

NUMERICAL MODELING FOR THE VAPORIZATION AND COMBUSTION OF WATER- HEAVY FUEL OIL EMULSION DROPLET

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Abstract: *The vaporization and combustion characteristics of a heavy oil-water emulsion droplet are investigated by analyzing the multicomponent heat and mass transport processes in the gas phase and the gasification of an immiscible liquid mixture at the gas-liquid interface.*

Keywords: *fuel, combustion, numerical modelling, mass concentration.*

1. INTRODUCTION

We shall postulate in the following a theoretical model to describe the vaporization and combustion of oil/water emulsion droplets, aiming to substantiate and/or clarify the various potential benefits of their utilization. In the model the dependence of the combustion characteristics such as the flame size and temperature, the droplet temperature and its surface regression rate, and the concentrations of the various species, will be studied as functions of the ambient parameters such as the pressure, and the emulsion parameters such as the fuel type and the water content.

The problem of interest is the spherically symmetric, isobaric vaporization, with or without an enveloping diffusion flame, of an emulsion droplet in a constant atmosphere characterized by its temperature T_∞ , pressure p_∞ , and oxidizer mass fraction $Z_{0\infty}$. The emulsion consists of water and marine fuel, although no distinction is made regarding which is the internal or the dispersed phase.

The gas-phase processes are assumed to be quasi-steady with respect to all the liquid-phase processes.

At the droplet surface both the fuel and water micro-droplets are accessible to the gas phase, and become vaporized upon receiving heat from either the ambience or the flame. In

the case of combustion the outwardly diffusing fuel vapor reacts stoichiometrically and completely with the inwardly diffusing oxidizer gas at an infinitesimally thin flame-front located at r_f , forming water vapor and other product species. Except for the interfacial phase change process, water behaves as an inert in all the chemical reactions.

Finally we shall also assume for simplicity that the gas phase specific heat C_p' and thermal conductivity coefficient k' are constants, and that its Lewis number is unity. An analysis of the phenomena consists of descriptions for the gas-phase processes, the liquid-phase processes, and their coupling at the gas-liquid interface including the phase change processes. These will be presented in the following.

2. THE GAS-PHASE SOLUTIONS

With the above assumptions, the governing equations for the gas-phase convective-diffusive heat and mass transport in the inner and the outer regions to the flame are given by:

a) inner region where $l < r < r_f$:

$$mZ_F - \frac{r^2 dZ_F}{dr} = m_F \quad (01)$$

$$mZ_W - \frac{r^2 dZ_W}{dr} = m_W \quad (02)$$

$$m(T - T_s) - \frac{r^2 dT}{dr} = -(m_F L_F + m_W + mL_H) \quad Li = \frac{L'_i}{L'_w}; \quad (03)$$

where:

$$m_i = \frac{m'_i}{4\pi r'_s c'_t / C'_p} \quad \text{and} \quad r = \frac{r'}{r'_s}$$

Outer Region where $r_f < r < \infty$:

$$mZ_0 - \frac{r^2 dZ_0}{dr} = -\omega_0 m_F \quad (04)$$

$$mZ_W - \frac{r^2 dZ_W}{dr} = m + (v_0 - v_p) m_F \quad (05)$$

$$m(T - T_s) - \frac{r^2 dT}{dr} = -(m_F L_F + m_W + mL_H) + m_F Q_F \quad (06)$$

where:

$$T = \frac{C'_p T'}{L'_w}; \quad Li = \frac{L'_i}{L'_w}; \quad Q_F = \frac{Q'_F}{L'_w}$$

In the above equations:

r - is the radial distance;

$$r = \frac{r'}{r'_s};$$

m_i - the mass flow rate of species i ;

$$m_i = \frac{m'_i}{4\pi r'_s c'_t / C'_p};$$

T - is the temperature;

$$T = \frac{C'_p T'}{L'_w};$$

Z_i - the mass fraction;

L_i - the specific latent heat of vaporization;

Q_F - the chemical heat release per unit mass of fuel vaporized;

$$Q_F = \frac{Q'_F}{L'_w};$$

v_i - the stoichiometrically mass ratio of species i to the fuel;

L_H ' - is the sensible heat required to heat the droplet interior per unit mass of liquid vaporized;

and

- the subscripts F, O, W, P, s, f, and ∞ respectively designate fuel, oxidizer, water, all the product species except water, droplet surface, flame, and infinity.

