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A DEVELOPMENT OF OIL-SPILL MODEL FOR KOREAN COASTAL WATERS

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ABSTRACT

We reviewed various oil-spill models and condensed the integrated information into a prediction model which is applicable to Korean Yellow sea coastal area. For the current data two-dimensional depth averaged Navier-Stokes equations are solved numerically by using the IAF finite difference scheme. As pre- and post-processor of the developed system we adopted an available commercial package. Various environmental data can be input through easy menu functions and the calculated current data can also be utilized. For the fate of the spilt oil we included effects of spreading, advection, evaporation, emulsification and shoreline interaction. Preliminary numerical experiment has proved that the developed oil-spill prediction system can be easily utilized in on-site oil recovery operations which usually require a quick and reasonable prediction.

1. INTRODUCTION

As the oil-based product consumption increases relocation of huge amount of crude or processed oil by marine transportation is also steadily increasing. As a result accidental oil spill events occur more frequently these days and some of the accidents are even catastrophic to the marine environment. Nevertheless because of the efficiency of the marine transportation the increasing oil transportation through the ocean seems to be unavoidable, hence well being prepared for the accidental oil spills may be one of the best ways we might have to pursue.

Under a given environmental condition, what we eventually want to know is how the spilt oil will evolve on the ocean. This information could be crucial for the cleanup operation to become more efficient and effective over all and, eventually, damages associated with the spill might become minimal. There have been numerous experimental and analytical investigations aiming at further understanding of the fundamental interaction mechanism between the contaminants and the environment, however, even up-to-date information we have is rather far behind what we need in order to fully understand it (see Lee et al.[1990]). Nevertheless, we still need to have prediction tools to cope with the frequently occurring oil spill accidents.

In this context, we developed a prediction system of the spilt oil's fate which can be applicable to Korean Yellow sea area and briefly report related studies here. We reviewed previous investigator's fate models and selectively included some of them which we believe important. For the current information, which is rather difficult to measure quickly, we also developed a two-dimensional current simulation module that produces surface current relatively quickly by solving depth averaged Navier-Stokes equations.

2. SIMULATION OF CURRENT

In order to have a reliable estimation of the oil slick's motion, providing prediction models with accurate environmental data is essential. In this context, even though wind often seems to play dominant role in determining the oil slick motion in general, an accurate current information near the spill site is also important. However, in general, the current data can not be easily measured on site compared to wind measurements. One way to resolve this difficulty is to have a reliable current estimation tool which can produce the required information in a reasonably short time.

So we developed a two-dimensional depth averaged Navier-Stokes equation solver which can include the effect of water depth variation. Wind effect on the surface current is also included by applying the shear stress associated with wind to the water surface.

In the following sections we briefly describe the formulation along with the numerical scheme used, and then present typical results with discussions.

2.1 Formulation and Calculation

In the following formulation the right handed cartesian coordinate is assumed as the reference frame and the x- and y-axis corresponds to the latitudinal and longitudinal direction, respectively. Based on the Boussinesq approximation, we ignore the density variation and the salinity conservation equation is not considered for now. As a result, the governing equations of the problem are obtained as follows and each of them are the continuity and two momentum equations.

$$\frac{\partial \eta}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{\partial (Hv)}{\partial y}=0, \tag{1}$$

$$\begin{aligned}\frac{\partial u}{\partial t} &+ \frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}=-g\frac{\partial \eta}{\partial x}+fv \\ &+ K_{H2D}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{1}{\rho H}(\tau_{w,x}-\tau_{b,x}),\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial v}{\partial t} &+ \frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}=-g\frac{\partial \eta}{\partial y}-fu \\ &+ K_{H2D}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{1}{\rho H}(\tau_{w,y}-\tau_{b,y}).\end{aligned} \tag{3}$$

