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A CALCULATION METHOD FOR TRANSPORT PROPERTIES FOR THE PREDICTIONS OF COMBUSTION CHARACTERISTICS OF MARINE FUEL OILS

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Key words: Variable transport properties, marine diesel fuel oils, undefined hydrocarbons, calculation method.

ABSTRACT

The primary purpose of this study is to propose a calculation method of transport properties in numerical studies on the combustion of marine diesel fuel oils which are composed of undefined hydrocarbon components and various extents of immiscible matters. This proposed method is further applied to the theoretical analysis for the combustion model for a single liquid droplet. It is shown that fuel oil A has the properties of higher flame temperature and burning rate constant while lower stand-off ratio and mass burning rate than those of heavy fuel oil C. The proposed calculation procedure is also suggested to be applied to other numerical studies on the combustion of fuel oils with variable transport properties.

INTRODUCTION

Most fuels used in marine powerplants are low-grade heavy fuel oils in order to fulfill economy purpose of ship operators (Habermann 1972). The properties of these fuels are in general high specific gravity and viscosity, and of mulit-components bearing with various extents of immiscible matters such as ash, metallic compounds, asphalt, and water. The number of the theoretical and experimental studies of the combustion of single-component liquid fuels or blended fuels of several known components are a lot (Law 1982, Annamalai and Ryan 1992, Wong and Lin 1992). However, the literature with the studies of combustion of liquid fuels composed of many undefined hydrocarbon components and immiscible contents are rather few (Tamaki et al. 1987, Elkobt and Aly 1991, Harbach and Agosta 1991). Presently the development on the numerical method for the combustion of marine fuel oils is still limited primarily because of the complex components of these fuels (Law 1977, Sangiovanni and Kesten 1977). In particular, the calculation of the variable transport properties of burning heavy fuel oils with the temperature fluctuation in the flame field has not been well considered in previous relevant numerical studies (Dwyer 1989, Curtis and Farrell 1992). The primary purpose of this study is to propose a calculating procedure for the transport properties of burning marine fuel oils in the numerical studies on the combustion of droplets or liquid sprays. For the sake of demonstration simplicity, this procedure is applied to the calculation of thè combustion characteristics of marine fie; po;s A amd C which approximate ASTM No. 2 and 6 fuel oils, respectively are commonly used in marine powerplants although they have widely different properties. Marine diesel fuel oil A is a distillate oil with a high boiling range to accord with small-sized high-speed diesel engines. In contrast, heavy fuel oil C is a residual oil, known as bunker fuel C in some countries, and contains relatively high carbon residue, ash, and water to ac-commodate large-sized low-speed diesel engines. The properties of these fuel oils are listed in Table 1. The burning characteristics such as temperature and mass fraction distributions, mass burning rate, and stand-off ratio are calculated and compared for these fuel oils.

CALCULATION METHODS

2.1 Calculation of combustion characteristics

The outer and inner regions to the flame-sheet

Table 1. Inspection data for marine fuel oils

Item	A oil	C oil
A.P.I.	37.6	15.9
Viscosity, Cst, 40°C	2.93	198.5 (50°C)
Gross heating Value, *cal*/g	10990	10370
Carbon residue, wt.%	0.09	8.8
C, wt.%	85.6	84.7
H, wt.%	13.2	11.4
S, wt.%	0.30	2.87
Ash, wt%	0.002	0.022
Saturates, vol.%	77.3	-
Aromatics, vol.%	22.7	-
Flash point, °C	90	127
Pour point, °C	-13	-
Distillation, °C		
I.B.P.	195.8	-
10%	283.3	-
30%	257.3	-
50%	276.8	-
70%	299.4	-
90%	333.4	-
End Point	360.9	-

position can be identified based on the approximation of double-film combustion model. The transport properties of the burning fuel drop are considered to be varied with drop flame temperatures distributing in these two distinct regions. The subscripts 1 and 2 are used to denote the inner and outer regions, respectively. The droplet diameter in practical combustors are rather small so that the time period of the droplet heating is relatively short in comparison with the overall burning time. The effect of droplet heating on combustion characteristics can therefore be neglected. Moreover, the heat and mass transfers are almost dominated by diffusion transport for a considerably small droplet. The convective transfer is thus not considered in this study. Equality of Lewis number is also assumed. The conservation equations for mass and energy can thereafter be set for inner region ($r_s \le r \le r_f$),

