MATHEMATICAL MODEL OF WATER-OIL EMULSION BURNING PROCESS

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Abstract: The paper presents the mathematical model of the processes involved in combustion of water-in-oil emulsion and the examination of the past research efforts in the field of oil combustion The model uses the oil properties and the emulsion characteristics, such as the water percentage present in the emulsion and the surrounding conditions as input data. The mathematical model is solved numerically using finite difference method.

Keywords: water-in-oil emulsion, combustion, droplet, emulsion burning, emulsion breaking temperature, oil vaporization

1. INTRODUCTION

Extensive studies by Buist and McCourt [1], Bech *et al.* [2], and Guenette *et al.* [3] have shown that emulsions containing more than a certain amount of water do not burn. Unburnable slicks of emulsion are reported to have water content ranging from as low as 20% to 30% for extremely weathered oils that form stable emulsions, to as high as 70% for less weathered oils that form less stable emulsions. This maximum possible water fraction in an emulsion that can be burned depends on various factors Also it is reported that the use of emulsion breakers to aid the ignition of emulsions often does not extend the maximum ignitable water content for emulsions of a given type of oil (Buist *et al.*[1]). The mechanism of water-in-oil emulsion combustion is far more complex than oil combustion. It has been postulated that it is not the emulsion that burns; rather a layer of oil separated out of emulsion and floating on top of emulsion that burns (Guenette *et al* [4]). Thus, the controlling factor in emulsion burning is the rate of removal of water. This can be done either by breaking the emulsion (especially for unstable emulsions) or boiling it out (emulsion must reach about 100 °C). In an extensive experimental study on liquid fuel layer combustion on water, Inamura *et al.* [6] estimated that a considerable amount of heat could be "lost" to the water via in-depth radiation absorption and conduction, making the water boil, breaking through the oil layer, and affecting the oil combustion. In the case of emulsions, water present in the emulsion layer also may boil away, making the process very complex.

Some observations of emulsion burning reveal that:

1. Incident heat helps separate water and oil in emulsion (Strom-Kristiansen *et al.* [7]).
2. When water content exceeds 25%, the emulsion is difficult to ignite (Buist *et al* [8]).
3. For a stable emulsion, water must be removed by boiling before igniting.
4. Emulsions above 50% can be successfully ignited and burned only if demulsifiers are introduced in the emulsion (Guenette *et al.*,[4]).
5. Burn efficiencies with emulsions, even with water content as high as 50%, are in excess of 90%.
6. Emulsions under certain conditions show a peculiar behavior of combustion characterized by flashing and then extinguishing over a large surface in a repetitive manner (Buist *et al.*[8]).

The efficiency of burning is the percentage of the original oil that is removed by burning. As there are finite heat losses to the water surface, the burn efficiency is always less than 100%.Burn efficiency decreases with increasing water content and evaporation (Buist *et al.*[8]). Important to note is that the efficiency is strongly dependent on the initial thickness of the emulsion, since the final thickness is governed by the heat loss mechanisms that cause the extinction of the fire. A detailed analysis of combustion of oil-emulsion was presented by Guenette *et al.*,[3] which was based on the work of Brzustowski and Twardus [9].

A large amount of research has been carried out in the field of emissions Polyaromatic Hydrocarbons are found to be lower in the soot than in the starting oil and are consumed by the fire to a large extent. The burn products are typically CO2- 75%, water vapor- 12%, soot- 10%, CO- 3% and other products including Polyaromatic Hydrocarbons- 0.2% (Tennyson,[10]). A series of tests was conducted in 1994 and 1998 to study emissions from oil burning.

It has been known in the field of fire research that several materials, such as most woods and certain plastics, do not sustain fire on a small scale unless assisted by external heat flux. Prior work shows that when a material (normally incombustible in the absence of external heat flux) is subjected to a minimum (also known as threshold or critical) heat flux, it can be ignited, and a sustained fire can be achieved (Brehob and Kulkarni,[11]).

2. MATHEMATICAL MODEL AND NUMERICAL SOLUTION OF W/O EMULSION BURNING PROCESS

The in-situ burning of water-in-oil emulsions involves several different processes as compared to the burning of unemulsified oils. Mathematical models are available in the literature for oil pool fires but not for emulsion pool fires. The basic premise of this model is that it is not the emulsion, that burns, but rather the oil that evaporates and burns. Therefore, to cause ignition, the emulsion must first separate into water and oil. It is the layer of oil floating on top of the emulsion that burns. This model incorporates the separation of emulsion into water and oil, a phenomenon that governs the emulsion pool fires.

