Research Article

Water/Heavy Fuel Oil Emulsion Production, Characterization and Combustion

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ABSTRACT. In order to produce a water/heavy fuel oil emulsion (W/HFO) with different water contents to cover the daily needs of a fire tube boiler or a water tube boiler, a special homogenizer is designed, constructed and tested. The produced emulsion is characterized and compared with the pure HFO properties. It is found experimentally in fire tube boiler that, the use of W/HFO emulsion with 8% of water content ($W_{0.08}$/$HFO_{0.92}$) instead of HFO leads to a saving rate of 13.56% in HFO. For explaining the obtained energy saving the term "equivalent heat value (EHV) of the W/HFO emulsions", defined as the ratio of the W/HFO emulsion net calorific value to the HFO content in the emulsion, is used. Based on direct measurements, provided in this work, it was found that the equivalent heat value (EHV) increases with the water content in the water/heavy fuel oil (W/HFO). It reaches 1.06 times of HFO net calorific value at water content of 22.24%. The obtained, in the present work, experimental results demonstrate the dependence of the emulsion EHV on its water content. These results are in agreement with the results of other authors. Therefore, the contribution of water droplets in the emulsion combustion is verified. It is found experimentally that, the emitted CO, SO_2 and H_2S gases from the fire tube boiler chimney decreases by 5.66%. 3.99% and 48.77% respectively in the case of ($W_{0.08}$/$HFO_{0.92}$) emulsion use instead of HFO.

Keywords: Water-Heavy Fuel Oil Emulsion, Homogenizer, Structural Study, Vibrations, Equivalent Heating Value, Emulsion Combustion, Pollution Reduction

1. Introduction

An emulsion is a dispersion of two liquids that are immiscible where one of these two liquids is in the form of droplets (the dispersed phase) in another liquid (the continuous phase). So, the emulsified fuel is a mixture of a combustible liquid, either oil or a fuel as a continuous phase and a small amount of water with or without a surfactant as a dispersed phase. Although emulsion of petroleum fuel in water is the most common form of emulsions (Jhalani *et al,* 2019), emulsifiers are widely used in many industries including food industry, cosmetics, pharmacy, paints, agrochemicals, and others (Chappat, 1994).

The emulsification process could lead to either macro-emulsion (where, the dimensions of the droplets are of 100 nm up to over 1 micrometer) or micro-emulsion (where, the dimensions of the droplets are of 10 nm up to 100 nm). Anyway, one can conclude that, in comparison with the traditional petroleum fuel, the emulsified fuel is preferable based on five criteria such as relative NOx reduction, effect on PM emission, lubricating oil dilution, variability of water addition, and expenditure (Nowruzi and Ghadimi, 2016). Thus, the emulsified fuel is one of the main strategies to substitute the conventional fossil fuel for the purpose of emission control and enhancement of fuel efficiency. Moreover, several authors (Li *et al*, 2014; Carneiro *et al*, 2015; Chen and Lee, 2008; Lin *et al*, 2011;

Melo-Espinosa *et al*, 2018; Tseng and Cheng, 2011; Chelemuge *et al*, 2012) showed that the use of emulsified fuels leads also to the energy saving. So, advantages to using emulsified fuels instead of the fuel itself are of environmental and economic benefits. The emulsified fuels are effective in reducing NOx and PM emissions simultaneously.

Since the constituents of the macro-emulsion are not miscible, energy must be provided to form droplets. The provided energy increases the energy of the system. This increase in energy is proportional to the interface area between the two phases. This energy is known as interface energy, surface energy, or surface tension. The surface tension of the droplet is proportional to the droplet radius and the Laplace pressure. Emulsions are unstable from a thermodynamic point of view because the surface tension of the material is positive. So, the droplets of the dispersed phase tend to coalesce and form larger drops. In the absence of the stabilizing components together with the emulsion components, the fabrication of the density of the two emulsion compounds leads to the separation of the two phases and thus to the absence of emulsification. However, in (Li *et al*, 2014) and (Chelemuge *et al*, 2012) the (W/HFO) emulsion was produced, in a commercial scale, without any surface active agents. Moreover, factors such as temperature, droplet size, agitation, time and type

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of emulsifying agent are the main stabilizers of an emulsion.

Numerous studies have demonstrated the possibility of reducing harmful gas emissions, such as CO, NO_x, SO_2, H_2S and C_xH_y), from power plants by controlling work patterns. The maximum yield of combustion in boilers must be secured from an economic and environmental point of view to use the fuel in boilers. When dealing with the combustion of W/HFO emulsion the micro-explosion phenomena occurred. This means that, when the W/HFO emulsion droplet is heated by radiation and by convection, its temperature rises and the temperature of its water component becomes higher than the temperature of boiling water, which causes it to swell quickly and to burst. As a result of the water droplet explosion, the surrounding fuel layer burst too. This leads to the formation of small droplets of fuel, and the specific surface of the fuel droplets is greatly increased. The water droplet evaporation breaks up the oil droplets as the particles that measure 30–50 µm when fired without water are reduced to a size of 2–5 µm when fired with water (Sjögren, 1977). The micro-explosion phenomenon improves fuel mixing with air, increases combustion efficiency, reduces harmful gas emissions, and raises the total value of the boiler efficiency (Califano *et al*, 2014). Moreover, the process of micro-explosion caused by the presence of water in the emulsion affects the physics of combustion and its chemical kinetics (Samec, 2002).

