplet burning had in view to state the measure in which the emulsification would interfere for carrying out the secondary atomization [1]. We also tried to determine the characteristics of induced flames following their configuration and radiation and to assess the igniting
and burning behavior of droplets by laying down comparison criteria of the following times:

\( \tau_i \) – self-ignition delay, the time between the moment of introduction inside the combustion chamber and the ignition of the droplet which is marked by the appearance of flame; \( \tau_e \) – burning time of volatile matters; \( \tau_c \) – burning time of cenosphere.

### 2.1 Self-ignition delay time \( \tau_i \)

The physical model for theoretical calculation of self-ignition time [1]:

\[
\tau_i = \frac{\rho L_s (T_0 + r_i)}{\varphi C_i \left( \frac{T_m}{100} - \frac{T_0}{100} \right) + \alpha_c (T_m - T_0) + \gamma C_v Q}
\]

(1)

The theoretical expression of time \( \tau_i \) shows that its value can be reduced by increasing the ambient temperature of droplet, the coefficient of heat-transfer from the gas flowing around the droplet to its surface, the oxygen concentration in the environment around the droplet, the constant of reaction rate, the quantity of heat released up to the flame ignition and by decreasing of the droplet initial diameter and the latent heat of vaporization and the liquid fuel density as well.

### 2.2. Burning time of droplet \( \tau_a \)

The burning of residual fuel droplet is achieved in a period of time given by [1]:

\[
\tau_a = \tau_i + \tau_c \text{ (s)}.
\]

(2)

where: \( \tau_i \) is burning time of volatile matters; \( \tau_c \) – burning time of cenosphere.

The life of droplet \( \tau_c \) is longer than the burning time because it also includes the self-ignition delay times \( \tau_i \):

\[
\tau_c = \tau_i + \tau_v \text{ (s)}.
\]

(3)

The liquid fuel droplet is considered a porous sphere in the middle of which the liquid volatile matters are concentrated. By vaporization and porous mass diffusion the volatile matters get out of the burning range and burn. After consuming the volatile matters, the carbon porous lattice also burns due to the oxygen diffusion from the environment to its surface.

### 2.3. Burning time of volatile matters \( \tau_v \)

Based on the usual physical model, the theoretical relation for calculating the burning time of volatile matters was determined by [1]:

\[
\tau_v = \frac{\rho_v \left( \frac{M_c}{100} \right)}{8C_v \frac{P_v}{\mu_v}} = \frac{d_0^2}{K_v},
\]

(4)

where: \( \rho_v \) – is the density of liquid volatile matters (kg/m\(^3\)); \( M_c \) – the content of volatile matters (%); \( \mu_v \) – coefficient of dynamical viscosity of volatile matters (kJ/kg K); \( d_0 \) – initial diameter of droplet (mm); \( C_v \) – on the surface of porous lattice where \( r = r_0 \) the volatile matter concentration is \( c = 0 \) and for \( r = r_c \) the concentration is \( c = c_0 \); \( K_v \) – vaporization constant of volatile matters, depending on the chemical analysis of liquid heavy fuel and the characteristics of oxygen carrier medium as well.

The decrease of time \( \tau_c \) is made by reducing the initial diameter of droplet and by increasing the ambient temperature as well and the initial diameter of droplet decreases by increasing the content of volatile matters in the fuel.

### 2.4. Burning time of cenosphere \( \tau_c \)

After burning of volatile matters the carbon spherical porous lattice with diameter \( d_c \) remains to burn at the surface due to the oxygen diffusion from the environment to it [1]:

\[
\tau_c = \rho_c \left( \frac{1 - \frac{M_c}{100}}{1 - \frac{K_v}{K_o}} \right)^{0.95} = \frac{d_0^2}{K_v}
\]

(5)

where: \( \rho_c \) – is the density of cenosphere (kg/m\(^3\)); \( \rho_0 \) – density of gaseous fluid; \( D_0 \) – diffusion coefficient of nitrogen at \( T_0 = 273 \) (K), \( m^2/s \); \( T_m \) – absolute average temperature of gaseous fluid surrounding the droplet (K).

The burning time of cenosphere \( \tau_c \) decreases with the temperature rise and the increase of oxygen concentration in the environment around the droplet and with the increase of the diffusion coefficient of oxygen as well [1]. The self-ignition delay time of cenosphere \( \tau_{ic} \) was experimentally stated by the period between the completion of volatile matters flame burning and the self-ignition of carbon residues.

\[
\tau_s = \tau_i + \tau_v + \tau_{ic} + \tau_c.
\]

(6)

### 3. THE COMBUSTION CHARACTERISTICS OF A HEAVY OIL-WATER EMULSION DROPLET INVESTIGATED WITH GRAPHOLOGICAL METHOD

The combustion graphology of fuel oil is defined as a new technical and scientific field which deals with the graphic transposition of the processes of fuel combustion development in a simulator [2]. Thus, it is easy to establish the ignition-combustion characteristics, including the laws that govern their changes depending on the combustion conditions and fuel specifications.

The combustion oscillogram is the graphic transposition of the development of the ignition and combustion processes of a liquid fuel droplet under the shape of a curve represented in coordinates of axes of a rectangular system. The \( t \)-time variation is represented on the abscissa and the \( I \)-radiation intensity variation of the burnt droplet on the ordinate, the radiation being transformed into voltage through a photoelectric cell with amplification, the latter receiving the light-infrared signals.
The graphic representation of the combustion processes development for a droplet of liquid fuel used in the industrial combustion can be made by means of the so-called "combustion oscillogram" (fig. 1).