Integrating equations (1) to (3) from $r = 1$ to r_f equations (4) to (6) from $r = r_f$ to, and $r = \infty$ requiring that $Z_{0(rf)} = 0$, it can be shown that the various parameters of interest are:

- the mass flow rate,

$$m = \ln(1 + B) \quad (07)$$

- the flame-front,

$$r_f = \frac{m}{\ln(1 + \frac{Z_{0\infty}}{\omega_0 \varepsilon_F})} \quad (08)$$

- the temperature of flame-front,

$$T_f = T_s + \frac{(B - Z_{0\infty} / \omega_0 \varepsilon_F)(\varepsilon_F L_F + \varepsilon_W + L_H)}{(1 + Z_{0\infty} / \omega_0 \varepsilon_F)} \quad (09)$$

- the mass concentration of water to the flame-front,

$$Z_{Wf} = \frac{Z_{W\infty} + (Z_{0\infty} / \omega_0 \varepsilon_F)[1 + (\omega_0 - \omega_p)\varepsilon_F]}{(1 + Z_{0\infty} / \omega_0 \varepsilon_F)} \quad (10)$$

- the mass concentration of fuel to the surface of the droplet,

$$Z_{Fs} = \frac{(B - Z_{0\infty} / \omega_0 \varepsilon_F)\varepsilon_F + (1 + Z_{0\infty} / \omega_0 \varepsilon_F)Z_{Ff}}{(1 + B)} \quad (11)$$

- the mass concentration of water to the surface of the droplet,

$$Z_{Ws} = \frac{(B - Z_{0\infty} / \omega_0 \varepsilon_F)\varepsilon_W + (1 + Z_{0\infty} / \omega_0 \varepsilon_F)Z_{Wf}}{(1 + B)} \quad (12)$$

where:

ε_F - is the fractional mass evaporation rate such that $\varepsilon_F + \varepsilon_W = 1$;

B - the transfer number.

The solutions specialize for pure vaporization is $Z_{0\infty} = 0$, $Z_{Ff} = Z_{F\infty}$, and to combustion $Z_{Ff} = 0$.

3. DETERMINED BURNING CHARACTERISTIC

To solve the equations 7-12 I used a program conceived for mathematical application interpreter MathCAD 7, in which the solutions obtained by algebraic iteration of equations mentioned above, were transposed into digital functions and graphically represented.

The characteristic data used in this program for expressing the physical values was chosen for marine heavy fuel from the technical literature.

Figures 1 and 2 show the characteristic of a droplet of emulsion water – marine heavy fuel subjected to burning in standard atmosphere at the combustion chamber's temperature of 1000 [K] as functions of emulsion water volume fraction V_{W1} .

Figure 1 shows the variation of transfer rate of total mass, m , with the emulsion water concentration.

The vaporization rate of droplet decreases when the fuel emulsification degree increases but this reduction being small it is entirely neglected for determining the vaporization rate of atomization when the micro explosion appears.

Figure 2 presents the variation of droplet

temperature with emulsion water concentration.

The emulsification induces a decrease of droplet temperature and therefore the possibility of reducing the carbon block (soot) in the liquid carbonization processes.

Figure 3 shows the radius variation of flame front with emulsion water concentration.

So, for a moderate content of water, be it said $V_W < 0.3$ when the emulsion coefficient V_W increases, the dimension of flame front exponentially decreases and according to figure 4 the flame temperature decreases a little.

The rates of chemical reactions being exponential functions of temperature, these results show that at a high water emulsion, the intensity and the volume of chemical reactions in the flame area decrease exponentially.

The determined burning characteristics show that when the water volume in emulsion V_W increases, the values of transfer rate of total mass, m , of droplet surface temperature T'_s , of flame front temperature T'_f , of flame front radius r_f and of fuel mass fraction on it's surface V_{FS} decrease and the values of water mass fractions on the droplet surface Z_{WS} and at the level of flame front Z_{WF} increase.

