PREPARATION AND BURNING OF WATER-IN-LIQUID FUEL EMULSION

BUZDUGA ROXANA STEFANIA [1]**, SAJIN TUDOR** [1]**,**
CRACIUN ALEXANDRU [2] **, ANITEI FLORIN** [1]

[1] *University of Bacau, ROMANIA*
[2] *State University of Moldova, Chisinau, REPUBLIC OF MOLDOVA*

Abstract: The basis of liquid combustion and the particularities of water-in-liquid fuel emulsion burning are presented in this paper.

Keywords: liquid combustion, pool burning, droplet burning, burning time, burning rate, mass transfer driving force, water-in-liquid fuel emulsion.

1. INTRODUCTION

The combustion of liquids begins with the accumulation of heat in the liquid mass from radiation from the flame or from hot refractory walls, from recirculating burned gases, or from a pilot burner. Eventually, the fuel approaches its boiling point and it begins to vaporize. The fuel vapors then diffuse from the liquid surface, mixing with oxygen in the air and increasing in temperature. At some point, the rate of oxidation reactions and associated heat release is high enough that full ignition and combustion ensues [1].

In most situations it is desirable to subdivide the oil into small droplets in order to enhance vaporization rate (increasing the combustion rate per unit volume), to minimize smoking, and to ensure complete combustion. In some simple ‘‘pot-type’’ heaters, in pit incinerators, and occasionally in highly unusual waste disposal situations, sludge or liquids are burned in a pool [1].

The well-known data of burning process and intensification of toxic impurities reduction by firing in fire-chamber of water-in-liquid fuel emulsion [2].

Comparative data about burning of water-free and emulsified fuel makes it clear that emulsified fuel burns more effectively than the water-free one, at that burning of water-fuel emulsion in steam generating units and stoves provides the 10…18% fuel oil economy in comparison with pure fuel burning [2]. Besides, the factor determining the effectiveness of water-in-liquid fuel emulsion use in boiler – furnace processes is the possibility to resolve a number of ecological problems on this basis.

2. LIQUID COMBUSTION

2.1. Pool burning

Fires above horizontal liquid pools have been studied both experimentally and analytically to clarify the relationship between burning rate and the properties and characteristics of the system [1].

In small pools (up to 3 *cm* in diameter), burning is laminar and, unexplainedly, the burning rate per unit area $\dot{m}''$ decreases in approximate proportion as diameter increases. In a 3- to 5-*cm*-diameter pool, the flame is still laminar but regular oscillations occur.

For diameters greater than 7 *cm* and less than 20 to 30 *cm*, a transition to turbulent burning takes place. Convection is the primary source of feedback energy influencing $\dot{m}''$ in this pool size range, and the overall $\dot{m}''$

is essentially independent of pool diameter. For flames that yield little radiation (e.g., methanol), the constant $\dot{m}''$ range extends to diameters over 100 *cm*.

A constancy of $\dot{m}''$ (average) for a range of pool diameters does not imply a constant $\dot{m}$ with radius. Akita and Yumoto [3] report a 44% maximum radial mass flux variation for a 14.4-*cm* diameter methanol fire, and Blinov and Khudakov [4] report an 18%, 18%, and 27% maximum radial variation for benzene, gasoline, and tractor kerosene, respectively, in a 30-*cm* tank. These variations, however, may be considered small.

Studies by DeRis and Orloff on pool burning rates in the convectively controlled region [5] identified a relationship between burning rate and characteristics of the fuel which appears to satisfactorily correlate several sets of data for values of B (a dimensionless mass transfer driving force) greater than unity. Below $B=1$, the burning rate $\dot{m}''$ is lower than predicted, apparently due to the onset of unexplained extinction processes.

