Experimental Study on the Swirling Flame Combustion of Heavy Fuel Oil/Water Emulsion

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Abstract

Due to its high energy density, low cost, and extensive availability, heavy fuel oil (HFO) is considered an interesting alternative fuel for use in combustion systems, either for power generation or transportation (*i.e.* in the marine sector). However, HFO is very difficult to burn, leading to the formation of pollutants (*e.g.* particulate matter, soot, cenosphere, etc.) that may cause detrimental effects not only to the combustion systems themselves, but also on the environment. In order to improve the combustion process of HFO and therefore reduce the formation of hazardous pollutants, an attractive pathway to enhance its performance is to emulsify HFO with water. In this regard, the present investigation addresses fundamental, as well as practical aspects of the combustion of HFO-water emulsions under swirling-flame conditions, which aim to mimic the combustion process in typical industrial-scale boilers. Emulsions were prepared via sonication, and samples with water contents of 0 (pure HFO), 5, 10, 15, 20, and 30 wt. % were obtained. The combustion experiments were carried out in a lab-scale burner with an air-blast nozzle and swirling airflow, which generates an environment similar to the one in real boiler burner operation. Laser diagnostics were implemented in order to gain insights regarding the impact of micro explosion phenomena on soot, cenosphere, and particulate matter (PM) formation during the combustion of emulsified HFO. Furthermore, advanced analytical techniques, including Scanning Electron Microscope (SEM) and X-Ray Photoelectron Spectroscopy (XPS) were utilized to study the fundamental characteristics (morphology, structure, sulfur content, etc.) of the PM/cenosphere collected from the experimental campaign. Experiments showed that the emulsified HFO flame tends to be very unstable for water contents higher than 15 wt.%, and even hard to maintain when this content is 30 wt.%. The addition of 15 wt. % of water in HFO resulted in a decrease in the soot concentration and size, which was attributed to the micro-explosion phenomenon taking place during the emulsified HFO combustion. Similarly, micro-explosions seem to induce the conversion of thiophene constituents (dominant sulfur-containing compounds in the collected PM) into sulfones due to better oxidation characteristics. Overall, the obtained results presented in this study aim to provide fundamental knowledge needed to implement HFO-water emulsions on an industrial scale.

Keywords: Heavy fuel oil, water emulsions, swirling flame combustion, particulate matter

1. Introduction

Heavy fuel oil (HFO) is a low-grade fuel currently used in different applications including marine engines, industrial blast furnaces, and utility boilers for electricity generation, among others. HFO has been recently denoted as an opportunity fuel in the energy sector due to its high energy density (HHV = 42.47 MJ/kg), extensive availability, low cost, as well as the scarcity of easily extractable light-sweet crude oils. However, HFO is characterized by having a high viscosity (617.740 cSt), high molecular weight (750 g/mol), high asphaltenes content (8.2 wt. %), and complex compositional diversity. In addition, high carbon residues, trace metals such as vanadium (18 mg/kg) and nickel (11 mg/kg), and fuel-bound nitrogen (0.239 wt. %) and sulfur (3.5 wt. %) are also some of its main features [1], [2]. All these aspects lead to a rather complex combustion process, which results in the formation of hazardous pollutants such as particulate matter (PM), soot, cenosphere, etc. Consequently, severe regulations regarding its use have been put in place; for instance, the IMO2020 (International Marine Organization) has restricted the use of HFO in the marine transport sector, mainly due to its high sulfur content. The marine sector is therefore moving towards alternative fuels such as diesel, marine gas oil (MGO), or other low-sulfur fuels which meet the IMO2020 requirements, thus causing a significant fall in the global demand for HFO.

In this context, it is foreseen that the displacement of HFO from the marine industry will be likely absorbed by the power generation sector in several countries, including among others Saudi Arabia, United Arab Emirates, Iraq, Lebanon, Bangladesh, Sri Lanka, South Korea, Cuba, Pakistan, etc. Even though there has been a strong push towards producing more power from both natural gas and renewable sources in some of these countries, the need for improving/developing existing and future HFO-based power plants to provide steady and reliable power will continue to be substantial. In fact, clean and efficient combustion practices of HFO in steam boilers remain essential for energy suppliers in Saudi Arabia [3]. Therefore, concentrated efforts are still required to continuously improve the efficiency of HFO combustion and minimize the formation of hazardous pollutants in order to be in line with the current normativity in terms of gaseous (SOx, NOx, etc.) and PM emissions.

Up to date, several strategies have been explored to tackle the challenges associated with the combustion process of HFO. For instance, oxidative desulfurization and flue gas desulfurization (FGD) have been widely studied to reduce the concentration of sulfur-containing compounds in the flue gases [4]–[6]. Likewise, emulsifying the fuel has been perceived as an attractive pathway to improve the combustion efficiency of HFO and reduce the formation of NOx and PM [7]. Roughly speaking, the combustion of an emulsified fuel results in a unique phenomenon known as a "micro explosion". When a droplet of an emulsified fuel is subjected to high temperatures, it undergoes preferential evaporation. Thus, the flash

evaporation of the lighter components contained in an emulsion droplet leads to micro-explosions, which cause subsequent fragmentation of the initial fuel droplets to form smaller ones [7]. Thereafter, intense and uniform mixing of the new small droplets with air takes place, hence increasing the efficiency of the burning process, as well as reducing the NOx and PM formation. Moreover, micro explosions may also break large asphaltene clusters, which facilitates the transformation of these difficult-to-burn fuel components contained in HFO, which are responsible for the formation of residual carbonaceous deposits, PM, etc.