Here conventional notations are used and the x- and y-directional current velocity u and v are depth averaged ones. The η is the surface elevation and $H=\eta+h$ where h is the water depth. Other variables are as follows;

$$\begin{aligned} g &= \text{acceleration of gravity,} \\ \rho &= \text{water density,} \\ f &= 2\Omega \sin\phi, \\ \Omega &= \text{angular velocity of the earth,} \\ \phi &= \text{latitude,} \\ K_{H2D} &= \text{effective frictional coefficient.} \end{aligned}$$

The shear stress terms coming from the top and bottom boundaries are

$$\begin{aligned} \tau_{w,x} &= \rho_a\gamma_a u_a\sqrt{u_a^2+v_a^2}, \\ \tau_{w,y} &= \rho_a\gamma_a v_a\sqrt{u_a^2+v_a^2}, \\ \tau_{b,x} &= \rho\gamma_w u\sqrt{u^2+v^2}, \\ \tau_{w,x} &= \rho\gamma_w v\sqrt{u^2+v^2}. \end{aligned}$$

where (u_a, v_a) and ρ_a are wind velocities and air density, respectively. The γ_w and γ_a are frictional coefficients which are generally determined empirically, and these values are known to be sensitive to velocity and boundary characteristics.

The equations (1) to (3) are solved numerically using the Implicit Approximate Factorization. The equations are discretized by using regularly spaced grid and the second order central differencing is used. In order to treat the checker board problem an artificial dissipation is introduced.

At closed boundaries velocities are set to be zero and the gradient of surface elevation across the boundaries is assumed to be zero. At open boundaries the surface elevation is given harmonically in time and the gradient of velocities across the boundaries are assumed to be zero. The presence of lands in the computing domain is treated simply by introducing very large values for the effective frictional coefficient (K_{H2D}).

2.2 Numerical Experiments and Discussions

The developed code was investigated rigorously by varying environmental conditions including water depth in order to check the performance. Even though we do not include the results from the preliminary numerical experiments we verified that the code generated physically correct and stable results as long as we carefully chose the CFL number.

One typical result we present here is from a trial run for the area given in figure 1. At the sides AB, BC, CD the surface elevations are given which are varying linearly between values given in table 1. The grid size used is $1000m$ and $1500m$ in the x- and y- direction respectively. The time step is $60s$ and other coefficients used are as follows;

$$\begin{aligned} K_{H2D} &= 10000\ m^2/s \\ g &= 9.8\ m/s^2 \\ f &= 0.000088\ s^{-1} \\ \rho &= 1025\ Kg/m^3 \end{aligned}$$

In figure 2 the velocity vectors are shown at different times for one period (12 hrs). As the simulation continues the flow repeatedly showed a reasonably good periodicity and the global behavior looked physically correct. Even though we could not compare our results with other validated more realistic numerical or experimental data, the developed code can be easily incorporated in a oil spill fate models which requires quick and reasonable current information.

3. FATE MODELING

3.1 Evolution of Spilt Oil

The fate of spilt oil can be understood as a process in which two different but closely related mechanisms are interacting each other. One is rather simple process which includes spreading and advection of oil, while the other is more complicated physical, chemical and biological process which enhances the change of material properties of oil. This later process is often called weathering and it includes evaporation, diffusion, dissolution, emulsion, tar-lump formation, photochemical reaction, degradation, sedimentation and plankton ingestion and so on. But frequently we use the terminology, weathering, as covering the spreading and advection also. Each weathering process depends on different environment parameter or parameters - material properties of oil and water, current, wind, sea state, temperature and so on

- and people include some of the aforementioned weathering processes depending on their specific objectives.

As previously mentioned, there have been quite plenty of related studies on this interaction problem. Here, we selected a few fundamental elements which are believed crucially important and also for which relatively reliable evolution equation are provided with bearing in mind this is our first trial model. We briefly explain each of the process included in our model in the following.

