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A model for oil spreading in cold waters

Janne K.Ø. Gjøsteen*

Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), Trondheim 7491, Norway

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Abstract

A model for oil spreading on sea is developed based on forces acting in the horizontal dimension. It consists of conservation laws for volume and momentum. The model is valid for a complex slick geometry, and is suitable for coupling to a discrete element ice model or other complex boundaries, for example coast lines. The numerical interpretation of the model is based on a finite difference approach.

Keywords: Oil spills; Sea ice; Modelling; Mathematical models; Numerical models; Simulation

1. Introduction

The spreading of oil in open calm sea has been investigated by numerous researchers. Different analytical models have been suggested based on theoretical knowledge of the relevant processes. Research and modeling of the spreading of oil under a solid ice cover or on top of ice began early in the 1970s. Some years later, the first models for oil spreading in brash ice were suggested. In general, the presence of ice makes the spreading process more complex than the corresponding open water spreading. For this reason, experiments have been an important part of the research and several of the models are empirically based.

Some of the most important contributions to the field will be mentioned here. Further reviews of different theories can be found in ASCE (1996), Belaskas and Yapa (1991) and the more recent Reed et al. (1999) among others. The models by Blokker (1964) and Fay (1969) can be considered to be the ancestors of the oil spreading models. Some other analytical models to be mentioned are the one by Hoult (1972), and Fannelop and Waldman (1972).

A real spill at sea will consist of an area covered with a thick layer of oil. Around this, there will be an area covered with only a thin film of oil. The first one is called the bulk-layer, the second is the mono-layer. As a rule of thumb, the bulk-layer contains 90% of the oil and the mono-layer 10%. Di Pietro and Cox (1979) developed a theory for both the mono-layer and the bulk-layer. Mackay et al. (1980) start from Fay's equations, making a model of a thick layer feeding a thinner layer.

When it comes to spreading of oil in ice-infested waters, a lot of names deserve to be mentioned. Glaeser and Vance (1971) were among the earliest doing experiments to measure oil spreading under solid ice. Hoult et al. (1975) made an extensive study of oil spreading on and under ice. Chen et al. (1976)

* Fax: +47-73-59-47-01.
E-mail address: janne.gjosteen@bygg.ntnu.no (J.K.Ø. Gjøsteen).

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conducted experiments in fresh water ice to simulate spreading of oil in rivers and suggested equations for this type of oil spreading. Based on the Navier–Stokes equations, Yapa and Chowdhury (1990) suggest equations for spreading of oil under an ice cover.

For oil spreading in brash ice, Ross and Energetex (1985) suggested a modified version of Fay's equation. Essentially, the viscosity is changed. Ross and Dickins (1987) compared data obtained from three field spills to those equations. Venkatesh and El-Tahan (1992) developed a new set of equations, based on similar considerations as Fay (1969), but including the viscosity of oil. Ovsienko et al. (1999) presented a model of oil spreading in between fixed circular ice floes. The basis of this model is the work of Di Pietro and Cox (1979).

A large number of computer models have been developed to forecast spreading for different areas, as OSCAR, ADIOS, OILMAP or COZOIL. Some of the models are an important part of the oil spill contingency. To cope with a general geometry of the slick, most models are based on a particle or spillet approach. Using particles, the oil consist of distinct parcels of oil that each are subjected to forcing from wind and currents, and also internal forces in the oil that serve to spread it. Random processes are added to simulate the spreading due to turbulence in the water body, and the distribution of particles are averaged to obtain a spatial view of the oil distribution. Spillets are a similar approach, but each of the parcels have in addition the ability to spread following some spreading theory like Fay's equation.

The reason why most existing models are based on one of the two approaches is the simplicity they offer. This reduces the amount of calculation needed to forecast the spreading. However, there are drawbacks. Obviously, the level of detail one can expect to obtain is limited by the size or number of particles used. This is because the particles must be averaged to obtain a physical picture of the situation. When increasing the requested level of detail, there comes a point when it is simpler to treat the spill as a fluid.