DeRis and Orloff 's correlation is

$$\dot{m}''=0.15\cdot\left(\frac{\lambda_1}{C_{P1}}\right)\cdot\frac{g\left(\rho_a-\rho_3\right)^{1/3}}{\mu_2 a_2}\cdot B\cdot\left[\frac{\ln(1+B)}{B}\right]^{2/3},\quad\left[\frac{kg}{m^2\cdot s}\right] \tag{1}$$

and

$$B=\frac{\Delta H_c}{\theta\cdot\Delta H_v}-\frac{H_s}{\Delta H_v},\quad\text{(an enthalpy driving force)} \tag{2}$$

where $\dot{m}''$ is burning rate, $[kg/(m^2\cdot s)]$; g - acceleration of gravity, $[m/s^2]$; ΔH_c - heat of combustion (HHV) of fuel, [*kJ*/*kg*]; θ - air (oxidant) rate, [*kg* air/*kg* fuel]; ΔH_v - heat of vaporization of fuel, [*kJ*/*kg*]; H_s heat content (sensible) of 1 kg of oxidant (air) at the liquid temperature at the surface of the burning pool, [*kJ*/*kg*]; ρ_a - density of air at ambient temperature, $[kg/m^3]$,

and where the following are the properties of the gas mixture formed upon stoichiometric combustion of the fuel and subscripted 1, 2, or 3 to correspond to evaluation at 25%, 50%, and 100%, respectively, of the total enthalpy of a stoichiometric mixture: λ - thermal conductivity, $[kW/(m\cdot{}^0C)]$; C_P specific heat, $[kJ/(kg\cdot{}^0C)]$; ρ - density, $[kg/m^3]$; μ - viscosity, $[Pa\cdot s]$; a - thermal diffusivity, $[m^2/s]$.

As the pool diameter increases beyond the 20- to 30-*cm* range, radiation from the flame plume plays an increasingly important role in setting the evaporation (burning) rate.

For these larger pools where the flame plume is optically thick, the burning rate of a liquid with a density ρ_l, $\left[g/cm^3\right]$ is given by

$$\dot{m}''=\frac{0.076\cdot\rho_l\cdot\Delta H_c}{\Delta H_v},\quad\left[\frac{kg}{m^2\cdot s}\right], \tag{3}$$

where terms are defined as for Eq. (1) and Eq. (2). An analysis by Steward [6] of the data of several investigators developed a relationship correlating the height of the visible flame plume with the pool size and burning characteristics. Steward's relationship showed that the tip of the visible flame plume corresponded to a condition of 400% excess air.

2.2. Droplet burning

For most liquid waste incineration and liquid fuel burning equipment, atomization is used to subdivide the feed for more efficient and complete burning (see Fig. 1). Atomization is effected by a number of means, including [1]: low-pressure (0.03 to 0.35 *atm*) air atomization; high-pressure (2 *atm* or more) air or steam atomization; mechanical atomization of fluid through special orifices at pressures from 5 to 20 *atm*; high-speed rotating conical metal cups.

The power requirements and characteristics of each atomizing method are described in [1].

Early analysis of droplet burning was based on analogies with coal combustion. These studies viewed droplet combustion as involving the diffusion of oxidant to the droplet surface followed by heterogeneous (two-phase) reaction. Later work led to the presently accepted concept that combustion occurs in a homogeneous diffusion flame surrounding an evaporating droplet (Fig. 1).

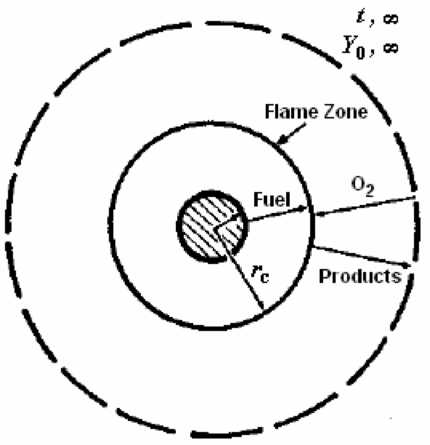

Fig. 1. Typical model of droplet burning

A review by Williams [7] suggested the following as the burning time t_b, $[s]$, of a droplet of initial diameter d_0, $[cm]$, of a hydrocarbon oil of molecular weight M_W at a temperature T, $[K]$, in an atmosphere with an oxygen partial pressure p_{O_2}, $[atm]$, as

$$t_b = \frac{29{,}800 \cdot M_W \cdot d_0^2}{p_{O_2} \cdot T^{7/4}} . \tag{4}$$

A more detailed theoretical analysis of the evaporation and burning of individual droplets was presented by Kanury [8] who considered the two-step process: gasification or vaporization of a liquid waste or fuel followed by gas phase combustion. For lightweight liquids, gasification is a purely physical (evaporation) process. For heavier fuels or wastes, pyrolysis or destructive distillation may be involved.