Spreading

Spreading is generally treated as three different stages in which different driving/resisting parameters play important roles. First two of them are gravity/inertia and inertia/viscosity stages (Fay[1969]). The third one is interfacial-tension/viscosity stage but this is less important in the context of a quick cleanup operation compared to the other two. Followings are the equations used to determine the spreading at the very beginning according to Fay[1969].

$$R(t) = 1.14\nabla^{1/3}\left[\frac{g(\rho-\rho_o)}{\rho\nabla^{1/3}}\right]^{1/4} t^{1/2} \tag{4}$$

$$R(t) = 0.98\nabla^{1/3}\left[\frac{g\rho_o(\rho-\rho_o)}{\rho\mu^{1/2}}\right]^{1/6} t^{1/4} \tag{5}$$

where $R(t)$ = radius of oil slick (m),
∇ = oil volume (m^3),
Subscript o = oil.

First we start with eq. (4) and once the slick thickness becomes $5mm$ we switch to eq. (5) until the slick becomes $1mm$ of thickness. After then we use, following Mackay's[1980], thick slick model since in the early stage of cleanup process slick area estimated with including very thin oil layer is meaningless.

$$\frac{dA}{dt} = K_1 A^{1/3} h^{4/3} \tag{6}$$

where A = slick area (m^2),
t = time (s),
K_1 = empirical spreading constant, $150/s$ in general (Spaulding[1988]),
h = slick thickness (m).

Advection

Oil's advection is mostly due to the surface current and the wind. In addition we include the effect of turbulent diffusion and write the spillet's transport velocity, $\mathbf{V_S}$ as follows.

$$\mathbf{V_S} = \mathbf{V_C} + \mathbf{V_W} + \mathbf{V_t} \tag{7}$$

where $\mathbf{V_C}$ = due to current(m/s),
$\mathbf{V_W}$ = due to wind (m/s),
$\mathbf{V_t}$ = due to turbulent diffusion (m/s).

The transport velocity associated with current is taken from the value of surface current itself. The transport velocity associated with wind is generally taken as 3.5 percent of the wind velocity with a righting drift angle varying from 0 to 20° (Reed[1989], Galt[1994]), which includes both wave drift and wind shear. Here we adopted the suggestion by Yossef et al.[1993] in which the drift factor (F) and the drift angle (θ) are given as follows.

$$F = 3.19 - 0.0318U. \tag{8}$$

$$\theta = 23.627 - 7.97\log U. \tag{9}$$

where U = wind speed (m/s). According to Ellegaard et al.[1992] the turbulent diffusion is included by using the random walk concept and the expression is

$$\mathbf{V_t} = R\sqrt{\frac{6D_t}{\Delta t}} \tag{10}$$

where R = random number between -1 and 1,
D_t = diffusion coefficient (m^2/s),
Δt = size of time step (s).

In the real calculation the above velocity is determined by following two scalar expressions which are for latitudinal (x-direction) and longitudinal (y-direction) component, respectively.

$$V_x = R_x\sqrt{\frac{6D_x}{\Delta t}}\frac{u}{V}, \tag{11}$$

$$V_y = R_y\sqrt{\frac{6D_y}{\Delta t}}\frac{v}{V} \tag{12}$$

where R_x, R_y = random number,
D_{tl} = longitudinal diffusion coefficient,
D_{tt} = transverse diffusion coefficient,
u, v = latit. and longi. current speed,
$V = \sqrt{(u^2+v^2)}$.

For the random number a random number (P) between 0 and 1 is generated first then $2(P-0.5)$ is selected. The diffusion coefficients used are determined as following based on the mixing length concept in which $D_x = l^2\partial u/\partial x$, for example, where l is selected as 0.09 times of the grid size used.

$$D_L = l^2\partial u/\partial x. \tag{13}$$

Evaporation

Once an oil spill occurs the most dominant weathering phenomenon is the evaporation during the first several days (Butler et al.[1976]). Consequently a significant amount of oil mass is transported into the atmosphere and the remaining oil's property is gradually changed.