In spite of the great scientific effort expended in the experimental evaluation of the micro-explosion phenomenon (Mura *et al*, 2012; Yahaya-Khan *et al*, 2016; Tarlet *et al*, 2016; Mura *et al*, 2014; Hou *et al*, 2013; Watanabe *et al*, 2010), this phenomenon still raises many questions (Fu *et al*, 2006). Mura and his colleagues (Mura *et al*, 2014) have indicated that the occurrence of the micro explosion phenomenon is related to several parameters, the most important of which is the separation into layers. Several studies have indicated the occurrence of the phenomenon of inflation before the phenomenon of the explosion (see, for example, Ogunkoya *et al*, 2015; Soulayman and Youssef, 2018) and some studies indicate the possibility of raising the yield of the water pipe boiler in different rates. This percentage reaches about 15% if using a water-fuel emulsion (see for example (Li *et al*, 2014)).

On the other hand, the presence of water in the emulsion leads to lowering the flame temperature and changing the chemical components of the reactants, which raises the concentration of the OH radicals that control the rate of formation of NO and oxidation of solid suspensions and dilute the concentration in the rich regions of the combustion chamber (Samec, 2002).

In the industrial boilers the most effective factors affecting harmful gas emissions from W/HFO emulsion power plants is the moisture content and excess air rate (Gavrilov, 1998; Grishkova, 2004). This idea was confirmed by Tran and colleague (Tran and Ghojel, 2005) and Debnath and colleagues (Debnath *et al*, 2013) who concluded that the combustion of a water-fuel emulsion in heat boilers can benefit from the difference in volatilization of its two components.

Several techniques were used in forming emulsions. Within these techniques one can mention Stirred Vessel (Schultz *et al*, 2004), Rotor-Stator System (Schultz *et al*, 2004; Nasir, 2013), High-Pressure Homogenizer (Schultz *et al*, 2004; Nasir, 2013), Ultrasonic Homogenizer (Schultz *et al*, 2004; Nazir, 2013), Cross-Flow Membrane Emulsification (Schultz *et al*, 2004; Nazir, 2013), Premix Membrane Emulsification (Schultz *et al*, 2004; Nasir, 2013), T-junction (Nasir, 2013) and Micro-channel Emulsification (Nasir, 2013).

For a given HFO, the water contribution in the W/HFO emulsions could be determined experimentally by measuring the net calorific values of the original HFO and the dependence of the calorific value of the W/HFO emulsion on the water content. In this case, it is justified to use the term "equivalent heat value (EHV) of the W/HFO emulsions", which is introduced by Tseng and Tseng (Tseng and Cheng, 2011) and it is defined as the ratio of the W/HFO emulsion net calorific value to the HFO content in the emulsion.

In (Tseng and Cheng, 2011), the W/HFO emulsions were prepared with water content of up to 30% using the emulsifier with content of up to 2%. According to (Tseng and Cheng, 2011), the measured EHV value increases with water content. It reaches 15% at water content of 25.7% and emulsifier content of 1.3%. At water content of 30% and emulsifier content of 2%, the EHV value increase is 3.00% only. Therefore, based on these results the contribution of water reported in (Tseng and Cheng, 2011) is positive.

In the present work a special homogenizer is designed, constructed and tested. The aim of the present work is to verify the performance of the constructed homogenizer and to determine the EHV value of W/HFO emulsion in dependence with the water content in the emulsion based on experimental data. For this purpose the net calorific value of $W_x/HFO(1-x)$, where x varies from 0 to 0.2, is measured using Parr calorimeter. Based on these measured data, EHV is calculated and its dependence on the water content is traced. The W/HFO emulsion, produced using the constructed homogenizer, is tested on the fire tube boilers, where the fuel saving and gas emissions are measured.

2. Materials and Methods

2.1 The Homogenizer

The homogenizer is designed to allow the production of W/HFO emulsion with a production capacity of 200,000 L / h or (20 tonnes/h) where some of its parts can rotate at 4000 rpm to achieve good emulsion mixing at a pressure of 10 bar. Figure 1 shows the design of the homogenizer. Elasticity theory (Sad, 2014), three-dimensional finite elements (Guido, 2004) and numerical methods such as ANSYS were used.
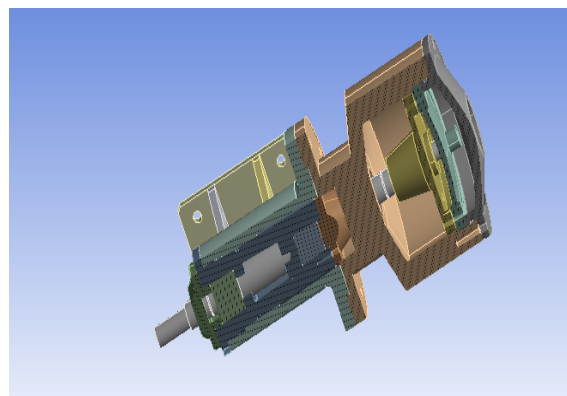

Fig. 1 The designed homogenizer

2.2 HFO and W/HFO emulsion characterization

The ASTM D5854 standard procedure (ASTMD5854, 2005) was followed for collecting the crude HFO samples. Following (Sad *et al*, 2015) and (Carneiro *et al*, 2015) the free water was separated from each sample by decanting over one-hour period before any characterization step. Then, the sample is dehydrated by adding 250 µl of commercial demulsifier and centrifuged at 2000 rpm for 20 min at 60°C. The water content in the oil was quantified by a standardized method ASTM D4377.

