FLAME SPREAD OVER OIL-SAND POOL

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ABSTRACT

The mechanism and process of the flame growth and development over oil-sand pool was studied numerically in detail. Considering the influence of the oil and sand, the oil-sand pool must be included in the simulating domain, which modeled by the porous medium approach. Heat release is described by a single-step, irreversible, global reaction for complete combustion. At the interface, the Stefan Flow was considered. Based on the numerical aspect and the calculated flame spread rate and the temperature distributions in glass bead layer, it is pointed out that under the flash point temperature, the behavior of the flame spread is affected by the two-phase heat transfer through the mixed media of glass beads and kerosene as well as glass beads and gas. The dominant mode of heat transfer to kerosene ahead of the leading flame edge is inferred to be the conduction through the liquid-solid phase.

NOMENCLATURE

C	experimental coefficient. [ ]
C_p	specific heat capacity at constant pressure. [J/kg·K]
D	reacting rate. [kg/m^3·s]
E	activation energy. [J/mole]
f	mixing fraction. [ ]
g	gravity acceleration. [m/s^2]
K	hydraulic conductivity. [m/s]
m	mass fraction. [ ]
n	porosity. [ ]
N	accretion of the liquid height. [m/s]
p	pressure. [Pa]
Pr	Prandtl number. [ ]
q	specific flux vector. [m/s]
Q	specific heat. [J/kg]
R	universal gas constant. [J/mole·K]
t	time. [s]
T	temperature. [K]
u,v	velocity in x-, y-direction, respectively. [m/s]
W	average molecular weight. [kg/mole]
x,y	Cartesian coordinate. [m]
z	height from one specific surface. [m]
α,β	dimensionless coefficient.
Γ	diffusive coefficient. [N·s/m^2]
γ	super-exponential parameter.
ρ	density. [kg/m^3]
μ	viscosity. [N·s/m^2]
φ	piezometric head (potential). [m]
λ	thermal conductivity. [W/m·K]

Subscripts

b	boiling point.
f	fluid.
fu	fuel.
i	index for species.
ox	oxygen.
s	solid.
T	temperature.
0	interface between gas and liquid.

INTRODUCTION

A large number of fire hazards have been caused by burning leaked or spilled combustible liquids. In the crude oil field, oil, which leaked from the oil reservoir, soaks into sands or soil. If a fire occurs, the fire will spread over the sands or soil soaked with oil. There are other similar cases, such as combustible liquid spills into the mat or carpet in hotel. To prevent such fire hazards, clarifying the mechanism and process of the flame growth and development over the porous materials soaked with combustible liquids is prominent.

Sand is often recommended to use as an extinguishant for the combustible liquid fire hazards. In such occasions, the sand will be soaked with the combustible liquid. This is another purpose to exploring the flame spread mechanism over porous solid soaked with combustible liquid.

The mechanism of flame spreading over single-phase (single- or multi-component) liquid or solid combustibles has been examined in numbers of previous studies. However, little knowledge is available over multi-phase combustibles such as oil-sand pool in experimental studies, and no similar works doing by numerical simulation method have been found up to now .

The purpose of the present study is to examine how does the oil-sand pool has the influence on the flame spread characteristics. Thus, the subsurface liquid-solid phase zone must be considered into the simulating domain. In the liquid-solid zone, a porous medium approach is utilized due to the complication of the modeling of both field and boundary in the liquid-solid zone, and to the restriction of the domain applied by continuum medium approach, and to the capability of the computer of today.

MATHEMATICAL ANALYSIS

The schematic diagram of the computational domain is shown in Fig.1, which was extended on both the gas phase zone and the subsurface liquid-solid phase zone with the porosity of 0.3. We used the mesh of 60 × 36, and it cost about 10 seconds of the computing time on IBM ps/2 Model 80 under NDP-FORTRAN 386. We assumed : (a) the ideal gas model; (b) by reason of the stationary ambient and the small Prandtl number of the gas flow,we used the models under the laminar condition; (c) gaseous radiation