This paper describes the development of a model based on the assumption that the oil is a viscous fluid. The level of detail that the model can describe will of course be restricted by the simplifications that are made, as well as the choices for its numerical implementation. One can always increase the accuracy of the implementation, and eventually make the error it introduces far smaller than the ones introduced by the simplifications of the model. However, this may greatly increase the amount of calculation needed.

The specific numerical implementation that is chosen makes the model suitable for coupling to a dynamic ice model. The choice of programming language was Fortran 90, combined with MATLAB for visualization purposes.

2. Physical model

When oil spreads on water, the process involves three different phases of matter, namely air, oil and water. For a very detailed description of the system, each of the phases can be described by the Navier–Stokes equation. At the boundaries between the different phases, boundary conditions have to be imposed. This approach will indeed lead to a detailed description of the dynamics, but it is also very complicated and would be impossible to solve at present time.

It is necessary to simplify, and this is done in the same manner as Venkatesh and El-Tahan (1992). This means that the focus is on the forces working in the horizontal direction of the slick, and that the concept of a flow parameter is adopted to describe the vertical velocity profile in the slick. The simplification that this parameter implies can be allowed because the aim is not to describe the detailed dynamics inside the slick, but rather the global behaviour. A general parcel of the oil is studied, instead of the whole slick as is done in most of the existing analytical approaches. This makes the theory valid for a general spill geometry.

It is assumed that the motion is relatively slow, this means that dynamic pressure due to waves is neglected. Moreover, it is assumed that the oil behaves as a Newtonian fluid, which allows the viscosity in oil to be expressed in a relatively simple way. Weathering of oil is neglected, which implies that density, viscosity and other parameters describing the oil are constant. The latter assumption is not essential. Parametric expressions for weathering could easily be included.

To develop the equation that states conservation of matter is quite straight forward. By neglecting physical and chemical changes such as evaporation and water uptake and assuming the oil to be incompressible, the only change that the oil can undergo is movement from

one place to another. Let U and V be the mean velocity in x- and y-direction, respectively, defined by

$$U = \frac{1}{h}\int_0^h u(z)\mathrm{d}z, \tag{1}$$

where h is the local thickness of the parcel. The flow of oil at the borders and inside the parcel in Fig. 1 during the period $[t_1, t_2]$ can now be written as:

$$\begin{aligned}
&\int_{y_1}^{y_2}\int_{x_1}^{x_2} h(x,y,t_2) - h(x,y,t_1)\mathrm{d}x\ \mathrm{d}y \\
&= \int_{y_1}^{y_2}\int_{t_1}^{t_2} h(x_1,y,t)U(x_1,y,t) \\
&\quad - h(x_2,y,t)U(x_2,y,t)\mathrm{d}t\ \mathrm{d}y \\
&\quad + \int_{x_1}^{x_2}\int_{t_1}^{t_2} h(x,y_1,t)V(x,y_1,t) \\
&\quad - h(x,y_2,t)V(x,y_2,t)\mathrm{d}t\ \mathrm{d}x.
\end{aligned} \tag{2}$$

This equation says that a change of oil quantity inside the parcel must equal the amount of oil that is transported across the borders of the parcel. To make the notation shorter, the free variables are omitted in the following. This means that h should be interpreted as $h(x, y, t)$, $h(x_1)$ as $h(x_1, y, t)$. When one assumes that h, U and V are all differentiable, one has

$$\begin{aligned}
&h(t_2) - h(t_1) = \int_{t_1}^{t_2}\frac{\partial}{\partial t}h\ \mathrm{d}t \quad \text{and} \\
&h(x_1)U(x_1) - h(x_2)U(x_2) = -\int_{x_1}^{x_2}\frac{\partial}{\partial x}hU\ \mathrm{d}x,
\end{aligned} \tag{3}$$

and correspondingly for hV. When substituting those expressions into Eq. (2) and change the order of integration, the following is obtained:

$$\begin{aligned}
&\int_{y_1}^{y_2}\int_{x_1}^{x_2}\int_{t_1}^{t_2}\frac{\partial}{\partial t}h + \frac{\partial}{\partial x}\{hU\} \\
&\quad + \frac{\partial}{\partial y}\{hV\}\ \mathrm{d}t\ \mathrm{d}x\ \mathrm{d}y = 0.
\end{aligned} \tag{4}$$