Studies regarding the combustion of emulsified fuels have been extensively reported in the literature [8]–[10]. However, a deep understanding of the combustion process of an emulsified HFO, giving special attention to the morphological and chemical characteristics of the formed PM/cenosphere, is still scarce. Therefore, the present investigation provides fundamental as well as practical insights into the combustion of HFO-water emulsions under swirling-flame conditions, which aims to mimic the combustion process in typical industrial-scale boilers. Here, laser diagnostics were implemented in order to gain insights regarding the impact of micro explosion phenomena on the soot, cenosphere, and PM formation during the combustion of different emulsified HFO samples with various water content. Furthermore, advanced analytical techniques, including Scanning Electron Microscope (SEM) and X-Ray Photoelectron Spectroscopy (XPS), were utilized to study the fundamental characteristics (morphology, structure, sulfur content, etc.) of the PM/cenosphere collected along the experimental campaign.

2. Materials and Methods

2.1 Test fuels: HFO-water emulsions

For this study, HFO-water emulsions were prepared via ultrasonically induced cavitation (UIC), and samples with water contents of 0 (pure HFO), 5, 10, 15, 20, and 30 wt. % were obtained. Initially, 300 g of HFO were weighted and then 15.8, 33.3, 52.9, 75, 128.6 g of water were added to the HFO to produce emulsions with water contents of 10, 15, 20, and 30 wt. %, respectively. More information regarding the UIC system used to prepare these samples, as well as the advantages of implementing this method, can be found in previous works [7].

2.2 Swirling flame experimental setup

A simplified diagram of the swirling flame combustion setup used to carry out this investigation is displayed in **Fig. 1**. The main objective of this system is to produce a high-swirl stable turbulent jet diffusion flame to combust the HFO-water emulsions efficiently. In order to achieve this purpose, the burner was designed with a swirl generator where air enters tangentially and axially to induce a swirl-air jet [11].

Likewise, a blast air nozzle (Ref. Siphon P/N 30609-2) was installed inside the burner to generate the fuel spray. In the rig illustrated in **Fig. 1**, the swirling flame combustion experiment is initiated by feeding the fuel into the inlet vessel and preheating it to 100 °C in order to facilitate its flow through the system. Then, by creating a negative pressure (opening the vacuum line), the fuel is transferred to the storage tanks, which are also maintained at 100 °C. Once all the fuel has been completely transferred from the inlet vessel to the storage tanks, nitrogen is used to move the fuel towards the syringes (kept at 150 °C) which are used to inject the fuel into the central tube connected to the burner. As soon as the burner is ready for operation, the fuel sample is delivered to the central fuel tube by a syringe pump, which precisely controls the fuel flow rate. It is important to highlight that all lines in the system are kept at 100 °C in order to avoid any blockages during operation. A glass fiber filter is installed at the top of the burner to collect the PM/cenosphere formed during the experiment. The filter holder is maintained at low temperature by means of a water chiller in order to avoid any damage to the filter. A vacuum pump is connected to the filter holder to direct the PM/cenosphere and flue gases towards the filter and the venting system, respectively.
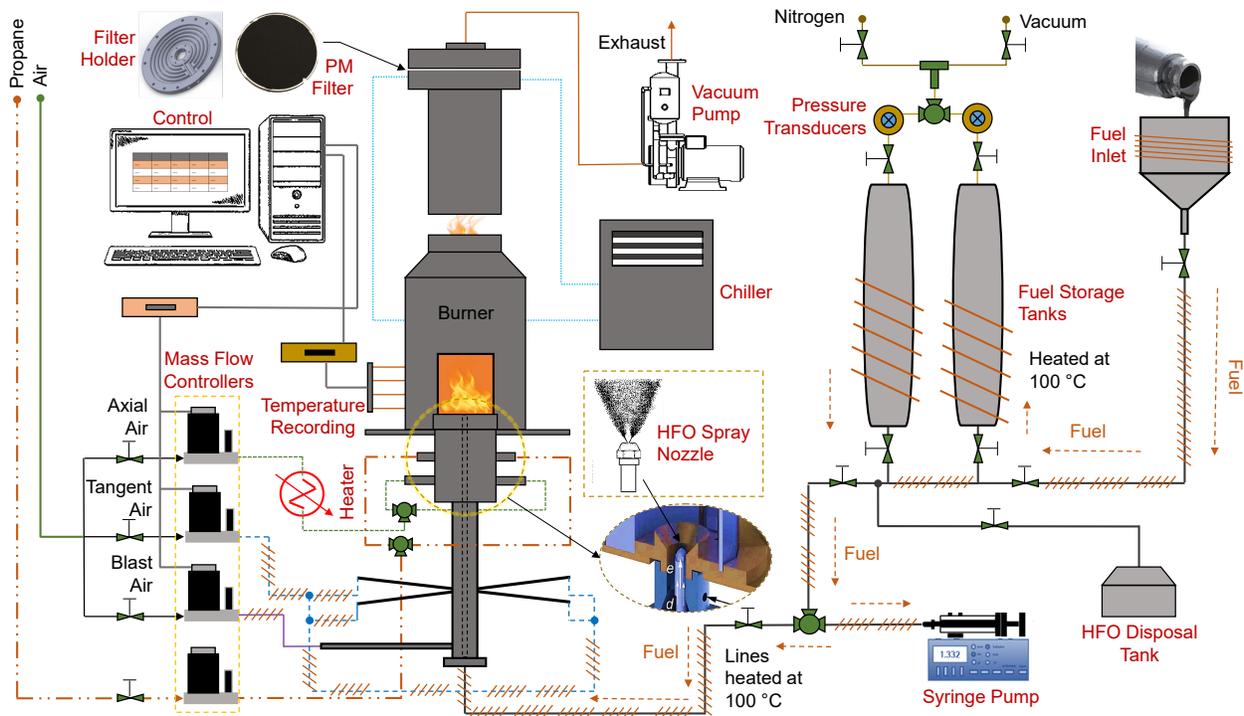
Fig. 1. Swirling flame combustion setup