The dehydrated HFO was characterized according to ASTM D1298 for the specific gravity, ASTM D1552 for sulphur content, ASTM D92 for flash point, ASTM D97 for pour point, ASTM D445 for kinematic viscosity, ASTM D482 for ash content and ASTM D240 for the heat of combustion. Asphaltenes and vanadium contents were characterized according to UOP614 and UOP391 respectively.

2.3 Place of Application

The Tartous Company for cement and construction materials is located about 1.5 km from the beach of Mediterranean sea 10 km North of Tartous city. The power station of this company consists of 5 fire tube boilers; one of them (boiler No. 3) is in the maintenance. The mentioned power station is used to heat HFO before feeding the cement kilns. Each of the working boilers is of 8 ton.h^{-1} steam capacity. The power station has been operated for 4 months with a regular heavy fuel oil HFO and W/HFO. A mini city for the employers of the company is located west of the company by 750 m approximately. Thus, the ecological effect of the company on the surrounding area is considered as a pro factor for the project of water/HFO emulsion.

2.4 Gas Emissions and Boiler Performance

In order to determine the effect of fuel on each of the used boilers, the combustion yield Ef (%), boiler efficiency η (%), the excess air ratio λ (%), the temperature of the gas emissions from the chimney Tf (ºC), the ambient temperature Ta (ºC) and the concentration of each of the emitted gases (oxygen O_2; carbon monoxide CO; carbon dioxide CO_2; nitrogen oxides: NO, NO_2 and NO_x; hydrogen H_2; sulphur dioxide SO_2; and H_2S) were measured using Testo 350XL.

2.5 Fuel consumption

The HFO flow and W/HFO emulsion flow were measured using highly accurate and reliable Yokogawa flow meter. Using this kind of flow meters one can get direct measurement of fuel density, fuel temperature and the actual mass flow in the pipes.

3. Results and Discussions

3.1 Homogenizer Structural Study

This study aims, through advanced robustness calculations, using analytical methods (relations of elasticity theory and its laws) and numerical methods (finite three-dimensional elements) to achieve safety conditions and high performance on stability under the surrounding conditions of the system.

3.1.1 Toughness on Torque

The shaft as a basic structural element of the system is subjected to torque (twisting moment) around the longitudinal axis provided by the motor, which creates tangential stresses in the main planes of the cross section that may lead to the collapse of this shaft on the shear, if not carefully studied.

For a power of 11 kW and a 4000 rpm, the value of torque applied to the shaft can be easily calculated from the relation of the power provided by the motor:

$$P = 2 \times \pi \times f \times M_t \rightarrow M_t = 26.261 \text{ N.m},$$

where: P is the power transmitted in Watt, f is the frequency (round per second), $M_{twesting}$ is the twisting moment applied on the shaft axis (N.m)

The numerical calculations were carried out by the finite element method of a 3D element on the ANSYS-V19,2 program. In the following, we review the values of stresses, total deformation, where Figure 2 represents the boundary conditions imposed on the shaft; Figure 3 represents the distribution of the shear stresses due to torque; and Figure 4 represents the distribution of the total deformation along the shaft.

3.1.2 Discussion

It is evident from Figures 3 and Figure 4 that the results obtained indicate that the values of stresses and strains are within the permissible values. Therefore, in the worst conditions imposed on the design, the smallest safety factor of 5 can be easily calculated.
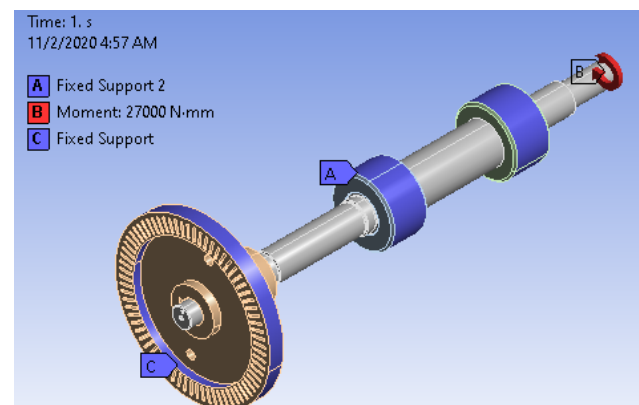