The most reliable evaporation formula has been developed by Stiver and Mackay[1984] in which they analytically calculate the evaporation by using oil distillation data. The fraction evaporated is given as

$$F_v = \ln\left\{1 + B(\frac{T_G}{T})\Theta \exp{(\alpha - \beta\frac{T_o}{T})}\right\}\left(\frac{T}{BT_G}\right) \quad (14)$$

where T = ambient temperature (K),
T_o = initial boiling point of the modified distillation curve (K),
T_G = gradient of the modified distillation curve,
α, β = constants ($\alpha = 6.3$, $\beta = 10.3$ in general).

The evaporative exposure required in the eq. (14) is given as

$$\Theta = \frac{K_m At}{V_o} \quad (15)$$

where K_m = mass transfer coefficient (m/hr),
A = slick area (m^2),
t = time (hr),
V_o = volume of oil slick (m^3).

And the mass transfer coefficient used is

$$K_m = 0.0292 U^{0.78} D^{-0.11} Sc^{-0.67} \quad (16)$$

where U = wind speed (m/hr),
D = slick diameter (m),
Sc = oil vapor Schmidt number, 2.7 is typical.

As mentioned previously, the consequent change in oil's viscosity is determined using the evaporation fraction as

$$\mu = \mu_0 \exp(C_3 F_v) \quad (17)$$

where μ_0 = initial oil viscosity (cP),
C_3 = 1 for light oils, 10 for heavy oils.

Emulsification

The water-in-oil emulsification also affects the oil's property such as density and viscosity. If these property changes are not taken into account, cleanup operations may become harder than expected so we need to predict these effect carefully. Mackay's[1980] model is believed reliable in general and we use his formula.

$$\frac{dW}{dt} = K_a(U+1)^2(1 - K_b\ W) \quad (18)$$

where W = fractional water content,
$K_a = 2 \times 10^{-6}$ for most emulsifying oils.
0 for non-emulsifying oils,
U = wind speed (m/s)
K_b = constant, 1.33.

The change of viscosity associated with the emulsification is also taken into account, according to Mooney[1951], as

$$\mu = \mu_o \exp{(\frac{2.5W}{1 - K_c W})} \quad (19)$$

where K_c is a constant between 0.62 and 0.65.

3.2 Numerical Experiments and Discussions

The developed prediction system is applied to an artificial oil spill event. We took the region roughly $100Km$ big in both horizontal directions near Inchon, Korea and 100 grids are used in both directions. We assumed 100 tons of oil is discharged for a half day. The current is modeled to start from a flow condition with a typical speed, $10cm/s$ and the wind is arbitrarily given mostly inshore with a typical speed $10m/s$. Time step used for the simple Euler integration is $1hr$. For the shoreline interaction, we simply modeled that once slicks reach shores they stick to the shores. Spill location is marked as a big circle in figure 3 along with small dots representing 100 oil spillets which make the sequential oil trajectory at four different times visible.
As we can see, 4 days after the spill most of the spilt oil has reached the lands since the wind given plays dominant role in this case.
Following figure 4 and 5 summarize the event. In figure 4 mass distribution of the spilt oil is shown as a function of time. As we saw in the previous picture, a significant amount of oil starts stranding on shore from the second day which is indicated by the rapidly ascending short dotted line. We also can see a considerable amount of oil mass is lost due to the evaporation. In figure 5 several averaged variables are shown as functions of time. Even though due to the oil's quick stranding the trends after the second day possibly mislead us, during the early stage information shown in the figure agrees reasonably well with the previously obtained experimental and observational results.

4. SUMMARY

We developed a prediction system of the spilt oil's fate which is applicable to Korean Yellow sea area. Most of the important weathering models such as spreading, advection, evaporation, emulsification and shoreline interaction are included based on the previous investigators' results. For the current data two-dimensional depth averaged Navier-Stokes equations are numerically solved by using the Implicit Approximate Factorization scheme. Although in the cases, especially when current is more important than wind, we have to be careful about the difference between the depth averaged velocity and the real velocity, the two-dimensional current calculation still seems to be valuable since it can provide the fate model with a reasonable surface current in relatively short time.