Due to the high viscosity and high auto ignition temperature of HFO-water emulsions, a preheating step must be carried out to increase the temperature of the burner. Thus, before injecting the emulsified HFO into the central fuel tube, a propane flame is maintained for 30 minutes to reach a steady temperature in the combustion chamber. The operational conditions regarding the propane flame are provided in **Table 1**. As soon as the system is warm enough, the flow rate of emulsified HFO is slowly increased by adjusting the

syringe pump, while the flow rate of propane is decreased. This preliminary step is fundamental to reach a steady flame, particularly in the early stages of the experiment. The axial temperature of the flame is continuously monitored with an R-type thermocouple rake as shown in **Fig. 1**. The operational conditions for the swirling flame experiments are listed in **Table 1**.

Table 1. Swirling flame combustion: Experimental conditions

Parameter	Tangent air (SLPM)	Atomizing air (SLPM)	Methane (SLPM)	Axial air (SLPM)	Fuel (ml/min)
Flow Rate	150	10	1	5	15
Temperature (°C)	300	150	25	300	150
Swirling Number (S_g)	19.2				
SLPM: Standard liters per minute					

A distinction aspect of this study is the use of laser diagnostics to understand in detail the impact of the micro-explosion phenomenon on soot, cenosphere, and PM formation during the combustion of emulsified HFO. In this regard, two types of experiments were conducted: (*i*) light extinction to estimate the soot volume fraction and (ii) light scattering to identify the size distribution of the soot/PM formed. A diagram of the laser setup used for the extinction and scattering measurements is shown in **Fig. 2**. Here, a CW solid-state laser (COHERENT Genesis 532-2000 S OPSL) capable of emitting at a wavelength of 532 nm was used. An optical chopper was utilized to modulate the laser intensity, while a lock-in amplifier improved the signal to noise ratio. After intensity modulation, the laser beam was expanded using lenses L_1 and L_2. The mirror M_2 directed the beam towards the flame, and the lens L_3 focused the beam towards the center of the flame. The laser beam passed through flame, where it was scattered by the soot particles formed.
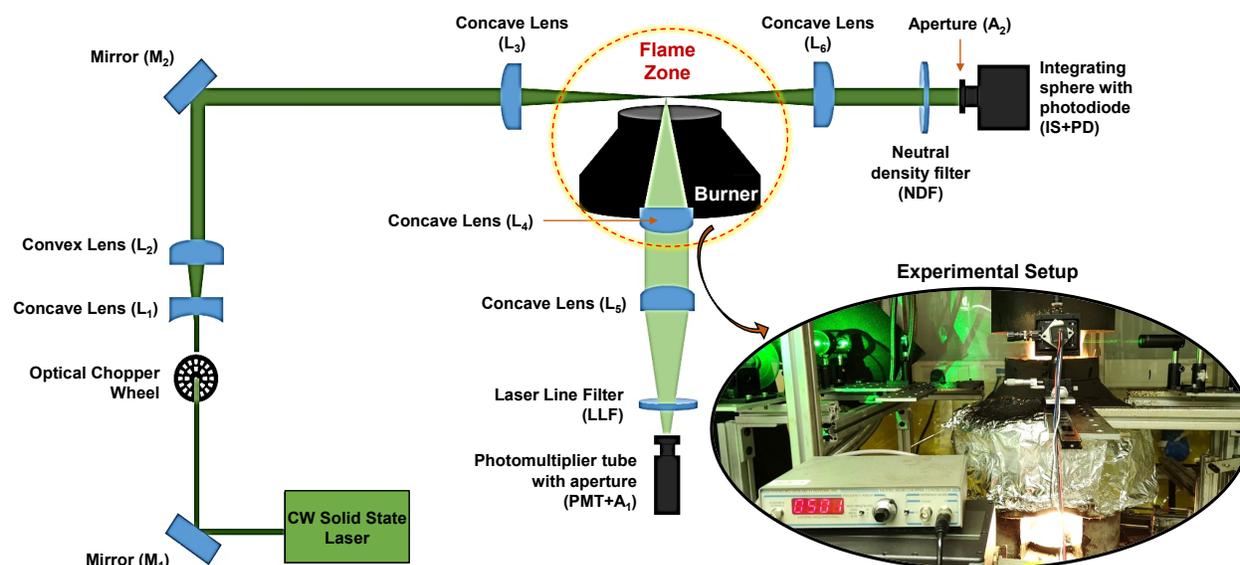
Fig. 2. Laser extinction and scattering setup

The scattered light was collected and focused on the Photomultiplier tube (PMT) by lenses L_4 and L_5, which were placed perpendicular to the beam path. Laser line filter (LLF) centered at wavelength 532 nm with FWH 3 nm together with aperture (A_1) was used to filter out unwanted radiation from the flame and surroundings.