One of the key steps in the analysis is the establishment of the conditions at the surface of the droplet. For lighter fuels, it is useful and usually accurate to assume that the surface temperature of the evaporating droplet approaches (but is always slightly lower than) the boiling temperature of the liquid at the extant total pressure. If pyrolysis is involved, there is often no discrete boiling temperature and the surface temperature is usually much higher.

For the lighter liquid fuels or wastes, Kanury's analysis considered the heat transfer and mass transfer processes involved in droplet evaporation. In most incineration scenarios, the temperature of the gaseous environment into which the droplet is sprayed (T_∞) is significantly higher than the liquid's boiling point T_B. Under these conditions, the mass transfer number (*B*) is given by

$$B = \frac{c_g \cdot (T_\infty - T_B)}{L + c_1 \cdot (T_B - T_R)}, \; [dimensionless] , \tag{5}$$

The evaporation constant λ_v is given by

$$\lambda_v = \frac{8 \cdot \rho_g \cdot a_g}{\rho_l} \cdot \ln(B+1), \; \left| \frac{cm^2}{s} \right| . \tag{6}$$

And the droplet evaporation time t_v is equal to

$$t_v = \frac{d_0^2}{\lambda_v} = \frac{\rho_l \cdot d_0^2}{8 \rho_g a_g \ln(B+1)}, \; [s] , \tag{7}$$

where c_g is specific heat of the liquid's vapor, [*kJ*/(*kg* ^{0}*C*]; T_∞ - temperature of the surrounding air, [^{0}*C*]; T_B - boiling point of the liquid, [^{0}*C*]; L - heat of vaporization of the liquid, [*kJ*/*kg*]; c_1 - specific heat of the liquid, [*kJ*/(*kg* ^{0}*C*]; T_R - bulk temperature of the liquid, [^{0}*C*]; ρ_g - density of the liquid's vapor, [*kg*/*m*^{3}]; a_g - thermal diffusivity of the liquid's vapor, [*m*^{2}/*s*]; ρ_l - density of the liquid, [*kg*/*m*^{3}]; d_0 - initial diameter of the droplet, [*m*].

Kanury's extension of the analysis to include the effects of combustion leads to a modification of the mass transfer number to

$$B = \frac{\Delta H \cdot f \cdot Y_{0\infty} + c_g \cdot (T_\infty - T_B)}{L + c_l \cdot (T_B - T_R)}, \quad [dimensionless] , \tag{8}$$

where the definitions are as above and ΔH is heat of combustion of the liquid, [*kJ*/*kg*]; f - mass stoichiometric ratio, [*kg* of liquid/*kg* of O_2]; $Y_{0\infty}$ - mass concentration of oxygen in the environmental gas, [*kg*/*kg*], and equal to 0.232 (23.2%) for air.

The application of burning time predictions based on Kanury's analysis must be cautious and conservative. Extrapolating from the single droplet model to the analysis of real, large-scale combustors requires addition of four rather complex refinements to the theory [1]:

1. In dense sprays, evaporation and diffusion burning of the vapor become the dominant mechanism.
2. Relative motion between droplet and the gaseous surrounding medium removes the simplifying assumptions of radial symmetry.
3. Initial droplet particle sizes are not uniform, and the evaporation characteristics are poorly described using models based on mean droplet sizes.
4. Mixing processes of fuel and oxidant take place in the aerodynamically complex flow in the burner and furnace (not in a simplified, one-dimensional reactor).

Unfortunately, such studies have not yet produced quantitatively useful correlations for use in combustion chamber design. However, the parameters in the equations give considerable insight as to the effect of user-controllable variables in enhancing the combustion rate. For example, droplet combustion rate is increased by reducing drop size, increasing the temperature of the ambient atmosphere, operating at high oxygen concentration, and preheating the fuel.