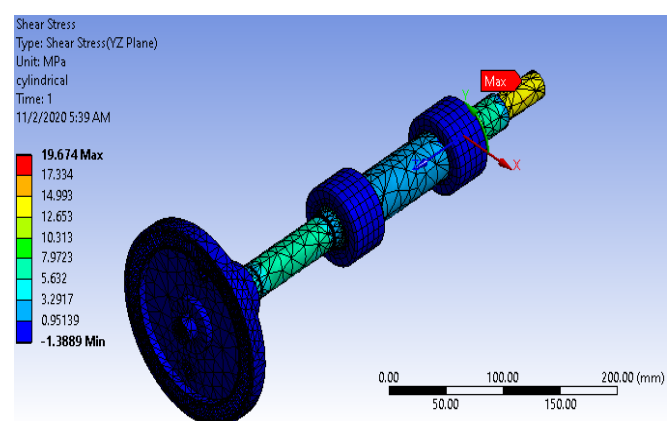**Fig. 2** The boundary conditions imposed on the shaft
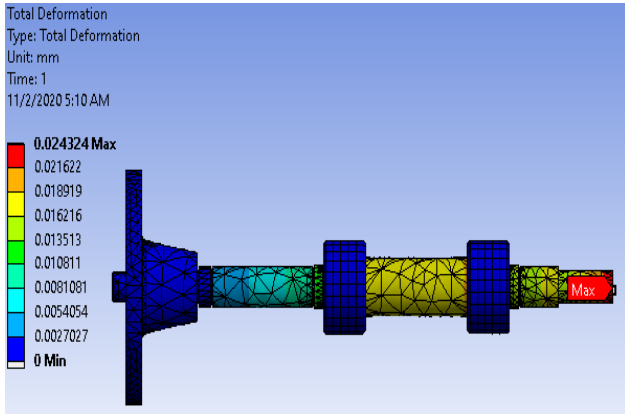

Fig. 3 Distribution of the shear stress

Fig. 4 Distribution of the total deformation

3.2 Homogenizer Vibrations (Modal Analysis)

The goal of modal analysis in structural mechanics is to determine the natural mode shapes and frequencies of an object or structure during free vibration. It is common to use the finite element method (FEM) to perform this analysis because, like other calculations using the FEM, the object being analyzed can have arbitrary shape and the results of the calculations are acceptable. The types of equations which arise from modal analysis are those seen in eigensystems. The physical interpretation of the eigenvalues and eigenvectors, which come from solving the system, are that they represent the frequencies and corresponding mode shapes. Sometimes, the only desired modes are the lowest frequencies because they can be the most prominent modes at which the object will vibrate, dominating all the higher frequency modes

3.2.1 Numerical calculations

The lateral vibrations in the designed homogenizer were studied by Ansys 19.2 (solver-modal), according to four types of installations (boundary conditions) for the homogenizer, that aims to increase the natural frequency (fundamental frequency) noted in Table 1, and getting it as far as possible from the working frequency (forced frequency):

- First type of boundary condition (free pattern): The system is isolated from the surroundings so that it can behave in the free mode as a coherent mass between them.
- Second type (free - rear terminal restriction): Installation is from the base only with the outer contour.
- Third type (free-posterior medial restraint): Fulcrum points have been added to reduce the amplitudes of vibrational motion.
- Fourth type (back and front end restriction): In this case the free ends are completely eliminated, which leads to smaller amplitudes and higher frequency (Hz).

The results of calculations are given in Table 1. It is noticeable from Table 1 that the first natural frequencies change from one state to another according to the boundary conditions of each installation type, and this is logical, as the non-null value of frequency reaches 70 Hz in the first type, 168 Hz in the second type while it is fixed to an average value of 321 Hz in the third and fourth types.

3.2.2 Discussion

We can avoid resonance phenomenon by comparing the natural frequency (mode fundamental) of all types with the forced frequency of the homogenizer.

The results of Table 1 show clearly that the fundamental frequency of the third type is considered the most stable and far from the forced frequency of the homogenizer. Therefore, we adopted the third type of boundary condition for our design.

Figure 5 represents the location of the installation and fundamental mode in the third type of installation where the frequency of the system equals to 322 Hz, and Figure 6 shows the second mode of vibrations in the third type of installation where the frequency of the system is equal to 323Hz. These results give a full description of the characteristics of the homogenizer.

Table 1
First six vibration modes frequencies for four types of installation (boundary conditions)

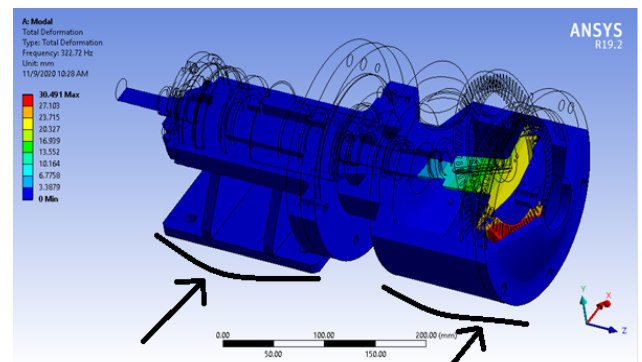| Mode	Frequency (Hz)			
	1st type	2nd type	3rd type	4th type
Fundamental	0	168.4	322.72	320.49
2	8.31×10^{-4}	194.37	323.66	321.39
3	4.01×10^{-3}	336.71	530.77	528.25
4	70.639	341.66	1571.5	864.03
5	71.567	388.68	1577.8	969.74
6	109.75	468.11	1631.8	1115.3