Regarding the laser extinction measurement, a collimating lens (L_6) collected the attenuated laser beam, which passed through the flame. A Photodiode (PD) attached to the Integrating Sphere (IS) was used to measure intensity changes in the laser beam by scattering. The integrating sphere diminished the effects of beam steering in the flame environment. Aperture (A_2) was used to avoid unwanted radiation from the surroundings. Finally, a neutral density filter (NDF) was used before the integrating sphere to reduce laser intensity and avoid saturation of the PD.

3. Results and discussions

3.1 Combustion characteristics of emulsified HFO

Fig. 3a and **Fig. 3b** show images obtained from the flames of pure HFO and the HFO-water emulsion with 15 wt. % of water content, respectively. In contrast to the flame observed with pure HFO, the micro-explosion phenomenon is noticed in the emulsified fuel flame. This phenomenon can be seen as a secondary atomization of the fuel droplets, which results in a distinguishable number of sparks surrounding the flame (white circle in **Fig. 3b**). Roughly speaking, during the combustion of HFO-water emulsions, the difference in the boiling points of the dispersed phase (water) and the continuous phase (HFO) leads to the formation of bubles in the liquid medium. At the fuel spray stage, the smaller water droplets trapped inside the big HFO droplets absorb latent heat and reach the boiling temperature. Thereafter, they become superheated before being released via micro explosions [12].

| a) Pure HFO | b)   HFO + 15 wt.% water |
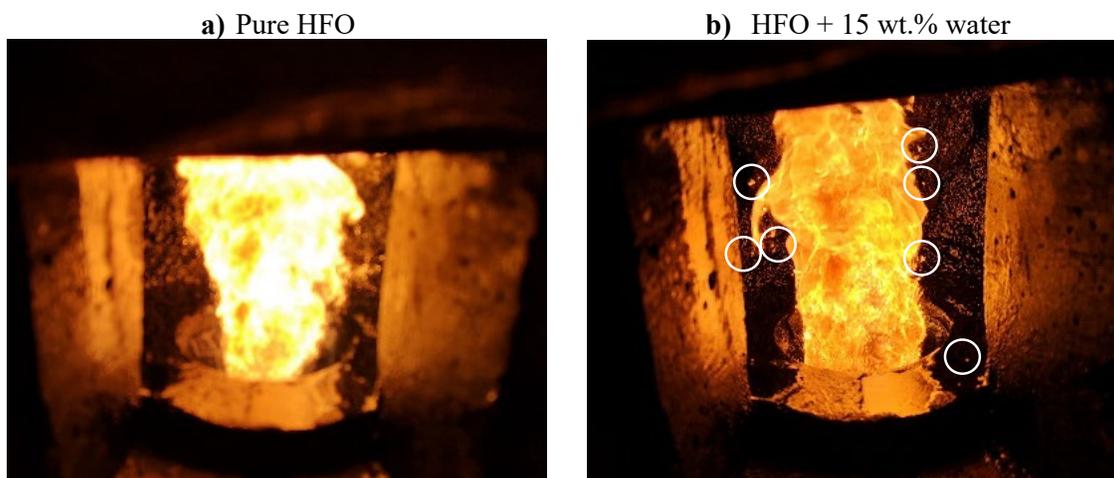
Fig. 3. Images taken from swirling flame combustion experiments

Regarding the axial flame temperature, a significant reduction was observed as the water content in the emulsion increased (**Fig. 4**). This evident drop in the flame temperature can be attributed to the heat absorbed by the water contained in the emulsion as latent heat of vaporization. The lowest flame temperature was obtained with emulsions with water content of 30 wt. %, which indicates that in this case, the heat loss associated with the vaporization of water becomes dominant. It is worth mentioning that, for emulsions with water contents higher than 15 wt. % (20 and 30 wt. %), the flame was quite unstable and difficult to maintain during the experiment. This may be linked to the negative influence of the high water content on the heating value of the fuel. In addition, previous studies showed that the higher the water content in the emulsion, the higher the dynamic viscosity [7]. This effect on viscosity may certainly influence the spray characteristics, hence the combustion efficiency. All these factors would undoubtedly interfere with the normal/continuous operation of the burner, which is unacceptable in conventional combustion systems such as boilers and turbines. Similarly, if these issues dominate the combustion process, the micro explosion phenomenon would not be effective and the soot formed may remain unoxidized. Taking this into account, the obtained experimental results suggest that a water content of 15 wt. % may be optimal since it strikes a balance between the micro explosion effects, a high temperature of the flame, and maintaining a proper heating value of the fuel, which all give rise to a continuous/normal operation.
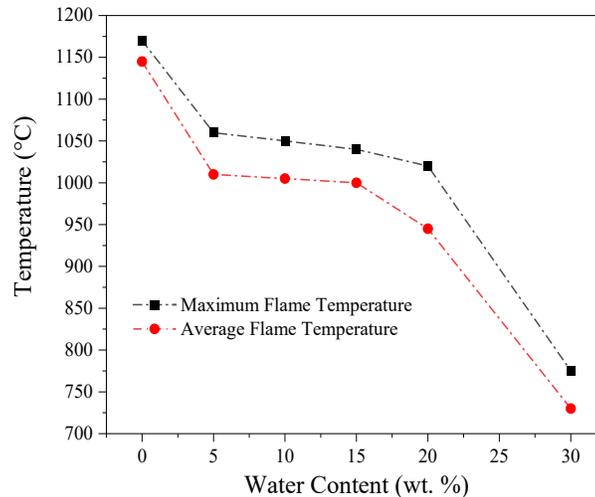
Fig. 4. Axial flame temperature depending on the water content in the emulsion