$$\dot{m} Y_F - 4\pi(\rho D)_1 r^2 \frac{dY_F}{dr} = \dot{m} \tag{1}$$

$$\dot{m} C_{p1}(T - T_s) - 4\pi\kappa_1 r^2 \frac{dT}{dr} = -\dot{m} H \tag{2}$$

and for outer region ($r_f \le r \le r_\infty$),

$$\dot{m} Y_o - 4\pi(\rho D)_1 r^2 \frac{dY_o}{dr} = -\frac{\dot{m}}{\sigma} \tag{3}$$

$$\dot{m} C_{p2}(T - T_s) - 4\pi\kappa_2 r^2 \frac{dT}{dr}$$

$$= -\dot{m}(H - q) + \dot{m}(C_{p2} - C_{p1})(T_f - T_s) \tag{4}$$

with the boundary conditions:

$$\begin{aligned} &r = r_s : Y_F = Y_{Fs} \ , \ T = T_s \\ &r = r_f : Y_F = 0 \ , \ T = T_f , Y_o = 0 \\ &r = \infty : T = T_\infty \ , \ Y_o = Y_{o\infty} \end{aligned} \tag{5}$$

Equation (1)-(4) can be integrated along with Eqn. (5) for the boundary conditions to obtain the explicit expressions for mass gasification rate $\dot{m}$, flame-front stand-off ratio r_f/r_s, and flame temperature T_f as follows,

$$\frac{\dot{m}}{4\pi r_s} = \ln\{[1 + \frac{C_{p1}(T_f - T_s)}{H}]^{\kappa_1/C_{p1}} [1 + Y_{o\infty}\sigma]^{(\rho D)_2}\} \tag{6}$$

$$\frac{r_f}{r_s} = 1 + \frac{(\kappa_2/C_{p1})\ln[1 + C_{p1}(T_f - T_s)/H]}{(\rho D)_2 \quad \ln[1 + Y_{o\infty}\sigma]} \tag{7}$$

$$C_{p1}(T_f - T_s) + \frac{C_{p2}(T_f - T_\infty)}{[(1 + Y_{o\infty}\sigma)^{1/Le_2} - 1]} = (q - H) \tag{8}$$

The solutions of the distributions of fuel mass fraction (Y_F) and fuel temperature (T) for the inner and outer regions are derived here,

(I) For inner region:

Rearranging Eqn. (1) to have

$$\frac{dY_F}{dr} - \frac{\dot{m}}{4\pi(\rho D)_1 r^2} Y_F = \frac{-\dot{m}}{4\pi(\rho D)_1 r^2} \tag{9}$$

By integrating the above first order ordinary differential equation and using the boundary condition, $Y_F = 0$ at $r = r_f$, we have

$$Y_F = 1 - \frac{c_I}{\exp(\frac{\dot{m}}{4\pi(\rho D)_1 r})} \tag{10}$$

in which $c_I = \exp(\frac{\dot{m}}{4\pi(\rho D)_1 r_f})$ is a constant. The temperature distribution are derived in a similar manner to obtain

$$T_1 = T_s - \frac{H}{C_{p1}} + \frac{c_{II}}{\exp(\frac{\dot{m} C_{p1}}{4\pi\kappa_1 r})} \tag{11}$$

in which $c_{II} = \frac{H}{C_{p1}} \exp(\frac{\dot{m} C_{p1}}{4\pi\kappa_1 r_s})$ is a constant.

(II) For a outer region:

Similarily, the mass fraction of the oxidizer tem-

perature distribution in this region can be expressed by

$$T_2 = T_s - \frac{H - q - (C_{p2} - C_{p2})(T_f - T_s)}{C_{p2}} + \frac{c_{III}}{\exp(\frac{\dot{m} C_{p2}}{4\pi\kappa_2 r})} \quad (12)$$

and

$$Y_o = \frac{1}{\sigma} - c_{IV} \exp[\frac{\dot{m}}{4\pi(\rho D)_2 r}] \quad (13)$$

in which

$$c_{III} =$$

$$\{T_f - T_s + [\frac{H - q - (C_{p2} - C_{p1})(T_f - T_s)}{C_{p2}}]\} \exp(\frac{\dot{m} C_{p2}}{4\pi\kappa_2 r_f})$$

and

$$c_{IV} = -\frac{1}{\sigma} \exp[-\frac{\dot{m}}{4\pi(\rho D)_2 r_f}]$$

are constants.