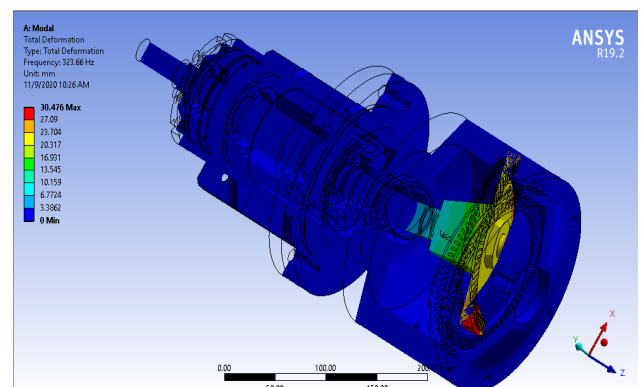**Fig. 5** The location of the installation and first mode in the third type of installation

Fig. 6 The second mode of vibrations in the third type of installation

3.3 Physical Properties of $W_x/HFO_{(1-x)}$ Emulsions

Vegard's law for mixtures such as alloys says that the property of the mixture is a linear function of the respective properties of its pure constituents (Denton and Ashcroft, 1991):

$$E_{mixture} = xE_A + (1 − x)E_B \qquad (1)$$

where:

- E_A is the respective properties of pure A,
- E_B is the respective properties of pure B,
- $E_{mixture}$ is the respective properties of $A_xB_{(1-x)}$,
- x is the fraction of one ingredient in a material point.

The question: Is Vegard's law applicable for binary emulsions? In order to verify the applicability of the Vegard's law on the Wx/HFO(1-x) emulsions, several physical properties of Wx/HFO(1-x) emulsions for different x were measured and calculated based on Equation 1. The results are given below.

3.3.1 Density

With regard to the density of Wx/HFO(1-x) emulsion, it was found (see Figure 7) that the application of ASTM D1298 in its measurement with respect to the emulsified fuel leads to results that differ from the results of the calculation based on Vegard's law. It is seen from Figure 7 that, contrary to the calculated results which could be approximated with a high accuracy by a linear function of water content, the measured density could be approximated by a polynomial function of second order. Thus, the applicability of Vegard's law for calculating the density of $W_x/HFO(1-x)$ emulsion is not proven.

3.3.2 Kinematic Viscosity

With regard to the kinematic viscosity of Wx/HFO(1-x) emulsion, it was found (see Figure 8) that the application of ASTM D445 in its measurement with respect to the emulsified fuel leads to results that differ from the results of the calculation based on Vegard's law.

3.3.3 Net Calorific Value

With regard to the net calorific value of $W_x/HFO(1-x)$ emulsion, it was found (see Figure 9) that the application of ASTM D240 in its measurement with respect to the emulsified fuel leads to results that differ from the results of the calculation based on Vegard's law. Li *et al.* (Li *et al,* 2014) measured the net calorific values of the W/HFO emulsions with water content ranging from 0% to 28% and showed that, the net calorific value (LHV) of the W/HFO emulsions, decreases with the water content. At 0% water content, which corresponds to pure HFO, the reported net calorific value of HFO is 41.64 MJ/kg (Li *et al*, 2014). Up to 14% of water content this decrease is very little while it is significant for higher water content. For water content of 7%, 14% and 21% the reported net calorific values are 38.52, 35.52 and 32.26 MJ/kg respectively (Li *et al,* 2014). Figure 9 shows that the corresponded measured values in the present work are 39.29, 36.83 and 34.00 MJ/kg.
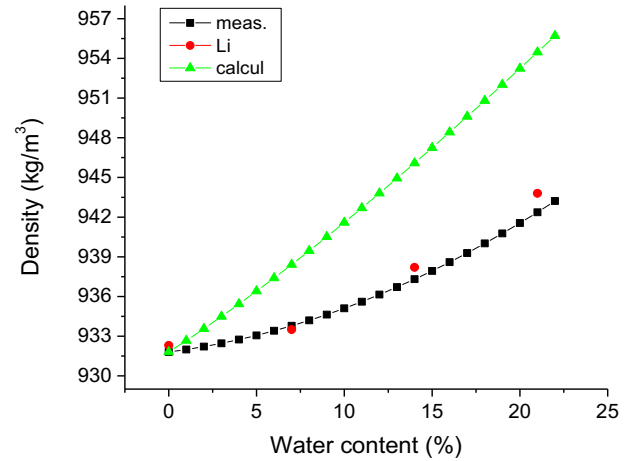

Fig. 7 Measured (■) $W_x/HFO_{(1-x)}$ emulsion density (kg/m³) and its calculated (▲) values at 15.6°C. The results of Li et al. (Li et al, 2014) are marked by (●).