3.2 Laser diagnostics

The concentration of soot (f_v) during the combustion of HFO-water emulsions with various water contents is shown in **Fig. 5a**. It is observed that the water contained in the emulsion causes a reduction in f_v, with a slight decrease for emulsions with water contents of 5 wt. % and 10 wt. %, while a more evident change when adding 15 wt. % of water. As mentioned before, the micro explosions taking place during the

combustion of an emulsified fuel can be seen as a secondary atomization of the initial fuel droplets to form smaller ones. This phenomenon may be reflected in an improvement of the combustion efficiency, and thus a reduction in the soot formation during the combustion process. Furthermore, previous works have reported that the addition of water causes an increase of the production of OH radicals, which can be effective in oxidizing soot precursors [7]. Therefore, a reduction in the soot formation tendency may be expected. However, **Fig. 4a** also shows an opposite behavior of f_v for emulsions with water contents of 20 wt. % and 30 wt. %. As highlighted before, the higher the water content in the emulsion, the lower the flame temperature. The significant reduction of the flame temperature can lead to, among others, an increase in the fuel viscosity and density, which ultimately affects the spray characteristics. The latter may cause a poor combustion performance induced by the instabilities associated with the relatively low global equivalence ratio [7]. Consequently, the improvements in the combustion efficiency linked to the micro explosion phenomenon are stifled due to the energy lost as heat of vaporization related to the phase change of the water contained in the emulsion. As a result, the fuel sample with the lowest flame temperature (30 wt. % water content) was also linked to the highest f_v.

The variation of primary soot particle diameter (Dp) is shown in **Fig. 4b**. In contrast to pure HFO, the emulsified HFO combustion generated smaller soot particles whose Dp decreased as the water content in the emulsion increased. Once again, these observations align well with the micro explosion phenomenon since it leads to the shattering of initial fuel droplets into a number of fine secondary droplets; in turn, smaller soot particles are formed. Moreover, during the combustion of fuel-water emulsions there is a reduction in the formation of polyromantic hydrocarbons (PAHs), which are known for being soot precursors; thus, smaller particles may be formed.
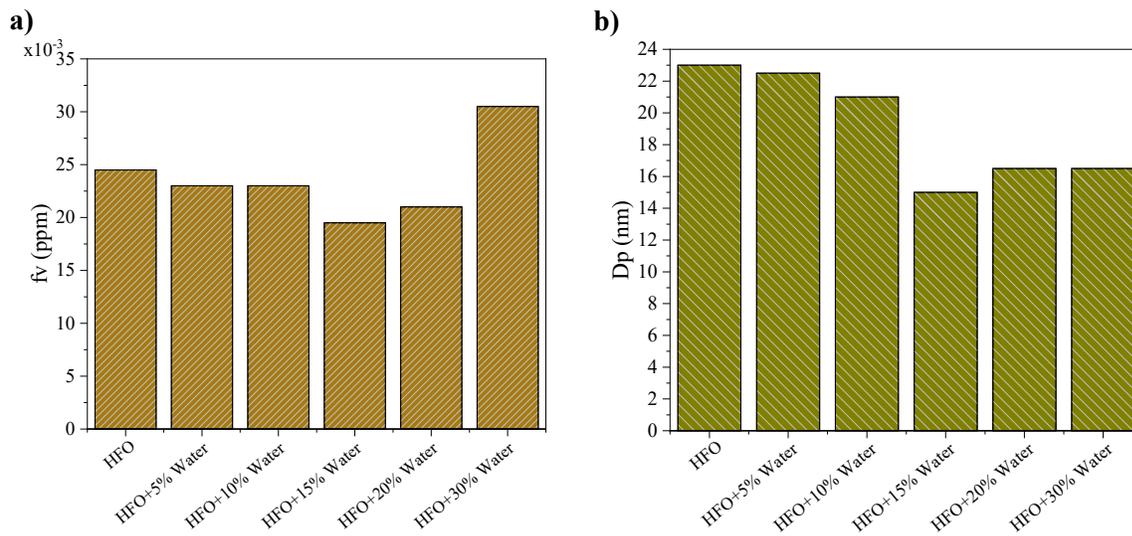
Fig. 5. Laser diagnostics: **a)** soot concentration and **b)** primary particle diameter

3.3 Morphological characteristics of the PM

SEM images of the PM/cenospheres collected from the glass fiber filters after swirl-flame combustion experiments of different emulsified fuel samples with various water contents are provided in **Fig. 6**.