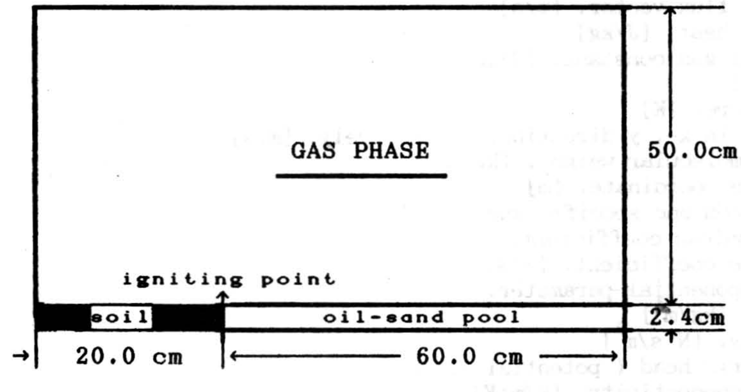


Fig.1 The Schematic Diagram of the Computational Domain.

was neglected because the flame height wasn't high; (d) in the course of the flame spread, the glass beads were not deformed; (e) the variations of the physical property of the oil-sand pool was ignored; (f) the porous media was isotropic.

Kerosene was used in the present study, which is a multicomponent of hydrocarbons which can[1] be represented quite accurately by the average molecular formula $C_{11.6}H_{23.2}$, the boiling point of which are in the range from 453 K to 503 K, the density of which is 780 kg/m^3 at 300 K.[2] The sand was replaced by the glass beads in present study, of which diameter is 0.5 mm.

The kerosene-air oxidation was modeled using a single-step irreversible reaction for complete combustion so that the only species involved were $C_{11.6}H_{23.2}$, O_2, N_2, CO_2 and H_2O. The reaction rate constant was given by

$$k = C_k \exp\left(-\frac{E}{RT}\right).^{[3]}$$

The governing equations were written by incorporating convection, conduction, diffusion, buoyancy and combustion mechanisms.

The universal form of the governing equations in gas zone were then :

$$\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial(\rho u\phi)}{\partial x} + \frac{\partial(\rho v\phi)}{\partial y} = \frac{\partial}{\partial x}\left(\Gamma_\phi\cdot\frac{\partial\phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\phi\cdot\frac{\partial\phi}{\partial y}\right) + S_\phi$$

Parameters of the equation are shown in Table 1.

Table 1. parameter for the universal equation

Equations	ϕ	Γ_ϕ	S_ϕ
continuity	1	0	0
x-momentum	u	μ	$-\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu\frac{\partial v}{\partial x})$
y-momentum	v	μ	$-\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial y}) + \frac{\partial}{\partial y}(\mu\frac{\partial v}{\partial y}) - \rho g$
energy	T	μ/Pr_T	$D_{fu}H_{fu}$
species	m_i	μ/Pr_{mi}	D_{mi}
mixing fraction	f	μ/Pr_f	0

Equation of State :

$$\rho = \frac{W\cdot p}{RT} \quad , \quad \mu = \mu_0\left(\frac{T}{T_0}\right)^{\gamma}\ ^{[4]}$$

The governing equations in liquid-solid zone were :[5]

Continuity Equation :

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

Momentum Equation :

$$q_{xi} = -K\frac{\partial\varphi}{\partial xi} \quad , \quad \text{where } xi = x,\ y$$

Potential Equation :

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} = 0 \quad , \quad \text{where } \varphi = z + p/(\rho_f g)$$

Energy Equation :

$$\frac{\partial T}{\partial t} + \alpha\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \beta\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

where

$$\alpha = \frac{n\rho_f Cp_f}{n\rho_f Cp_f + (1-n)\rho_s Cp_s}, \qquad \beta = \frac{n\lambda_f + (1-n)\lambda_s}{n\rho_f Cp_f + (1-n)\rho_s Cp_s}$$

Here we assumed a simple parallel conduction model, i.e., a model which conduction through the fluid phase and the conduction through the solid phase occur separately but simultaneously, with no interchange of heat between the two media.

Initial Conditions and Boundary Conditions

At the initial moment, the kerosene surface was flush with the top surface of the glass bead layer. In the course of the flame spread, the oil surface at one end of the oil-sand pool kept up at one specific position.
At the interface between the gas phase and liquid phase, there existed :

$$Q_{gl} = Q_T + Q_v$$

where Q_{gl} is the global heat flux from gas phase to liquid-solid phase; Q_T is the heat flux used to raise the temperature of the liquid-solid phase; Q_v is the heat flux used to vaporize the liquid combustible, which was simulated by

$$Q_v = C_v \cdot \rho_f \cdot Q \exp\left(-\frac{E}{RT}\right), \quad T \le T_b .$$

The boundary condition of the unsteady kerosene surface was :

$$n\frac{\partial \varphi}{\partial t} + (K+N)\frac{\partial \varphi}{\partial y} - N = 0$$

Above the kerosene surface, considering the influence of the Stefan Flow, The boundary condition for the species was :

$$\rho_0 v_0 m_{fu,0} - \rho_0 D_0 \left(\frac{\partial m_{fu}}{\partial y}\right)_0 = \rho_0 v_0 \quad [6]$$

The other initial conditions and boundary conditions are shown in Fig.2.