It is noted that the fuel drop temperature is varied with the position of flame field to a great extent. A Sparrow's 1/3 rule formula (Hubbard *et al.* 1975) given by

$$T_{r1} = \frac{1}{3} T_s + \frac{2}{3} T_f \qquad T_{r2} = \frac{1}{3} T_f + \frac{2}{3} T_\infty \quad (14)$$

for the reference temperatures was used for the calculations of the transport properties in the inner and outer regions.

2.2 Calculation of transport properties

The calculating procedures of transport properties are varied and dependent on whether the distillation temperatures of fuel oils are available. Residual fuels such as heavy oil C is blended from residuum left from the various processes in a refinery, whereas distillate fuels like marine diesel fuel oil A leave the refinery as a distillate. Therefore, the data of the volumetric boiling point can not be found for heavy oil C in Table 1. The present informations are still not sufficient for calculating variable transport properties. Instead, three more factors, namely the molecular weight M, Waston Characterization factor K, and mean average boiling point Γ_b of liquid fuels (Technical data committee 1988) should be determined before those calculations. The calculating procedures in accordance with the type of fuels are explained in the following.

(I) Distillate fuel

(i) The volumetric average boiling point (*VABP*) of a petroleum fraction can be computed by averaging the distillation temperature at each of the 10, 30, 50, 70, and 90 volume percent distillated points to be

$$VABP = \frac{\tau_{10} + \tau_{30} + \tau_{50} + \tau_{70} + \tau_{90}}{5} \quad (15)$$

in which τ_{10}, τ_{30}, ...τ_{90} are the boiling points at the 10, 30, ...90 volume percent distillated.

(ii) SL = the 10-90 percent slope in Farenheigh degree/percent distilled.

$$= \frac{\tau_{90} - \tau_{10}}{90 - 10} \quad (16)$$

(iii) Mean average boiling point Γ_b of petroleum fraction in degree Rankine is thereafter obtained from

$$\Gamma_b = VABP - \Delta \quad (17)$$

in which Δ is the correlation factor of boiling point, which is defined as

$$\ln\Delta = -0.94402 - 0.00865 (VABP - 32)^{0.6667} + 2.99791 SL^{0.333} \quad (18)$$

(iv) The Watson Characterization factor K and the molecular weight of fuel can thus be calculated from the formulae

$$K = \frac{\Gamma_b^{1/3}}{S} \quad (19)$$

and

$$M = 20.486 [\exp(1.165 \times 10^{-4} \Gamma_b - 7.78712S + 1.1582 \times 10^{-3} \Gamma_b S)] \times \Gamma_b^{1.26007} S^{4.98308} \quad (20)$$

in which S = specific gravity (60° F/60° F)

(II) Residual Fuel

(i) The distillation temperature is not available for this type of fuels so that the calculating procedures are somewhat different. The molecular weight of these fuels can be estimated if the kinematic viscosity at 100° F and 210° F in centistokes (denoted by ν_{100} and ν_{210}, respectively) and specific gravity S are known. Figure 2B 2.5 of Technical data Committee (1988) can be used to obtain ν_{210} based on the data of API gravity and ν_{100}. The estimated molecular weight is calculated by

$$M = 223.5 \nu_{100}^{(-1.2435 + 1.228S)} \nu_{210}^{(3.4758 - 3.0.8S)} S^{-0.6665} \quad (21)$$

(ii) The Watson characterization factor K may thus be looked up from Fig. 2B 2.2 of Technical data Com-