a) Pure HFO

b) HFO + 5 wt.% water

c) HFO + 10 wt.% water

d) HFO + 15 wt.% water

e) HFO + 20 wt.% water

f) HFO + 30 wt.% water
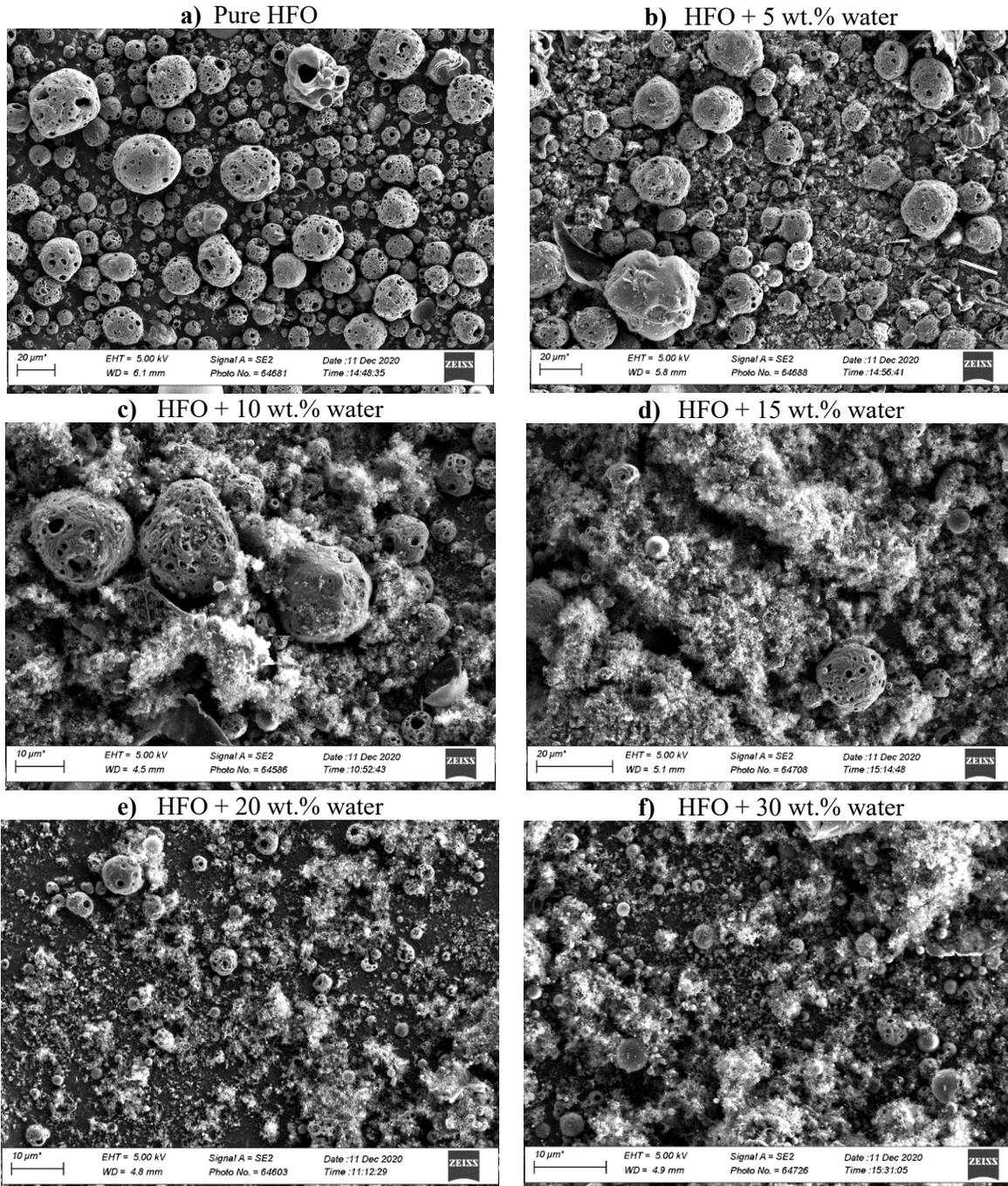
Fig. 6. SEM images of the PM obtained from the combustion of emulsified HFO with various water contents

As described in a previous work conducted by our group [13], typical cenospheres obtained from the combustion of HFO can be classified into three types: (*i*) *Type A*: a particle with a carbonaceous and porous shell, which exhibits a diameter smaller than the initial HFO droplet, (*ii*) *Type B*: a globular particle whose diameter is larger than the initial HFO droplet, and which can be hollow on the inside and contain a skeleton and some bubbles, and (*iii*) *Type C*: a particle which has a perfectly spherical and smooth morphology, whose diameter is much smaller than the other two types of cenosphere, ranging from 10 to 100 μm. In addition to the previous previous characteristics, the globules found in *Type B* do not show blowholes on the surface as seen on *Type A*, while *Type C* cenospheres are hollow but they do not exhibit any porous structure on the surface. Based on this classification, the PM/cenospheres obtained from the experimental campaign are predominantly *Type A* (spherical particles with hollow centers) for all cases. Nonetheless, it was observed that aside from the highly porous structure, the water content in the emulsion has an influence on the average size of the resulting particles. Thus, at higher water contents in the emulsion, the distribution of the average size of the particles tends to shift to the left (**Fig. 7**), implying smaller particles. All these features may be induced by the occurrence of micro explosions, which are more intense at higher water contents.
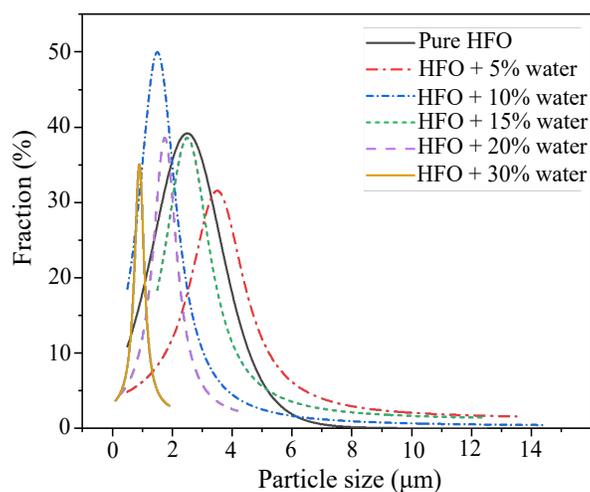
Fig. 7. Particle size distribution of cenosphere obtained from SEM images