Preliminary numerical experiment has demonstrated a possibility that the developed oil-spill prediction system could be easily utilized in on-site oil recovery operations which usually require a quick and reasonable prediction. The prediction system developed so far is equipped with more or less primitive fate models and we believe that further improvement should be made based on results from more rigorous field experiments.

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Table 1 Trial tidal wave boundary condition.

Location	*Amplitude* (*m*)	*Phase Lag* (deg)
A	0.5	7.0
B	0.6	5.0
C	1.0	0.0
D	1.11	0.0

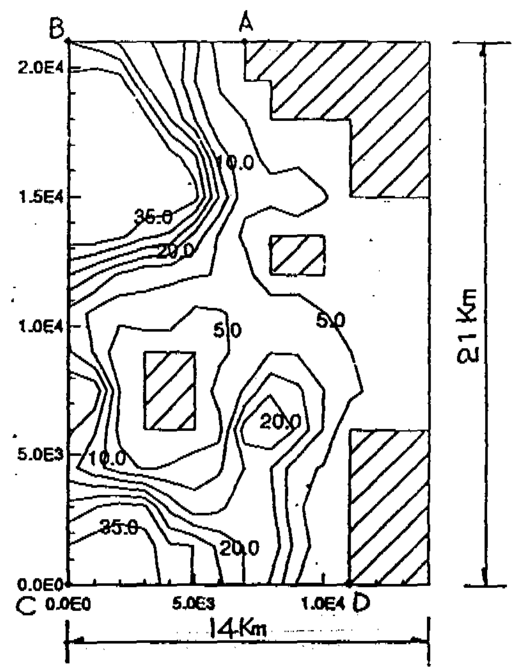

Fig. 1 Artificial coastal map and bathymetry.