As a starting point in burner analysis, the flame length relationship in [9, Eq. (1)] could be used for jets of liquid fuel droplets. Application of [9, Eq. (1)] is subject to the qualification that the flame will be longer than predicted with the difference in predicted and actual decreasing as [1]:

- the number of coarse droplets decreases;
- the latent heat of evaporation (less any preheat) decreases.
- and/or the mean droplet diameter decreases.

Also, the flame will be considerably shortened by swirl effects.

3. PREPARATION AND BURNING OF WATER-IN-LIQUID FUEL EMULSION

Water-in-liquid fuel emulsion (WLFE) burning reduces NO_x outlet in gas emission (about at 50%), approximately in 3-4 times – carbon black emission, CO outlet – on average at 50%, the benzapilene outlet at 2-3 times, sulfur outlet at 60…85% and so on [2].

Continuous accumulation of hundred thousands of ballast waters, containing the mineral oils, is also among the problems complicating the ecological situation. The sources of the said substances are industrial plants, sea and river transport. And particularly existing now system of fuel oil unloading out of railway tanks leads to the considerable saturation of fuel with water in depositories (up to 10%). At the same time according normative documents watering of fuel oil given for burning shouldn't exceed 0,3-1%. Traditionally fuel oil preparation for burning contains in general 2 grades: dewatering and heating. Measures on fuel oil dewatering via water evaporation are power-consuming and leads to volatile light fraction loss in the fuel, that for its turn decreases its combustion value. There is also dewatering method by means of settling in order to deny water ingress into the fire-chamber, consequences of which leads as a rule to breaking in burning, and occasionally to flame failure. Phase disengagement of fuel oil –water requires sufficiently much time and is ineffective because of thickness closeness of fuel oil and water. The problem of such utilization couldn't be solved via chemical or biological methods, as they require great additional areas, capital and working costs. Often water containing fuel oil are simply pouring out into sewerage system without any cleaning, that conflicts with environmental requirements and with a common sense as well.

The usage of equipment destined for WLFE preparation allows withdraw the entire problems complex, connected with dewatering of fuel oil and another mineral oils.

The phase proportions water – mineral oil in emulsion according to problem put could change in wide limits and reach aqueous phase to 50%.

The largest economic effect and at the same time decrease of toxic impurities are provided by adding (or supporting) 10-18% of water into fuel. And the greatest ecological effect as for utilization of water polluted with organic substances can be reached at the water phase level near 50%.

Physical particularities of WLFE burning, as a new fuel, comparing with those known before, is to be determined by imperfect burner devices, that practically can not provide liquid fuel dispersion at the dispersion level less than 100 *µm*. At the same time one drop of emulsion of the same size (100 *µm*) contains several thousand of water micro drops, covered with the finest fuel layer. As a result a micro-drop explores in the high-temperature environment, providing the complete burning of the covered fuel. Moreover with temperature in the flame fuel 1100…1150^{0}C there is dissociation of water molecule into H^+ and OH^-, and hydrogen, as commonly known, has the highest combustion value – about 75360 *kJ/kg*, and which further reacts into burning and serves as additional fuel.

Such effect has a particular significance at burning of coal tar pitch and reduced high-viscosity fuel oil, which are used in metallurgy.

As a result of such micro explosions turbulent pulsation centers appear in the fireboxes and the number of elementary fuel drops increase, due to which the flame raises in its volume and fills up the combustion chamber evenly, what in its turn results [2]:

- leveling of the firebox temperature with local maximum temperature decreasing and with the average temperature in the firebox increasing;
- flame luminosity raise due to augmented irradiation surface;
- essential decreases the fuel chemical underburning;
- allows to decrease the quantity of the air blown and heat losses.

Possibility of decreasing coefficient of excess of the air blown when burning the hydrocarbon fuel is extremely important, since practice confirms that efficiency factor of a boiler unit increases on 0.5-1.2% when the coefficient of excess of the air blown decreases. Nevertheless no heating efficiency happens in the boiler unit of a big steam rate (50…100 tons per hour) if emulsion specific humidity is in 8…14% limits. Simultaneously catalytic reactions go on in the flame that decreases dangerous toxic substances emission together with outlet combustion gases.