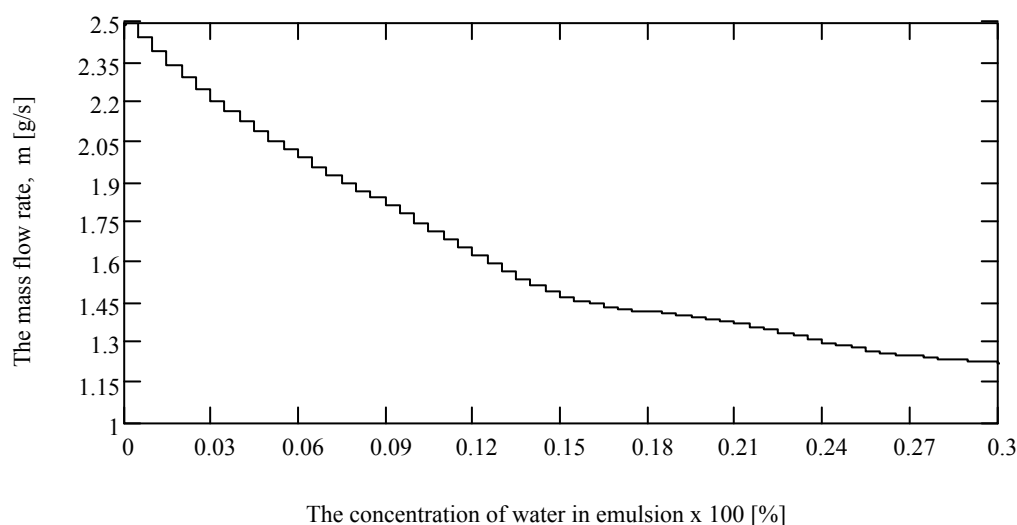


Fig. 1 The variation of transfer rate of total mass, m , with the emulsion water concentration