3.3.4 Equivalent Heat Value

Basing on the measured net calorific values of the used $W_x/HFO(1-x)$ emulsions according to ASTM D240 for water content of 0% to 22.24% (see Figure 10) and on the definition of the equivalent heat value, the corresponded change of EHV values could be calculated easily:

$$\Delta EHV= 100*[LHV_{W_x/HFO(1-x)}/(x*LHV_{HFO})-1], \qquad (2)$$

Where:

- $LHV_{W_x/HFO(1-x)}$ is the measured net calorific value of the used Wx/HFO(1-x) emulsions,
- LHV_{HFO} is the measured net calorific value of the used HFO.
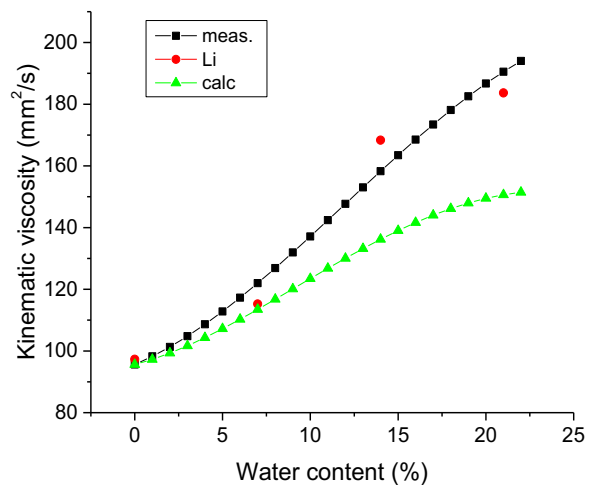- x is the water content ratio in the emulsion.

Fig. 8 Measured (■) $W_x/HFO_{(1-x)}$ emulsion kinematic viscosity (mm²/s) and its calculated (▲) values at 50°C. The results of Li *et al.* (Li *et al*, 2014) are marked by (●).
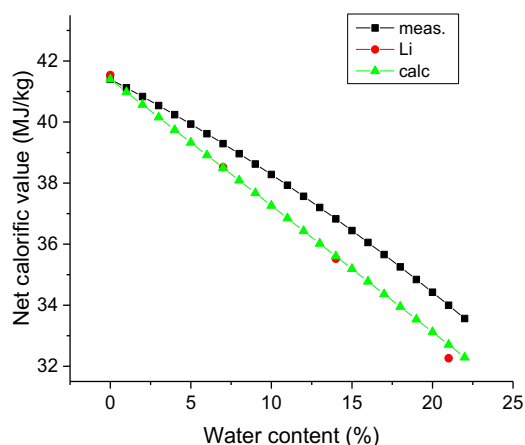
Fig. 9 Measured (■) $W_x/HFO_{(1-x)}$ emulsion net calorific value and its calculated (▲) values. The results of Li *et al*. (Li *et al,* 2014) are marked by (●).
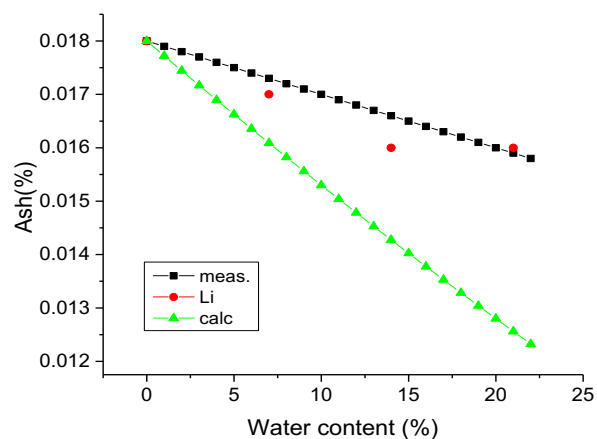

Fig. 11 Measured (■) $W_x/HFO_{(1-x)}$ emulsion ash percentage and its calculated (▲) values. The results of Li *et al*. (Li *et al,* 2014) are marked by (●).

3.3.5 Ash

With regard to the ash of $Wx/HFO(1-x)$ emulsion, it was found (see Figure 11) that the application of ASTM D480 in its measurement with respect to the emulsified fuel leads to results that differ from the results of the calculation based on Vegard's law. Moreover, it is seen from Figure 11 that the results of the present work agree well with those of (Li *et al*, 2014). On the other hand, it is seen from Figure 11 that, the use of $W_x/HFO_{(1-x)}$ emulsion leads to a remarkable soot reduction compared to HFO on its own (the ash percentage at zeros water content). Finally, from Figures 7 to 9 and 11 one can conclude that the results of the present work agree well with those of (Li *et al*, 2014).

3.4 Emulsified water-HFO fuel droplet temperature chronogram

The combustion of a single droplet of $W_x/HFO_{(1-x)}$ emulsion with x of water content was studied using the same experimental set-up, described in (Soulayman, 2018). In order to present data with practical significance, Figure 12 gives the time dependences of the HFO and emulsified $W_{0.1749}/HFO_{0.8151}$ droplets. The mentioned water content of 17.49% corresponds to the applied mixing ratio in the Banyas power station where the emulsified W/HFO is used.