First it is described the physical processes that occur during the in-situ burning of water-in-oil emulsions. Heat is transferred from a source, such as an igniter or adjacent fire, to the emulsion. As the emulsion heats up, it separates into water and oil. The breaking of emulsion into water and oil can occur in two ways: by boiling off the water contained within the emulsion and by reduction of the surface tension force between the oil and the water as the emulsion heats up. Both of these processes may be present simultaneously (Buist *et al.*[1]). When the emulsion is heated, the surface tension between the entrapped water droplets and the continuous oil phase decreases because of increasing temperature. As the surface tension forces fall below a certain level, the water droplets cannot be held in the oil phase any longer. Thus these droplets coalesce and form bigger droplets that drop out of the emulsion, thus creating an oil layer that floats on top of the emulsion. For some emulsions, however, the emulsion temperature may reach around 100 °C before the thermal separation of emulsion into oil and water can occur. For such stable emulsions, the water will start boiling off the emulsion layer. In case of thermal separation, the separation starts at the top of the emulsion layer, as the emulsion is heated from the top. However due to high viscosity of the emulsion layer, the separated water may not be able to escape through the bottom of the slick until the viscosity of the entire slick becomes low enough (Guenette *et al.*,[3]). As the emulsion starts to break into oil and water, the oil floats on top of the emulsion layer.

The condensed phase now consists of an oil layer, an emulsion layer and the water base. At the free oil surface, there is partial absorption of incident heat flux, in depth radiation absorption, heat loss to the surroundings by radiation and convection, and conduction in the condensed phase. As the top layer of oil receives heat, it heats up, vaporizes, and pyrolyzes. The pyrolysis gases mix with the oxidizer from the air, which is supplied by diffusion, aided by wind and turbulence. The mixture is ignited by the available ignition source or fire above the oil layer. The oil burning process is sustained by partial energy feedback to the emulsion slick from the combustion [5].

For the modeling purpose, the overall burning process is divided into three regimes as follows:

1. *Initial Regime* (t = 0 to t1): The model starts with an application of external heat flux to an emulsion layer. A constant heat flux is incident on the emulsion surface. The heat flux may be because of an igniter placed on the emulsion surface or by the surrounding fire. The emulsion layer is heated and eventually the top surface reaches the emulsion-breaking temperature. This marks the end of initial regime.

Governing equations:

$$\frac{\partial T_{e1}}{\partial t} = \alpha_e \frac{\partial^2 T_{e1}}{\partial x_e^2} \tag{1}$$

$$\frac{\partial T_{w1}}{\partial t} = \alpha_w \frac{\partial^2 T_{w1}}{\partial x_w^2} \tag{2}$$

Initial conditions:

$$\text{If } t = 0 \quad \begin{matrix} T_{e1} = T_i \\ T_{w1} = Ti \end{matrix} \tag{3}$$

Boundary conditions:

$$\text{If } x_e = H, \; k_e \frac{\partial T_{e1}}{\partial x_e} = q'' - h_e (T_{e1} - T_i) - \sigma \varepsilon_e \left(T_{e1}^4 - T_i^4 \right) \tag{4}$$

$$\text{If } x_e = 0, \; x_w = 0 \qquad k_e \frac{\partial T_{e1}}{\partial x_e} = -k_w \frac{\partial T_{w1}}{\partial x_w} \tag{5}$$

$$\text{If } x_w = \infty, \; T_{w1} = T_i \tag{6}$$

The initial regime ends when $T_{e1} = T_{eb}$ for $x_e = H$, and at the end of the initial regime, $t = t_1$, $H = H_i$

2. *Intermediate Regime* (t = t1 to t2): As the emulsion surface reaches the emulsion breaking temperature, the emulsion separates into water and oil.[5] Water being heavier than the emulsion, it sinks to the bottom. This results in the appearance of oil on top of the emulsion. Though it is believed that the emulsion separation occurs over a range of temperatures, we model this as a process occurring at a constant temperature. Thus, there are three layers in this regime: oil, emulsion, and water. The oil layer grows and the emulsion layer thins out. Now the oil layer receives incident heat flux directly. The oil, not being optically thick, absorbs only a part of the incident heat flux at the surface, and some of the radiation energy is absorbed in-depth. A part of the heat flux that reaches oil emulsion interface, without getting absorbed in oil, is completely absorbed at the oil emulsion interface. The temperature of the oil layer increases while the oil-emulsion interface temperature remains constant at the emulsion breaking temperature. When the oil surface temperature reaches vaporization temperature, the intermediate regime ends.