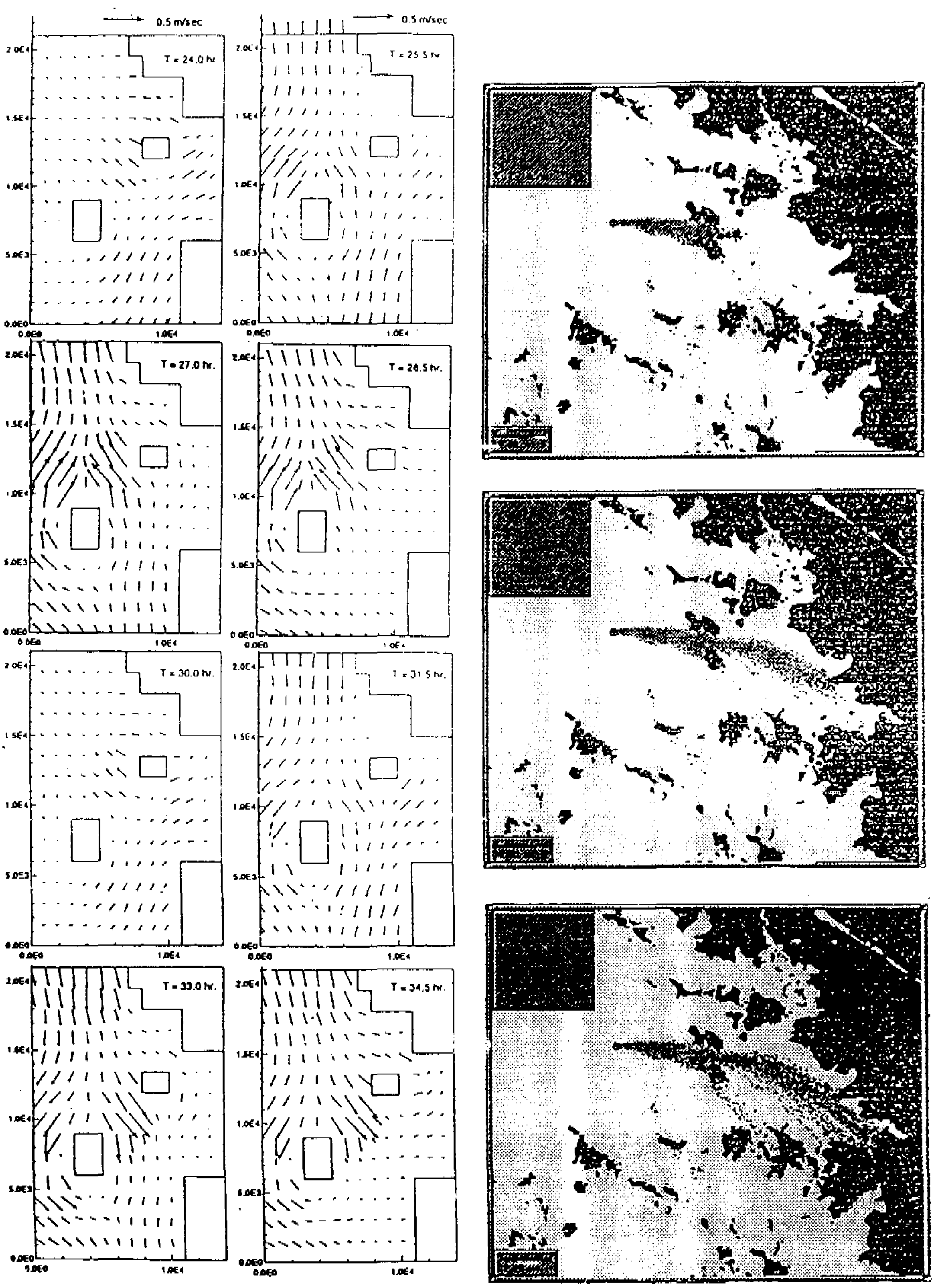

Fig. 2 Simulated tidal currents for one period.

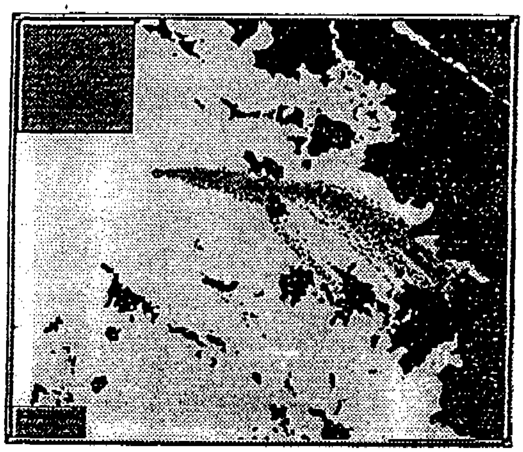

Fig. 3 Simulated evolution of oil slick. 1, 2, 3 and 4th day after the spill from the top.

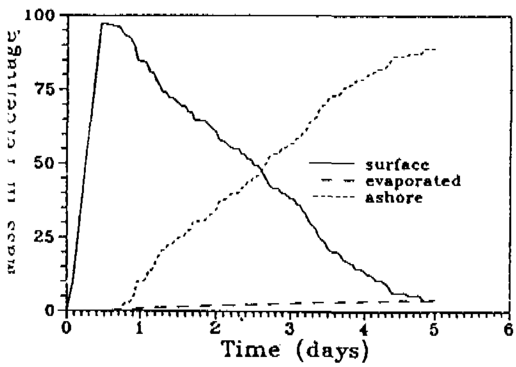

Fig. 4 Oil mass distribution as functions of time.

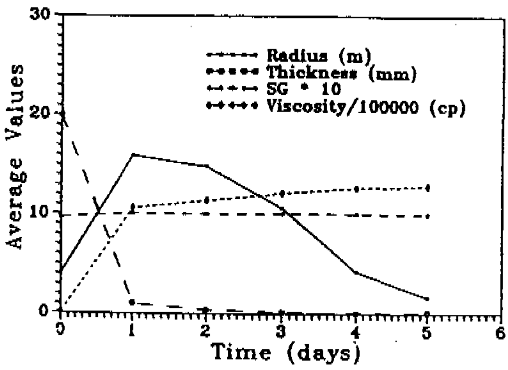

Fig. 5 Various averaged values during the spill event.