It is seen from Figure 12 that a) the peak temperature of $W_{0.1749}/HFO_{0.8151}$ emulsion occurs much earlier in time than that of the HFO itself. This shift in the peak temperature could be considered as characteristic for the emulsified $W_{0.1749}/HFO_{0.8151}$ and b) there is an important difference in the time droplet temperature derivative for HFO and W/HFO emulsion. This indicates that, according to (Villasenor and Garcia, 1999) and (Ocampo-Barrera *et al*, 2001), the use of $W_{0.1749}/HFO_{0.8151}$ emulsion in water tube boilers should lead to a remarkable soot reduction compared to HFO on its own. Therefore, a reduction of pollutant emissions from the power station should be expected. The experimental results found in the present work are in a good agreement with those reported in (Ocampo-Barrera *et al*, 2001).
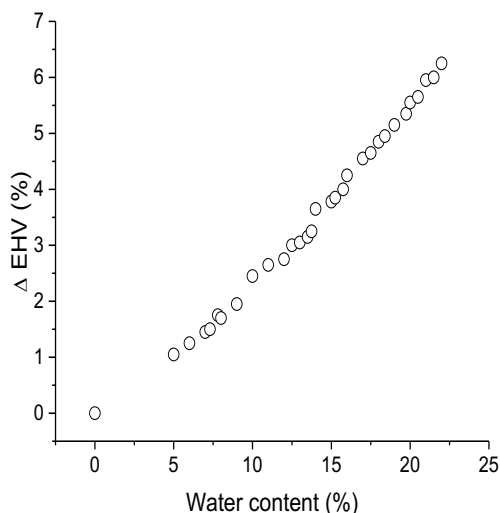

Fig. 10 The measured EHV change of the produced W/HFO emulsions with water content.

The dependence of the EHV change on the water content is presented in Fig 10, which shows that this dependency is not linear.

Fig. 10 shows that the experimental values of EHV increase with the water content. The EHV increase reaches 6.39% at water content of 22.24%. The obtained results on the dependence of the EHV in the present work agree well with those presented in (Tseng and Cheng, 2011). According to the experimental results of the present work and those of (Tseng and Cheng, 2011) one can conclude that the influence of water is rather positive.

To explain the observed results, two assumptions could be made:

- Either, the water content does not contribute in the combustion of W/HFO emulsion, according to the combustion theory, and in this case the Hess's law is not applicable.
- Or water is directly involved in the reaction and therefore Hess's law could be applied.
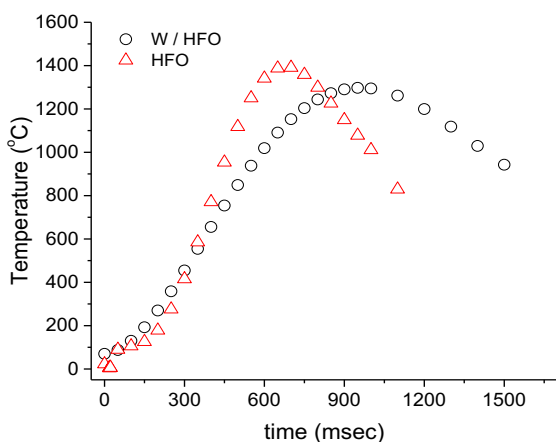
Fig. 12 Time dependence of emulsified $W_{0.1749}/HFO_{0.8151}$ fuel (○) and HFO (Δ) droplet temperature.

In order to predict the ignition temperature for HFO and $W_{0.1749}/HFO_{0.8151}$ emulsion, it is sufficient to estimate them by calculating the first derivative dT/dt of the curves presented in Fig. 12 in accordance to Van't Hoff condition. The results are presented in Fig. 13. According to the obtained results, the ignition of HFO occurs at 350 ms which corresponds to the temperature 554.4°C (see Fig. 12). With regard to the $W_{0.1749}/HFO_{0.8151}$ emulsion, Fig. 13 shows two critical points: one at 100 ms and the other one at 400 ms.

At both points the ignition could occur. The first point corresponds to the temperature 105.9°C while the second one corresponds to 770.8°C. Ocampo-Barrera (Ocampo-Barrera *et al*, 2001) has noticed the occurrence of the first point for $W_x/HFO_{(1-x)}$ emulsion of water content "x" of 10% and 25%. Therefore, the mentioned point could be attributed to water presence. Ocampo-Barrera (Ocampo-Barrera *et al,* 2001) also noted that, at 105°C the secondary atomization occurs resulting in increased fuel droplets surface area. The second point depends mainly on the water content value. The visualized ignition for W/HFO with 17.49% of water content was noticed at 375 ms which corresponds to the droplet temperature of 677.3°C. This shows that an acceptable agreement between the calculated and measured ignition temperature is achieved.
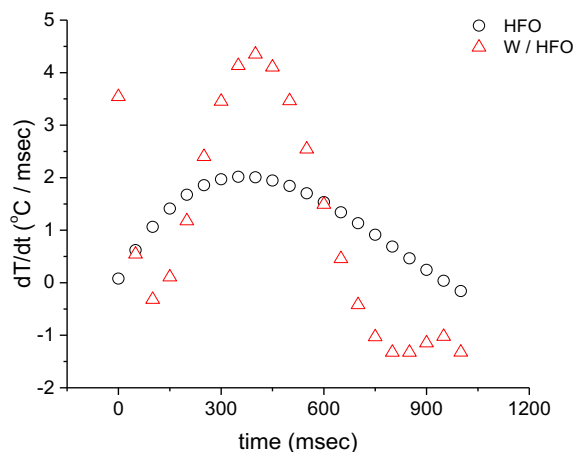

Fig. 13 First derivative of the droplet temperature as a function of time. Δ is for $W_{0.1749}/HFO_{0.8251}$ and ○ is for HFO.