3.4 Distribution of sulfur-containing compounds in the collected PM/cenosphere

Fig. 8 shows the XPS spectra and their deconvolution results for different sulfur-containing compounds distributed in the PM/cenospheres collected for emulsions with water contents from 0 to 20 wt. %. Each peak resolved in **Fig. 8** is associated with a specific sulfur-containing compound. In the spectra displayed in **Fig. 8**, the area under the curve was associated with the concentration of the specific compound. As mentioned before, for the emulsion with 30 wt. % of water, the flame was quite unstable and hard to

maintain; thus, the uncertainties regarding the experimental process were higher. In view of this, the PM/cenosphere sample collected from this sample was not included in this analysis.
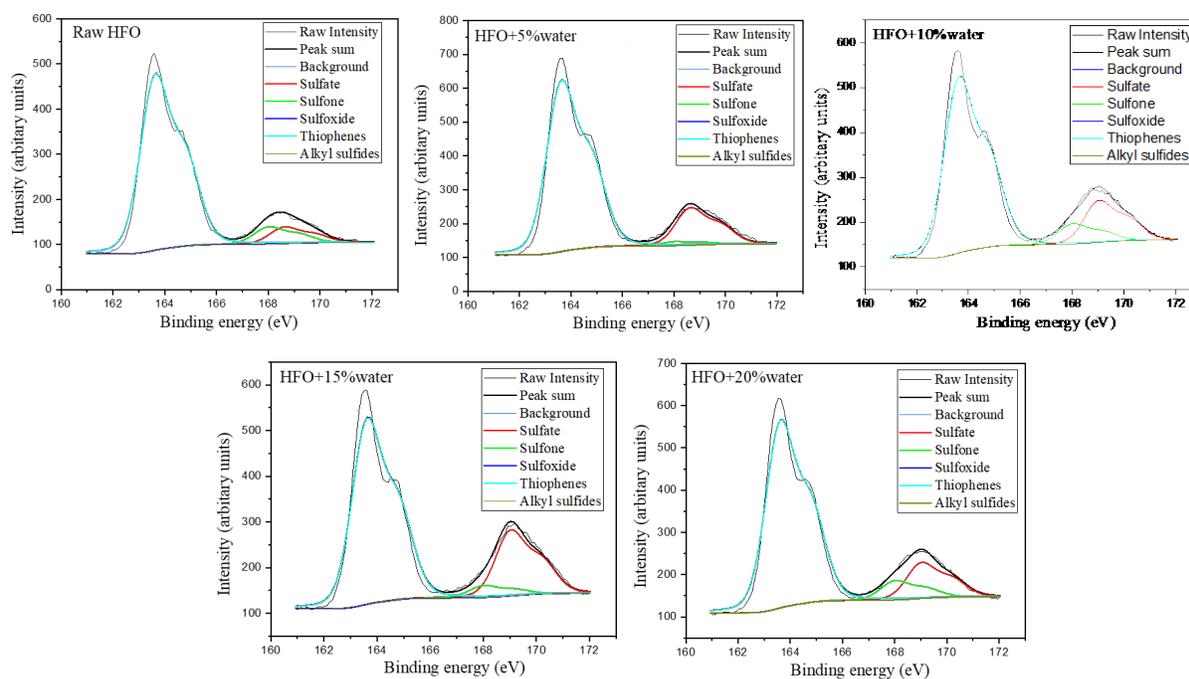
Fig. 8. XPS spectra for cenospheres collected from different emulsified HFOs

Based on the information reported in **Fig. 8**, **Fig. 9** shows the distribution of the resolved sulfur-containing compounds in the collected PM/cenosphere. It is worth to point out that sulfur compounds such as sulfoxides and alkyl sulfides are negligible in the PM/cenosphere composition in this particular case; thus, for the sake of simplicity and to facilitate the reader understanding, they have not been included in the distribution shown in **Fig. 9**.
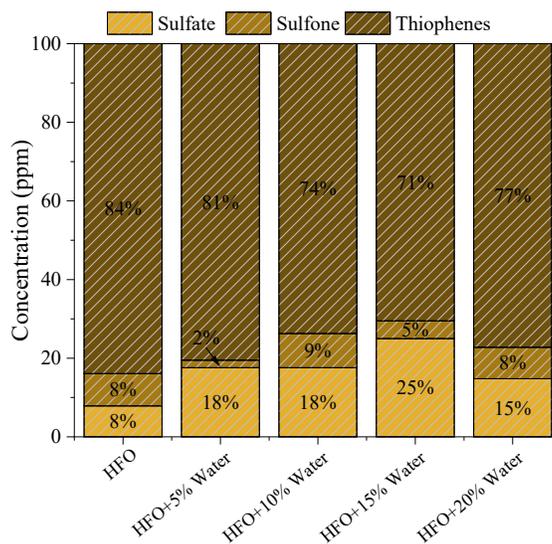
Fig. 9. Distribution of sulfur-containing compounds in the cenospheres obtained from HFO emulsions

As observed, the dominant sulfur-containing compounds in the PM/cenospheres collected from both pure HFO and HFO-water emulsions in the form of thiophenes. Nonetheless, the amount of sulfur-containing compounds present in aromatic structures seems to decrease as the water content in the HFO-water emulsion increases. These results indicate that the presence of water enhances the decomposition of thermally stable aromatic sulfur to form other sulfur-containing compounds such as sulfones and sulfates, which can be treated more easily in order to minimize their hazardous effect to the environment and public health.