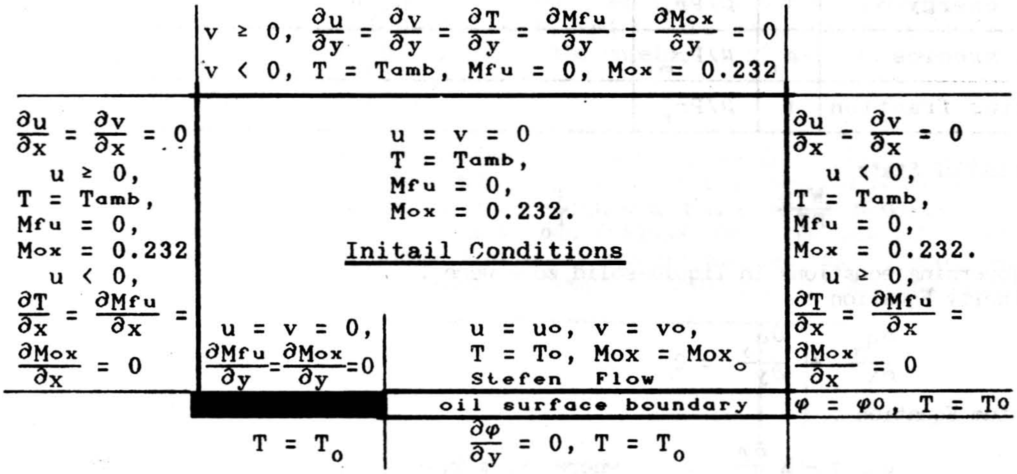
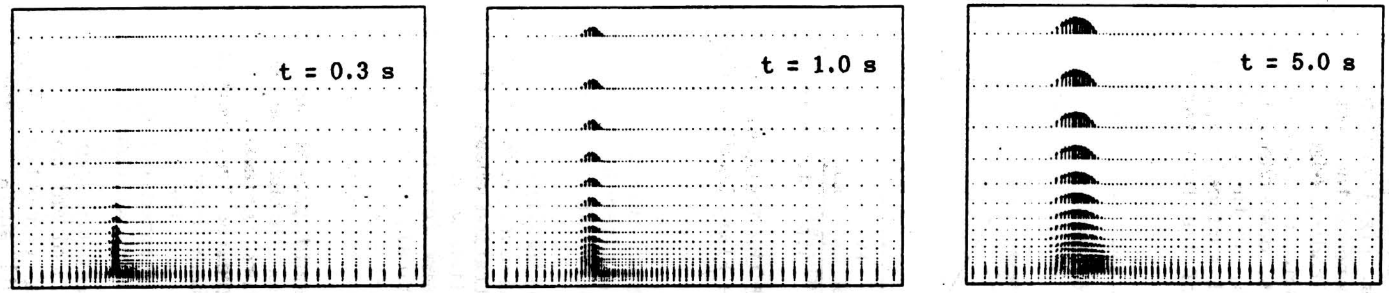


Fig.2 The Initial Conditions and the Boundary Conditions.