Governing equations:

$$\frac{\partial T_{o2}}{\partial t} = \alpha_o \frac{\partial^2 T_{o2}}{\partial x_o^2} + \frac{C_0 q'' \beta e^{-\beta (L - x_o)}}{\rho_o c_{po}} \tag{7}$$

$$\frac{\partial T_{e2}}{\partial t} = \alpha_e \frac{\partial^2 T_{e2}}{\partial x_e^2} \tag{8}$$

$$\frac{\partial T_{w2}}{\partial t} = \alpha_w \frac{\partial^2 T_{w2}}{\partial x_w^2} \tag{9}$$

Initial conditions:

$$t = t_1, \; T_{o2} = T_{eb}, \, T_{e2} = T_{e1}, \, T_{w2} = T_{w1}, \, L = 0, \; H = H_i \tag{10}$$

Boundary conditions and auxiliary conditions at the boundaries:

$$x_o = 0, \; T_{o2} = T_{eb} \tag{11}$$

$$x_o = L, \qquad k_o \frac{\partial T_{o2}}{\partial x_o} = (1 - C_o) q'' - h_o (T_{o2} - T_i) - \sigma \varepsilon_o \left(T_{o2}^4 - T_i^4 \right) \tag{12}$$

$$x_e = 0, \; x_w = 0, \qquad k_e \frac{\partial T_{e2}}{\partial x_e} = -k_w \frac{\partial T_{w2}}{\partial x_w} \tag{13}$$

$$x_e = H, \; T_{e2} = T_{eb} \tag{14}$$

$$x_w = \infty, \; T_{w2} = T_i \tag{15}$$

$$x_o = 0 \;\; , x_e = H, \qquad k_o \frac{\partial T_{o2}}{\partial x_o} - k_e \frac{\partial T_{e2}}{\partial x_e} = aC_o q'' e^{-\beta L} \tag{16}$$

The intermediate regime ends when $T_{o2} = T_{ow}$, $x_o = L$ and at end of the intermediate regime, $t = t_2, \; H = H_2, \; L = L_2$

3. *Final Regime* (t = t2 to t3): The vaporized oil burns, the energy is released by oil combustion, and a part of it is fed back to the oil.[5] The incident heat flux increases rapidly to the prescribed maximum value, which depends on the type of crude oil and other combustion conditions. The surface temperature of the oil now remains at the oil vaporization temperature. The vaporization causes the oil layer to deplete, while the breaking up of the emulsion layer causes the oil layer to grow. The process continues until the emulsion layer completely depletes, the oil layer continues to burn, and finally extinction occurs because the loss of heat to the water becomes greater than the heat feedback to the oil surface.

Governing equations:

$$\frac{\partial T_{o3}}{\partial t} = \alpha_o \frac{\partial^2 T_{o3}}{\partial x_o^2} + \frac{C_0 q'' \beta_e^{-\beta(L-x_o)}}{\rho_o c_{po}} \tag{17}$$

$$\frac{\partial T_{e3}}{\partial t} = \alpha_e \frac{\partial^2 T_{e3}}{\partial x_e^2} \tag{18}$$

$$\frac{\partial T_{w3}}{\partial t} = \alpha_w \frac{\partial^2 T_{w3}}{\partial x_w^2} \tag{19}$$

Initial conditions:

$$t = t_2, \; T_{o3} = T_{ov}, \, T_{e3} = T_{e2}, \, T_{w3} = T_{w2}, \, L = L_2, \; H = H_2 \tag{20}$$

Boundary conditions and auxiliary conditions at the boundaries:

$$x_o = 0, \; T_{o3} = T_{eb} \tag{21}$$

$$x_o = L, \qquad T_{o3} = T_{ov} \tag{22}$$

$$x_e = H, \; T_{e3} = T_{eb} \tag{23}$$

$$x_e = 0, \; x_w = 0, \qquad k_e \frac{\partial T_{e3}}{\partial x_e} = -k_w \frac{\partial T_{w3}}{\partial x_w} \tag{24}$$

$$x_w = \infty, \; T_{w3} = T_i \tag{25}$$

$$x_o = 0, \; x_e = H, \qquad k_o \frac{\partial T_{o3}}{\partial x_o} - k_e \frac{\partial T_{e3}}{\partial x_e} = aC_o q'' e^{-\beta L} \tag{26}$$

$$x_o = L, \; k_o \frac{\partial T_{o3}}{\partial x_o} = (1 - C_o) q'' - h_o (T_{o3} - T_i) - \sigma \varepsilon_o \left(T_{o3}^4 - T_i^4\right) - \rho_o Q_{Lo} \frac{dL}{dt} \tag{27}$$

The governing differential equation is the transient one-dimensional conduction equation. It is applied to oil, emulsion and water layers. For the governing equation in the oil layer, a source term accounting for in-depth radiation absorption is introduced. Depending on the regime, different boundary conditions are applied at the top surface. Since the domain is semi-infinite, at the semi-infinite boundary, the temperature is always equal to the initial or surrounding temperature *(Ti).* As the emulsion starts separating into oil and water, the oil-emulsion interface temperature is fixed at the emulsion breaking temperature *(Teb).* As the temperature of the top surface of the oil layer reaches the oil vaporization temperature, *(Tov)* it is kept constant.