This graphic representation specifies the time variation of the light-thermal energy radiation intensity $I_c$ for a burning droplet, transformed into electric signals by means of an optical-electronical system provided with a photoelectrical cell (fig.2). From (fig.1) we can see that the energy (power) radiated by the volatile matters $E_v$ is much higher than the energy of cenosphere represented on the scale by the area under the curve $I_c = F(\tau)$. Thus, for a heavy fuel oil, this ignition and combustion graphic representation establishes, under standard conditions: the self-ignition delay $\tau_1$, the volatile matters combustion time $\tau_v$, the cenosphere combusion time $\tau_c$, the maximum radiation intensity $I_{\max}$ obtained at the combustion of the cenosphere $L_c$, the maximum radiation intensity $I_{\max}$ obtained at the combustion of the cenosphere $L_c$, the energy radiated by the burning of volatile matters $E_v$ and cenosphere transformed by the photocell into electric energy $E_c$, etc. $T_i = \Psi(\tau)$ is the temperature characteristic of the combustion.

$$E_v = k \int_I f(\tau) d\tau \quad (6) \quad E_c = k \int_I F(\tau) d\tau \quad (7)$$

4. EXPERIMENTAL PART

Oscillogram for burning a marine heavy fuel droplet. The heavy fuel droplet utilized for experimental part was marine fuel RMD 15 (Table 1). The oscillogram for burning of three marine heavy fuel droplets with different initial diameters $d_1 = 2.4$ (mm), $d_2 = 2.0$ (mm), $d_3 = 1.6$ (mm) are shown in fig. 3. Following the burning of the three droplets $d_1, d_2, d_3$ we came to the conclusion that together with increasing the initial diameter of the droplet, the self-ignition delay time $\tau_1$, the burning time of volatile matters $\tau_v$, the burning time of cenosphere $\tau_c$ and the radiation intensity $I$ of a burning droplet are increased.

Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>RMD 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume mass at 15°C, [kg/m$^3$]</td>
<td>max 985.0</td>
</tr>
<tr>
<td>Kinematic viscosity at 100°C, [mm$^2$]/s</td>
<td>max 15.0</td>
</tr>
<tr>
<td>Flow point °C</td>
<td></td>
</tr>
<tr>
<td>- winter, max</td>
<td>30</td>
</tr>
<tr>
<td>- summer, max</td>
<td>30</td>
</tr>
<tr>
<td>Coke residue, [% (g/g)], max</td>
<td>14</td>
</tr>
<tr>
<td>Ash, [% (g/g)], max</td>
<td>0.10</td>
</tr>
<tr>
<td>Water, [% (v/v)], max</td>
<td>0.8</td>
</tr>
<tr>
<td>Sulphur, [% (g/g)], max</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Also, the smaller the droplet diameter the lower the intensity of radiated energy. We can state that the smaller the droplet diameter will be the more the chances that the cenosphere burns entirely are. The droplet diameter can be decreased up to the limit of mechanical fuel-atomizers, following that beyond this limit its decrease should be achieved by fuel emulsification resulting in a secondary atomiztion. The experiments with the simulator aimed at the ignition and burning behavior of a high-quality marine fuel. I used the marine fuel RMD 15. From this fuel we took three samples ($C_1$, $C_2$, $C_3$) analyzing the ignition and burning behavior of a droplet from each of them. The content of sample $C_1$ was non-emulsified and the other samples have the following quantities of emulsion water: $C_2 - 4\%$; $C_3 - 8\%$.

Fig. 4 presents the oscillogram for burning non-emulsified fuel droplet $C_1$ having a diameter $d_0 = 2 \pm 1\%$ (mm) ignited at the initial temperature in the combustion chamber $T_0 = 973 \pm 1$(K) for the environmental temperature $T_a = 295 \pm 1$(K), the flame temperature $T_f = 300$ (K) and the Reynolds number of the airflow inside the combustion chamber was practically 0 and 140, the air supplied through natural admission.
Fig. 4. The oscillogram for burning a non-emulsified droplet of marine fuel RMD 15.

Fig. 5. The oscillogram for burning a droplet of 4(%) emulsified-water fuel C2 of marine fuel RMD 15.

Fig. 6. The oscillogram for burning a droplet of 8% emulsified-water fuel C3 of marine fuel RMD 15.

5. CONCLUSIONS

The initial strain of the droplet under the action of water vapors contained in the emulsion, is followed by its breaking in more droplets of smaller diameters. The smaller values of $I_c$, $E_c$ and $\tau_c$ for C3 droplet as compared to the samples C1, C2 and the sudden variation in temperature $T_f$, make evident the possibility of reducing the losses by unburnt carbon, therefore, the decrease of carbon black (soot) quantity released in the flame leads to the increase in burning performance of cenosphere, as a result of the secondary atomization. The combustion of a water-in-oil emulsion is a result of the explosive vaporization caused by rapid heating of the water dispersed within the individual fuel droplets. The internal water droplets undergo spontaneous nucleation of steam bubbles, causing a violent conversion of the water droplet to steam. The vaporization, in turn, produces a rapid expansion of the surrounding oil droplets, fragmenting the oil into a vast number of smaller fuel droplets. The name for this process is secondary atomization.

REFERENCES