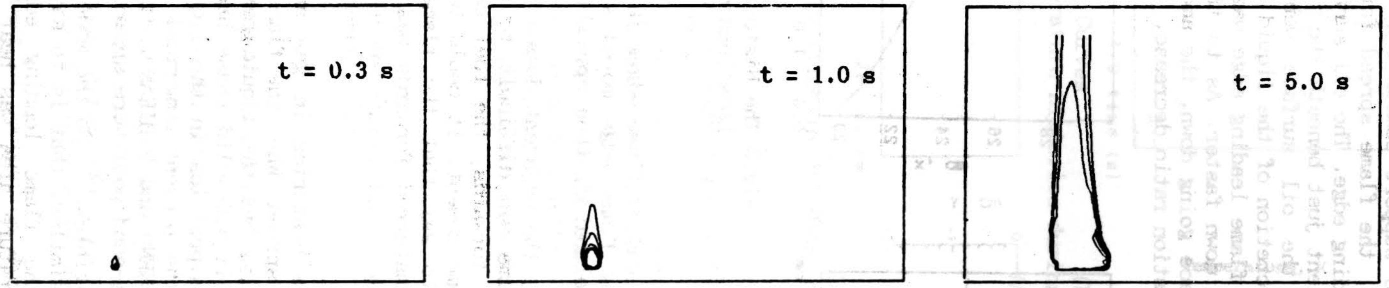
RESULTS AND DISCUSSIONS

1. Aspect of Flame Spread

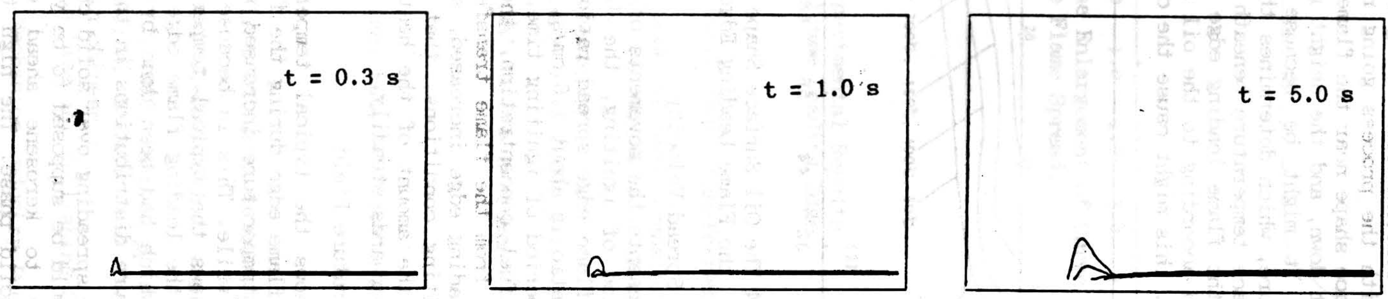
Under the flash point temperature in present study, the flame spread slowly. Fig.3(a)-(c) shows the instantaneous the velocity fields, the temperature fields and the fuel concentration fields at 0.3, 1.0, 5.0 second from the igniting moment. As



(a) Velocity Fields



(b) Temperature Fields



(c) Fuel Concentration Fields

Fig.3 The Process of Physical Scale Fields Variations during Flame Spread shown in this figure, having ignited, after a short time of gas expansion, a buoyant flow was invoked, which induced the plume. From the Fig.3(c), one can see in front of the flame leading edge there existed fuel component which mixed with the ambient air. The entrainment flow brought the pre-mixed fuel-air gas into the combustion area, it enhanced the combustion, so the heat released was intensified, and the liquid temperature went up, and the fuel concentration above the oil surface increased. When the fuel concentration was great to support combustion, the flame spread to this point. With the process going round, the flame spread forwards. Fig.4 presents the oil surface shape near the flame leading edge. The oil surface beneath the combustion area went down, and the height gradient just beneath the flame leading edge achieved ceiling. It might be because as the oil surface went down, the oil surface temperature, which determines the accretion of the liquid height, descended, but the oil surface temperature beneath the flame leading edge was high, so the oil surface beneath the flame leading edge went down faster. As to the oil surface temperature descended according to the oil surface going down, the amount of the fuel vaporized declined, this might cause the combustion ratio decrease.

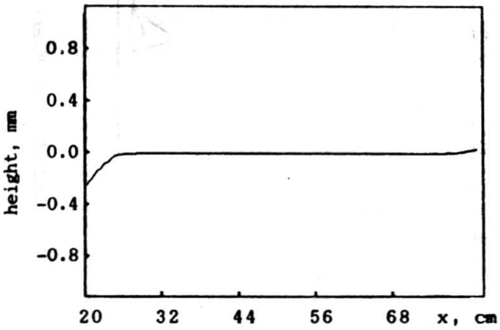


Fig.4 The Oil Surface Shape near the Flame Leading Edge.

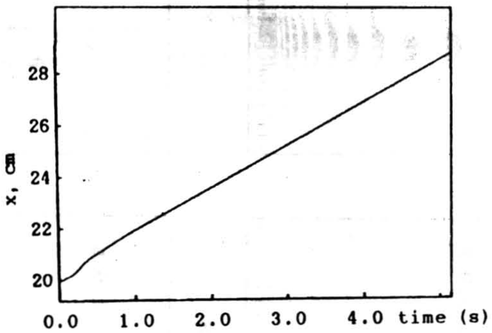


Fig.5 The Histories of the Instantaneous Locations of the Flame Leading Edge.