For the initial regime, the initial temperature is equal to *Ti* throughout the domain. The temperature field at the end of the initial regime is used as an initial condition for the intermediate regime and the temperature field at the end of the intermediate regime is used as the initial condition for the final regime. Governing equations and boundary conditions for each regime are presented below.

In order to determine the numerical solution the original semi-infinite region was transformed to a finite region in the transformed coordinate system. The transformation rule used was,

$$y_w = 1 - \frac{1}{1 + Cx_w} \tag{28}$$

where y_w is the transformed coordinate in water domain. Using this rule, equations (1), (8), (18) which are of the

$$\text{type } \frac{\partial T_w}{\partial t} = \alpha_w \frac{\partial^2 T_w}{\partial x_w^2} \tag{29}$$

were transformed to the type of

$$\frac{\partial T_w}{\partial t} = \alpha_w C^2 (1 - y_w)^4 \frac{\partial^2 T_w}{\partial y_w^2} - 4\alpha_w C^2 (1 - y_w)^3 \frac{\partial T_w}{\partial y_w} \tag{30}$$

The boundary conditions (4), (12),and (23) which are of the type $k_e \frac{\partial T_e}{\partial x_e} = -k_w \frac{\partial T_w}{\partial y_w}$ transformed to the type

$$k_e \frac{\partial T_e}{\partial x_e} = -Ck_w (1 - y_w)^2 \frac{\partial T_w}{\partial y_w} \tag{31}$$

A general partial differential equation selected for finite differencing can be represented as

$$\frac{\partial T}{\partial \tau} + \frac{\partial T}{\partial t} = \alpha C_{t1} \frac{\partial^2 T}{\partial x^2} + C_{t2} \frac{\partial T}{\partial x} + \frac{aC_0 q'' \beta_e^{-\beta(L-x)}}{\rho_o c_{po}} \tag{32}$$

Where $C_{t1} = C^2 (1 - x)^4$ and $C_{t2} = -4\alpha_w C^2 (1 - x)^3$ for water base, and $C_{t1} = 1$, $C_{t1} = 0$ for oil and emulsion. Also, *a = 1* for oil layer to account for the in-depth radiation absorption and *a = 0* for emulsion and water layers. The pseudo time *(τ)* derivative added to the governing equation is driven to zero by attaining steady state in pseudo time, for each time step in real time *(t)*, thus assuring a converged solution[5].

3. CONCLUSIONS

Extensive studies have shown that emulsions containing more than a certain amount of water do not burn. Unburnable slicks of emulsion are reported to have water content ranging from as low as 20% to 30% for extremely weathered oils that form stable emulsions, to as high as 70% for less weathered oils that form less stable emulsions.

The efficiency of burning is the percentage of the original oil that is removed by burning.

Burn efficiency decreases with increasing water content and evaporation and the efficiency is strongly dependent on the initial thickness of the emulsion.

The basic premise of the mathematical model is that it is not the emulsion, that burns, but rather the oil that evaporates and burns. Therefore, to cause ignition, the emulsion must first separate into water and oil. It is the layer of oil floating on top of the emulsion that burns This model incorporates the separation of emulsion into water and oil, a phenomenon that governs the emulsion pool fires.

Notations:
C- stretching factor, *Co*- fraction of heat flux not absorbed at the surface, *C1*- inverse of oil content of emulsion, on mass basis, *cpo*- specific heat of oil, *H*- emulsion thickness, *h*- convective heat transfer coefficient, *k*- thermal conductivity, *L*-Oil thickness, *q''* - incident heat flux, *QLo*- energy consumed in oil vaporization, *QLw*- energy consumed in water vaporization, *t*- time, *Teb*- emulsion breaking temperature, *Tov*- oil vaporization temperature, *T*- temperature, *xe*- emulsion coordinates, *xo*- oil coordinates, *xw*- water coordinates, *yw*- coordinates in transformed water region, α- thermal diffusivity, β- inverse absorption depth, ε- emissivity, ρ- density, σ- Stefan-Boltzmann constant; **subscripts:** *e*- emulsion, *o*- Oil, *w*- water, *1*- for initial regime, *2*- for intermediate regime, *3*- for final regime, *i*- initial conditions.

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