4. Conclusions

The present work aimed to provide fundamental insights regarding the characteristics of the PM/cenospheres formed during the swirling flame combustion of HFO-water emulsions. The results obtained from swirling flame combustion suggested that the PM/cenospheres produced by emulsified HFOs are smaller in contrast to pure HFOs. Likewise, as the water content in the emulsion increased, finer particles are obtained. These tendencies were associated with a phenomenon known as the "micro-explosion", which seems to be induced by the presence of water in HFO. It was observed that micro-explosions act as a secondary atomization and break the original fuel droplet apart, which gives rise to finer droplets, and thus smaller PM/cenospheres. The formation of smaller droplets as a result of micro-explosions can lead to a better combustion efficiency due to better air/fuel mixing. However, it was noticed that even though a higher water content in the emulsion intensifies this effect during combustion, it may also affect the stability of the flame. This would certainly interfere with normal/continuous operation of, for instance, boilers or gas turbines. In this regard, the obtained experimental results suggested that a water content of 15 wt. % may be optimal in order to reach a balance between the beneficial effect of micro-explosions, flame stability, and a proper heating value of the fuel. In addition to finer PM/cenospheres, the presence of water in the fuel seems to favor the transformation of sulfur-containing compounds in aromatic structures into smaller molecules which are less hazardous to the environment.

5. Acknowledgement

References

[1]   A. M. Elbaz, A. Gani, N. Hourani, A. H. Emwas, S. M. Sarathy, and W. L. Roberts, "TG/DTG, FT-ICR mass spectrometry, and NMR spectroscopy study of heavy fuel oil," *Energy and Fuels*, vol. 29, pp. 7825–7835, 2015.

[2]   A. G. Abdul Jameel, A. M. Elbaz, A. H. Emwas, W. L. Roberts, and S. M. Sarathy, "Calculation of average molecular parameters, functional groups, and a surrogate molecule for heavy fuel oils using ^{1}H and ^{13}C nuclear magnetic resonance spectroscopy," *Energy and Fuels*, vol. 30, pp. 3894–3905, 2016.

[3]   R. Shabaneh, H. Al Sadoon, and R. Al Mestneer, "Implications of IMO 2020: The potential for high sulfur fuel oil penetration in Saudi Arabia," 2019. [Online]. Available: file:/// Implications-of-IMO-2020-The-Potential-for-High-Sulfur-Fuel-Oil-Penetration-in-Saudi-Arabia.pdf.

[4]   J. Zongxuan, L. Hongying, Z. Yongna, and L. Can, "Oxidative desulfurization of fuel oils," *Chinese J. Catal.*, vol. 32, pp. 707–715, 2011.

[5]   R. Javadli and A. De Klerk, "Desulfurization of heavy oil-oxidative desulfurization (ODS) as potential upgrading pathway for oil sands derived bitumen," *Energy and Fuels*, vol. 26, pp. 594–602, 2012.

[6]   R. K. Srivastava and W. Jozewicz, "Flue gas desulfurization: The state of the art," *J. Air Waste Manag. Assoc.*, vol. 51, pp. 1676–1688, 2001.

[7]   X. Pei, P. Guida, K. M. AlAhmadi, I. A. Al Ghamdi, S. Saxena, and W. L. Roberts, "Cenosphere formation of heavy fuel oil/water emulsion combustion in a swirling flame," *Fuel Process. Technol.*, vol. 216, pp. 106800, 2021.

[8]   S. Park, S. Woo, H. Kim, and K. Lee, "Effect of diesel-water emulsified fuel on the NOx and PM emissions of a diesel engine," *Energy and Fuels*, vol. 30, pp. 6070–6079, 2016.

[9]   A. K. Hasannuddin *et al.*, "Performance, emissions and carbon deposit characteristics of diesel engine operating on emulsion fuel," *Energy*, vol. 142, pp. 496–506, 2018.

[10]   J. Oh, M. Im, S. Oh, and C. Lee, "Comparison of NOx and smoke characteristics of water-in-oil emulsion and marine diesel oil in 400-kW marine generator engine," *Energies*, vol. 12, pp. 1–15, 2019.

[11]   M. Bohon, "Experimental and kinetic investigation of the influence of OH groups on NO_X formation," PhD Thesis, King Abdullah University of Science and Technology, KSA, 2016.

[12]   M. M. Avulapati, T. Megaritis, J. Xia, and L. Ganippa, "Experimental understanding on the dynamics of micro-explosion and puffing in ternary emulsion droplets," *Fuel*, vol. 239, pp. 1284–1292, 2019.

[13]   L. Jiang *et al.*, "Cenosphere formation during single-droplet combustion of heavy fuel oil," *Energy and Fuels*, vol. 33, pp. 1570–1581, 2019.