Another important factor characterizing efficiency of the WLFE usage in the boiler processes, is effectiveness increase and long-lasting operating of the firebox equipment. A part of WLFE drops reaches heating surfaces, explodes on them, what results not only in the measures preventing, but also cleans previous carbon blacks. According to some foreign sources fuel overexepnditure because of contaminated heating surfaces with carbon blacks and coke participles in boilers can approximate to 30-35%.

A serious problem arising during burning fuel oil is high sulfur content. Sulphides fly away together with smoke fumes and pollute the air. When using fuel oil in the metallurgy, the sulfur containing in the fuel oil in colloid form, usually transfers into the liquid metal melt and lowers the metal's quality, due to what in its turn costs for the sulfur localization raise in the further processing of the furnace charge obtained.

Sulfur neutralization in fuel in the metallurgical industry, is obligatory if high-sulfur fuel oil is used. The method of the highest efficiency in this problem resolving is additives introduction, that will bind sulfur on the stage of the fuel preparation for burning, namely on WLFE preparation stage. It is the most effective method on the point of view of economizing, as the most of the additives applied is water-soluble.

When using cavitation devices when preparing WLFE directly at the fuel preparation stage before its burning in pipe furnaces one can notice reduction of sulfur containing in the ready-made products (fine melt) on 25…32%.

Instantly the problems of energy resources lack are rather acute. This especially concerns gas. That is why use of alternative fuel – fuel oil or stove fuel is of especially current importance. Stove fuel has several advantages comparing with normal fuel oil. Having high heat conductivity – (42…52)$\cdot 10^3$ *kJ/kg*, comparatively – fuel oil – (40…42)$\cdot 10^3$ *kJ/kg*, high fluidity and freezes at low temperature.

Applying cavitation devices will allow building a simple processing line to manufacture multicomponent stove fuel with heating value 50…60 *kJ/kg*. This also makes possible to utilize waste engine oil, under-goods bilge water.

Thus, using normal fuel oil with 10% of diesel oil or 5% of benzol and 8…12% of water and 15% of waste engine oil one can obtain stove fuel of calorie content $(50…60)\cdot10^3$ *kJ/kg*. Prime cost of this method does not exceed commercial fuel oil cost, and calorie content is 25-30% higher.

Given technology represents a number of measures, that are based on of hydrodynamic cavitation principles, leading to the polymeric links break, that is to getting low-molecular compounds, and as a result, to change (facilitation) of breakup of the processing diesel oil. This leads to significant diesel oil economy in process of operation of diesel engine, since all important hydrocarbon components - aromatic, naphthenetic, paraffin hydrocarbon and so on, which in the ordinary practice are separated and filtered out, had lower molecular structure and as a result better combustibility. It is known, that weighting of breakup increase fuel consumption at 2…3% and raise exhaust at 10-15%.

Running trials, conducted after fuel treatment at diesel of different power, showed essential reduction of fuel consumption (to 18%), softer engines work, essential reduction of ash level (over 50%), deposits of gum compounds have disappeared.

Since the diesel fuel devices have high-precision components (gaps in sensitive steams 2-5 mcm), that perform back-and-forth and rotatory motions one regarding to other with great speed, besides in connection with high pressure and temperature in combustion chamber, the components of pumps and sprayers are mechanically and thermally over-loaded. In process of batching and jetting the fuel flows inside the fuel devices canals with great speed. These factors specify rigid requirements to purity of diesel oil, and also to viscosity oiliness characteristics.

5. CONCLUSIONS

Technical efficiency of employment of WLFE tecnology for fuel oil processing

- can be built into existing fuel feeding system. No additional areas and great investments required;
- autocontrol and support of prescribed quantity of aqueous phase in emulsion;
- reduction in 2-3 times of detrimental impurities (soot, benzapirene, NO_x, CO);
- incineration of sulphureous fuel oils with observance of Sox atmosphere emission standards (without use of water-soluble additives binding sulfur);
- sulfur recycling at the storage and preparation of fuel stage;
- recycling of water, polluted with mineral oils (up to 60% water in volume);
- high-molecular fuels dispersion, viscosity reduction, averaging;
- destroying and dispersion mechanical impurities in fuel. Decrease of abrasive damage in burners;
- average temperature raise combustion chamber and heat irradiation.

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