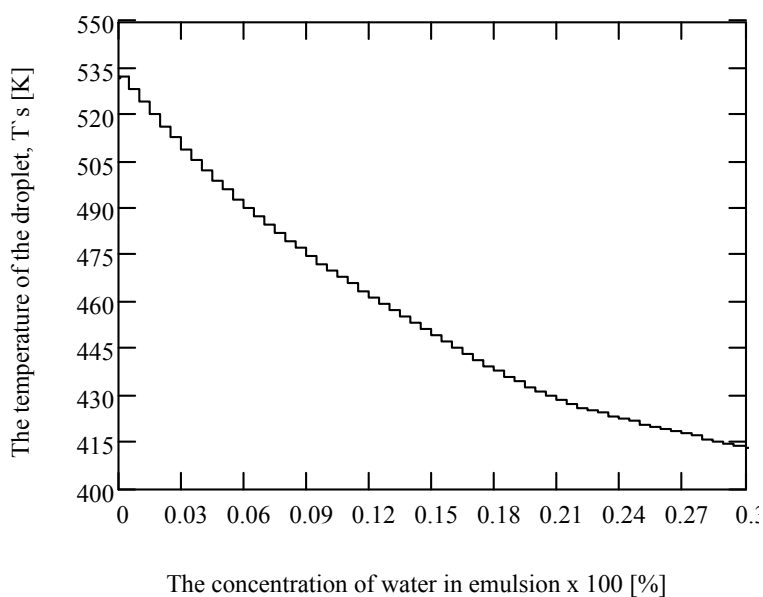


Fig. 2 The variation of droplet temperature with emulsion water concentration

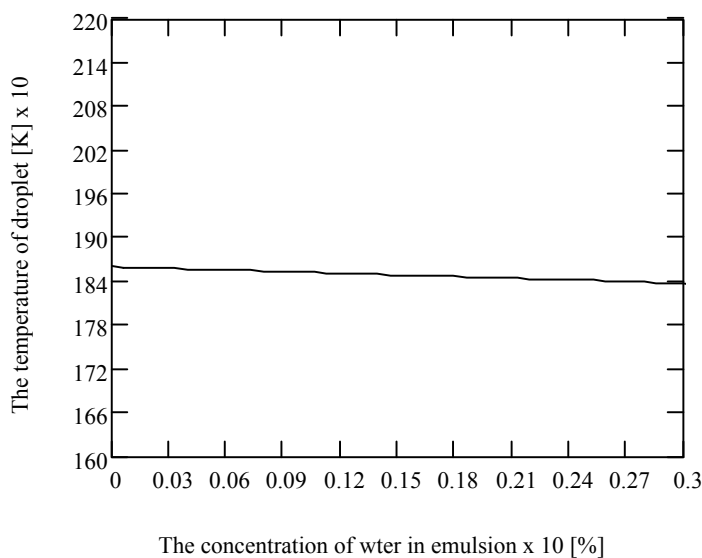


Fig. 3 The radius variation of flame-front with emulsion water concentration

It results that together with the increase of water percentage in emulsion the transfer rate of total mass decreases, the temperatures of droplet surface, of flame front and its radius decrease and on the droplet surface the fuel mass fraction reduces directly proportional to the increase of water mass fraction also influencing, to the same ratio, the flame front area.

Figures 5, 6, 7, and 8 show that at emulsion water fuel, the content of water vapors in the hot area rich in fuel between the flame and the droplet surface increases significantly.

The rich content appears in relative cold area near the droplet surface, where the reactions including those which lead to inducing gas carbon block (soot) are not intense.

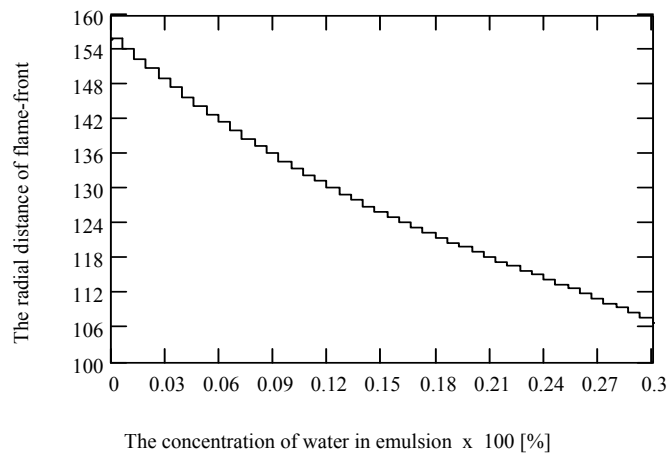


Fig. 4 The temperature variation of flame-front with emulsion water concentration

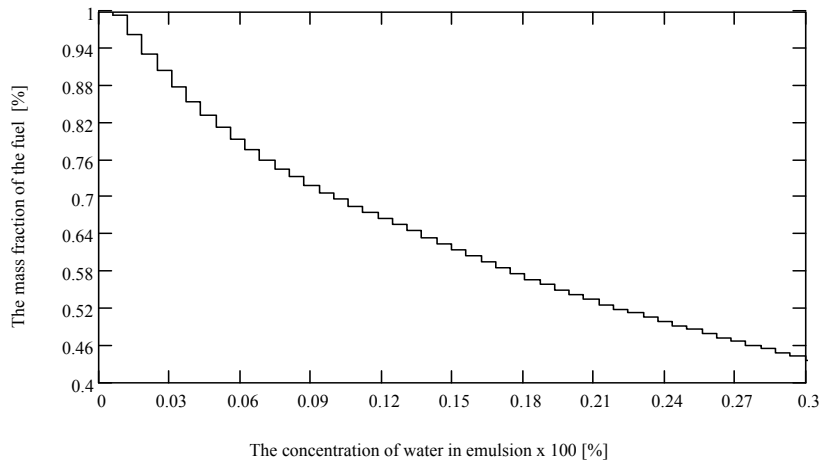


Fig. 5 The variation of the mass fraction of the fuel mass concentration of fuel to the surface of the droplet Z_{fS} , with emulsion water concentration