Table 2
The Measured Characteristics of the 5th Boiler on HFO and W/HFO Emulsion

Fuel type	Properties				
	E_f (%)	η (%)	T_a (°C)	λ (%)	T_f (°C)
HFO	94.33	89.15	34.04	35.08	137.08
W/HFO	94.56	89.35	34.11	37.86	130.75

3.5 W/HFO Emulsion Effect on Boiler Performance

As the boilers showed similar behavior approximately, the presented results will be related to the 5th one. Tartous Company for cement and construction materials used HFO for producing the clinker, the water content in the W/HFO emulsion was determined by the Company authority. The emulsion used during these experiments was $W_{0.08}/HFO_{0.92}$. The obtained results related to E_f (%), η (%), λ (%), T (°C) and Ta (°C) are given in Table 2. It is seen from Table 2 that the use of $W_{0.08}/HFO_{0.92}$ emulsion has a positive effect on the performance of the tested boiler. This result agrees well with that of Chen & Lee (Chen, 2008). Moreover, the emitted, from the boiler chimney, gas temperature decreases by 4.62%.

3.6 Gas Emission

The results related to gas emission concentration are given in Table 3. The provided measured results in Table 3 clearly demonstrate the amelioration of gas emission when the W/HFO emulsion is used in fire tube boiler. The heavy fuel oil is characterized by its high sulfur content (≈6000 ppm). Combustion of this fuel leads to air pollution. Using emulsified fuel W/HFO of water content of 8% in the fire tube boilers, the SO2 concentration was reduced by 3.99% and the H2S gas concentration was reduced by 48.77%.

3.7 HFO Consumption Rate

By providing real experiments with regard to the consumed HFO and $W_{0.08}/HFO_{0.92}$ emulsion, the provided averaged data are given in Table 4. It can be seen from Table 4 that the use of $W_{0.08}/HFO_{0.92}$ emulsion decreases the consumption rate by 6.05%. When considering that the water content of the used W/HFO emulsion is 8%, the required consumption rate of the HFO for obtaining the consumption rate of the W/HFO emulsion is 237.04*0.92=218.08 l/h. This means that the use of the W/HFO emulsion of 8% water content leads to a saving rate of 13.56%. The obtained results, in the presented work, are in a good agreement with those of (Li *et al*, 2014).

Table 3
The Measured Gas Emission from the Chimney of the 5th Boiler

Fuel kind	Gas emission					
	O_2 (%)	CO (ppm)	CO_2 (%)	NO_x (ppm)	SO_2 (ppm)	H_2S ppm
HFO	5.33	11.13	11.79	148	1955	4.88
W/HFO	5.74	10.5	11.48	145	1877	2.5

Table 4
The Consumption Rate

Fuel type	Consumption rate		
	Quantity (l)	Duration (h)	Consumption rate (l/h)
HFO	2594.36	10.28	252.30
W/HFO	2678.58	11.3	237.04

Finally, it should be mentioned here that, the dependence of the fire tube boiler performance, saving rate in fire tube boiler and gas emission, from the chimney of fire tube boiler, on the water content of W/HFO emulsion will be considered elsewhere.

3.8 W/HFO Emulsion Stability

It is well known that, asphaltenes and resins have a strong tendency to bind together into micelles (Spiecker *et al*, 2003). The polar part of resins interacts with the polar centres of the asphaltene molecules and these interact with other similar molecules, forming aggregates of solvated asphaltenes with resins in the HFO. These aggregates are adsorbed at the interface of the water droplets and form a rigid structure enveloped by the droplets, favouring stability of the emulsions (Sullivan and Kilpatrick, 2002). Thus, high levels of resins and asphaltenes in heavy oils, coupled with the presence of water in production steps and the shear induced during production, favor the formation of W/HFO emulsions that present high stability, which causes difficulty in oil dehydration during primary processing. When measuring the sizes of the formed water droplets using microscope it was found that droplet size distribution is between 2 and 3 μm. This means that the produced W/HFO emulsion could be classified as stable according to (Mikula, 1992).

Finally, it should be noticed here that the produced, in the present work, W/HFO emulsion stays nearly stable for several months. Thus according to (Da Silva *et al*, 2018), which mentioned that, stable W/HFO emulsions are defined as those that persist without phase separation for five days or more, one can conclude that, the produced emulsions are very stable.

4. Conclusion

Finally, one can conclude that, the required special homogenizer is designed, constructed and tested. It should be noted that the advanced calculations carried out by either the analytical method (Elasticity), or the numerical method (FEM) confirm that the conditions of durability and stability are verified.

The use of W/HFO emulsion with 8% of water content instead of HFO decreases the pollution of the emitted gases from the fire tube boiler chimney, improves the boiler efficiency and leads to a saving rate of 13.56% in HFO.

It was found that it is possible to produce water/heavy fuel oil (W/HFO) emulsion without adding a surfactant and the emulsion stays nearly stable for several months. The deviation of the physical properties of W/HFO

emulsion from Vegard's law for mixtures indicates that this emulsion is not a simple mixture.

The effect of $W_x/HFO_{(1-x)}$ emulsion use on the improvement of overall efficiency and on the reduction of the specific consumption rate in the electricity power stations will be treated separately.

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