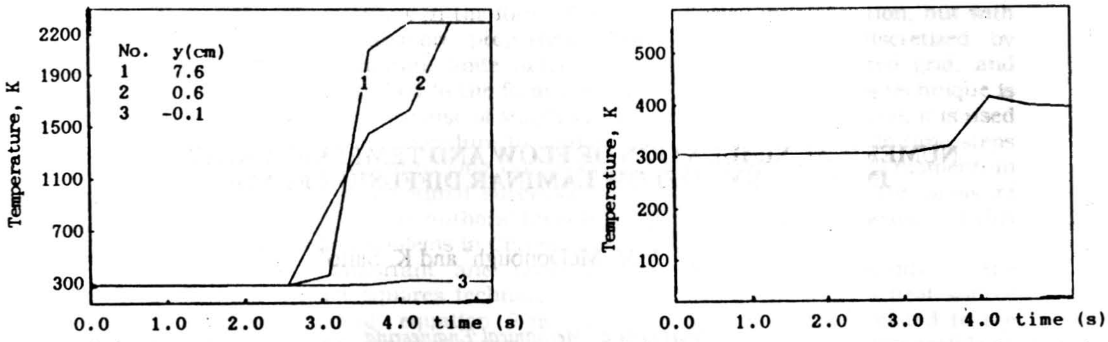
2. Flame Spread Velocity

Fig.5 presents the movements of the leading flame edges in position-time diagrams. In the period of igniting, the leading flame edge moved slowly, after a while, the leading flame edge spread ratio accelerated, then spread steadily. The steady flame spread ratio is about 1.6 cm/s.

In the period of igniting time, only the adjacent domain of the igniting source had greater fuel concentration, the flame was difficult to spread out. With the heat released from the flame transferred forwards, the fuel concentration ahead of the flame leading edge increased, at some moment, it could be ignited when it achieved the igniting conditions, that is to say that the flame spread forwards. At one moment, the amount of the heat transferred forwards was identical, then the flame spread forwards steadily.

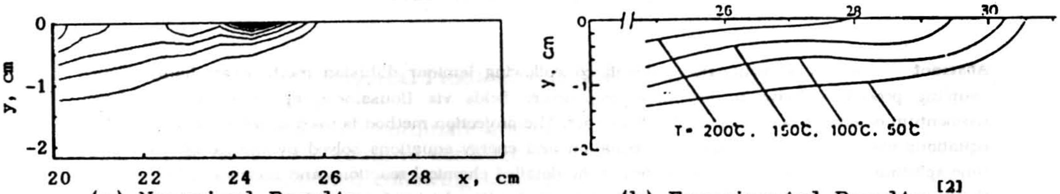
3. Temperature Field

Fig.6 shows the typical temperature histories in gas and liquid phases near the leading flame edge during the flame spread. When the flame passed through one point, the gas temperature increased rapidly, but the liquid temperature increased rapidly after a while. This is because the liquid-solid phase has a greater heat capacity. Fig.7 shows the typical temperature profiles in the liquid phase near the surface beneath the leading flame edge by the present numerical study and the experimental method which had been done by T.TAKENO and T.HIRANO. It was pointed out that the temperature distributions in the oil-sand pool were apparently very similar to those of flame spreading over solid combustibles.[2] So the mode of heat transfer for these cases could be supposed to be very similar, that is to say the dominant mode of heat transfer to kerosene ahead of the flame leading edge is conduction through liquid-solid phase. The high temperature area was near the oil surface where the flame occupied. Although the air in front of the flame leading edge had a higher temperature, the temperature of the liquid under it was low. Here one can see the heat conduction in the liquid-solid phase is important to the flame spreading.



(a) The Prototype of Curves (b) The Enlargement of Curve 3 of (a)

Fig.6 The Typical Temperature Histories during the Flame Spread.



(a) Numerical Results (b) Experimental Results [2]

Fig. 7 The Temperature Profiles in Oil Phase near Flame Leading Edge.

CONCLUSIONS

(1) The flame spread ratio is characterized by the heat flux transferred to the oil-sand phase from the flame.

(2) Under the flash point temperature, the dominant mode of heat transfer to oil ahead of the leading flame edge is inferred to be conduction through the liquid-solid phase.

(3) The porous media model for the oil-sand phase is acceptable.

(4) The employment of the laminar models and the negligence of radiation in present study is reasonable.

(5) The simulating results by numerical method are qualitative agreement with the experimental data.

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