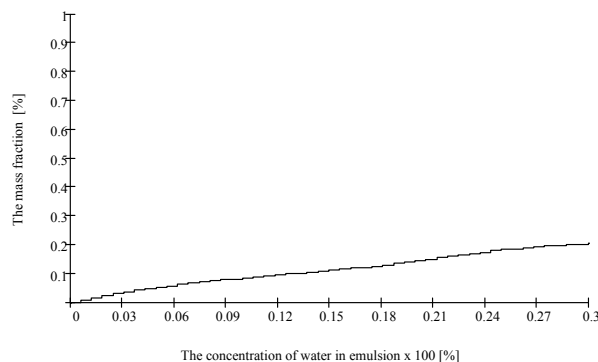


Fig. 6 The variation of mass concentration of fuel to the surface of the droplet Z_{wF} , with emulsion water concentration

The vaporization changes from being dominated by fuel to be dominated by water when emulsion water value rises above $V_w = 50[\%]$.

For a higher content of water, the flame temperature decreases rapidly and the droplet temperature reaches a constant value near to the boiling point of water.

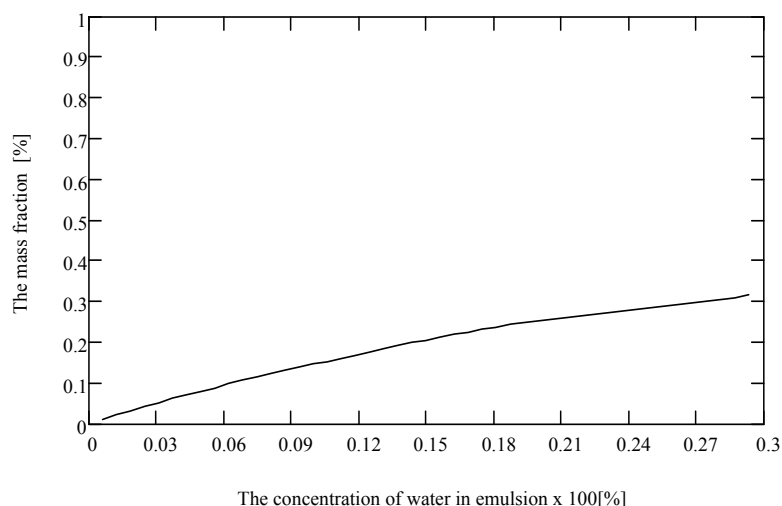


Fig. 7 The variation of mass concentration of water to the surface of the droplet Z_{ws} , with emulsion water concentration

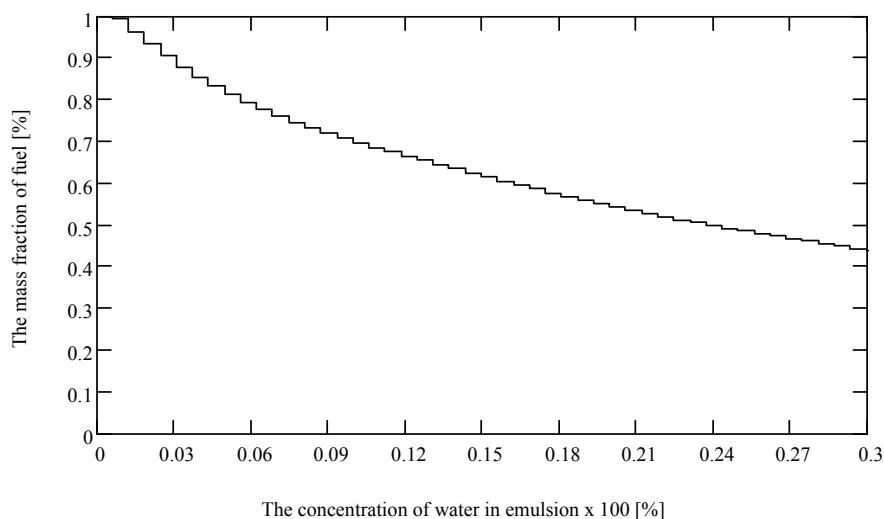


Fig. 8 The vaporization rate variation of the mass fraction of the fuel, with emulsion water concentration

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