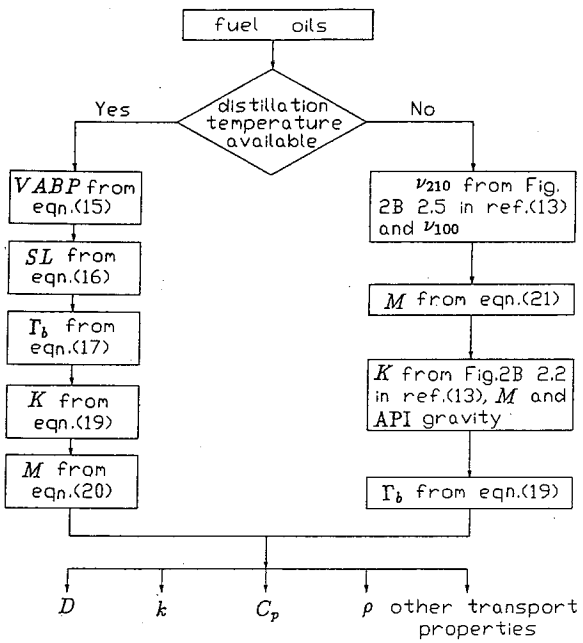

Fig. 1. Flow chart for the calculation of transport properties.

mittee (1988) if the molecular weight and API gravity of the fuel are available. After the data of M, Γ_b, and K for either distillate fuels or residual fuels are obtained, the transport properties which may vary with temperature in the lame field are ready to be calculated based on which the combustion characteristics of these fuels may be predicted. The constant pressure specific heat C_p, thermal conductivity k, density ρ, and viscosity of vapor fuels at various temperatures could be computed by the formulae in Huggins (1987). The equation for diffusion coefficient D and the other transport properties may be found from Reid *et al.* (1988). The flow chart for the calculations of the transport properties is shown in Fig. 1.

CALCULATION RESULTS AND DISCUSSIONS

A double film combustion model of a liquid drop is considered in this study. An initial drop diameter of 1000 μm and an initial drop temperature of 300K are assumed. The calculated results of the combustion characteristics of both marine fuel oils are listed in Table 2. It reveals that the estimated molecular weight of these two fuels are relatively high, and the molecular weight of heavy oil C is even twice of that of oil A. Moreover, the large mass burning rate, $\dot{m}$ for the former oil is possibly due to the higher molecular weight and specific gravity. The mass fraction and temperature distributions of these two fuel are illustrated in Fig. 2. It is shown that the flame-sheet of the burning fuels are located at the radii where the fuels are completely

Table 2. Calculated combustion characteristics of marine fuel oils

Item	A oil	C oil
T_f (°C)	1959.45	1945.25
$\dot{m}$ (10^{-6} Kg/sec)	1.12	1.20
r_f/r_s	21.85	23.43
M (Kg/Kmole)	216.03	432.43
H (KJ/Kg)	226.00	175.49
k (mm^2/s)	0.8203	0.7701

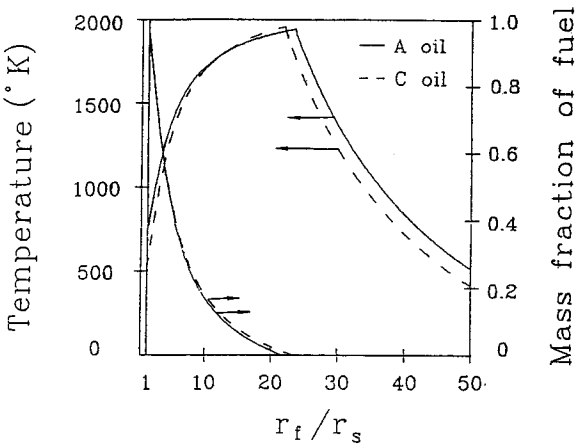

Fig. 2. Mass fraction and temperature distributions of the burning marine fuel oils.

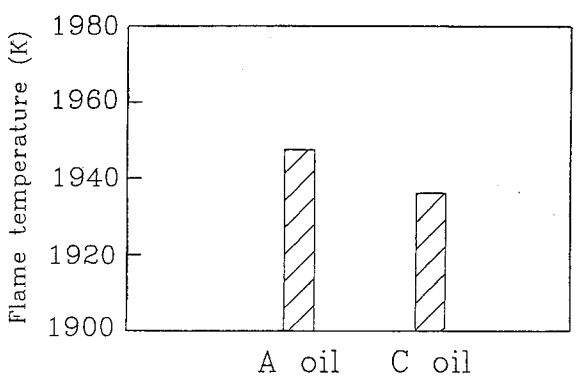

Fig. 3. Comparisions of the flame temperatures of fuel oil A and C.

burnt out to obtain their maximum flame temperatures. It also reveals that the standoff ratio (r_f/r_s) of heavy fuel oil C is larger than that of fuel oil A. The relatively lower latent beat than that of the former fuel is probably the major cause as predicted in Eqn. (7). The flame temperatures of these fuel oils are also compared in Fig. 3. The flame temperature of fuel oil A is shown to be somewhat higher. This is primarily ascribed to the higher deduction value of the gross heating value with latent heat, denoted by (q-H) of fuel oil A in Eqn. (8).

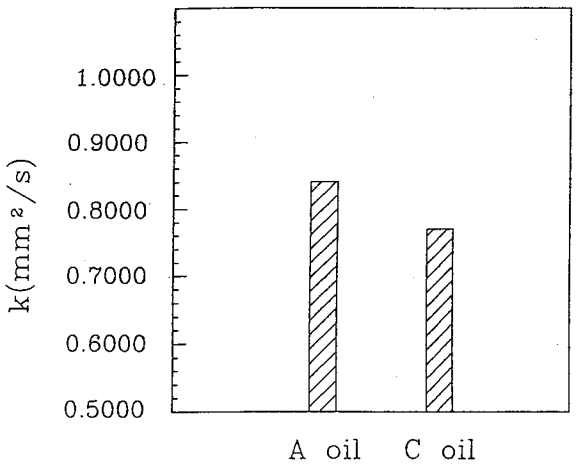

Fig. 4. Burning rate constants of the burning marine fuel oils

The burning rate constant k is calculated as well, which is defined as

$$k = \frac{8\rho_g D_g}{\rho_l} \ln(1+B) \tag{22}$$

in which ρ_g, ρ_l, D_g, and B are, respectively, the density of vapor fuel, liquid fuel, vapor diffusion coefficient, and Spalding transfer number. Marine diesel fuel oil A with smaller liquid density and larger vapor diffusion coefficient is considered to be vaporized faster which leads to a significant higher burning rate constant, k as shown in Fig. 4. In comparing with those previous studies (Faeth 1977, Law 1982, Kuo 1986) the predicted results of the present study are reasonable. The method for calculating transport properties is therefore recommended for other numerical studies on the combustion of fuel oils composed of undefined hydrocarbon components.

CONCLUSIONS

This study proposes a calculation method of variable transport properties for the numerical study of combustion of fuel oils which are composed of unidentifiable hydrocarbon compounds. This method is further applied to predict the combustion characteristics of marine fuel oil A and C based on a double-film droplet model. The properties of these two fuels are widely different although both of them are common fuels in marine power plants. The results of calculation show that fuel oil A which is composed of lighter components bears the characteristics of higher flame temperature and burning rate constant as well as lower standoff ratio than those of heavy fuel oil C. It is shown that the calculated results are acceptable in comparing with previous relevant literature. The present calculation method for transport properties are suggested to be applied to other numerical studies on such as droplet array, droplet group, or spray combustion of fuel oils.

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NOTATION

B:	Spalding transfer number
C_p:	constant pressure specific heat
D:	mass diffusion coefficient
d:	diameter of a liquid drop
H:	latent heat
K:	Watson characterization factor
Le:	Lewis number
M:	molecular weight
$\dot{m}$:	mass gasification rate at drop surface
q:	heat of combustion per unit mass of fuel
r:	radial distance
S:	specific gravity (60° F/60° F)
SL:	slope of distillation temperature
T:	temperature (in Rankine degree)
$VABP$:	volumetric average boiling point
Y:	mass fraction
k:	thermal conductivity
$\nu_{100,210}$:	kinematic viscosity at 100° F, 210° F
ρ:	density
σ:	stoichiometric oxidizer-to-fuel mass ratio

Subscripts

b:	boiling state
f:	flame
F:	fuel
g:	vapor phase
l:	liquid
o:	oxidizer
s:	droplet surface
1, 2:	inner, outer regions
∞:	ambiance

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