Since this must hold for every section $[x_1, x_2] \times [y_1, y_2]$ inside the slick, and for every time interval $[t_1, t_2]$, one can conclude that the integrand itself must be zero, that is

$$h_t + (hU)_x + (hV)_y = 0. \tag{5}$$

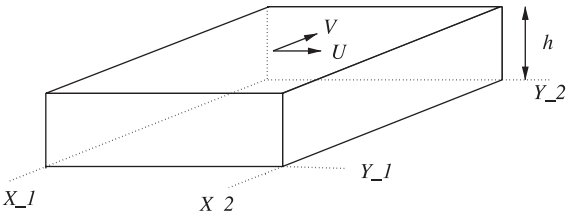

Fig. 1. Some dimensions in a parcel of oil.

To write down the equations for conservation of momentum, one must consider which factors to include. In addition to transfer of momentum at the borders (which is similar to the transfer of mass in the previous equations), forces are acting on the parcel of oil. They work as sources or sinks of momentum and must be included. Forces that are included are pressure, viscosity in oil, surface tension and surface drag between water and oil. It is assumed that no wind is present. However, this can be included by introducing a force similar to the water drag. To simplify the development of the equations, it is also assumed that there is no current. Background current in sea can be included by using relative velocity between water and oil instead of oil velocity in the expressions for the water drag. Equations for the x-direction will be developed in the following. Corresponding equations are valid for the y-direction.

Let ρ_o be density of oil, and write for x-direction:

$$\begin{aligned}
&\int_{x_1}^{x_2}\int_{y_1}^{y_2} \rho_o hU(t_2) - \rho_o hU(t_1)\mathrm{d}y\ \mathrm{d}x \\
&= \int_{t_1}^{t_2}\int_{y_1}^{y_2} \rho_o h(x_1)U(x_1)^2 - \rho_o h(x_2)U(x_2)^2\mathrm{d}y\ \mathrm{d}t \\
&\quad + \int_{t_1}^{t_2}\int_{x_1}^{x_2} \rho_o h(y_1)U(y_1)V(y_1) \\
&\quad - \rho_o h(y_2)U(y_2)V(y_2)\mathrm{d}x\ \mathrm{d}t + \int_{t_1}^{t_2}\int_{y_1}^{y_2} P(x_1) \\
&\quad - P(x_2)\mathrm{d}y\ \mathrm{d}t + \int_{t_1}^{t_2}\int_{y_1}^{y_2} S(x_1) - S(x_2)\mathrm{d}y\ \mathrm{d}t \\
&\quad - \int_{t_1}^{t_2}\int_{x_1}^{x_2}\int_{y_1}^{y_2} M_{\text{oil}}\ \mathrm{d}y\ \mathrm{d}x\ \mathrm{d}t \\
&\quad - \int_{t_1}^{t_2}\int_{x_1}^{x_2}\int_{y_1}^{y_2} M_{\text{water}}\ \mathrm{d}y\ \mathrm{d}x\ \mathrm{d}t.
\end{aligned} \tag{6}$$

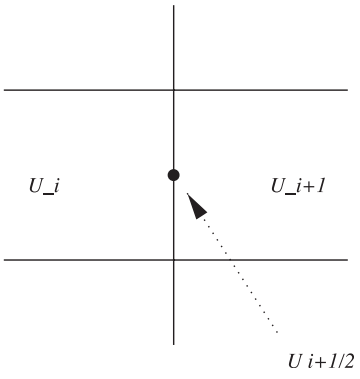

Fig. 2. Velocity on the border of two oil cells.

P is pressure, integrated over thickness and S is surface tension. M_{oil} and M_{water} are stresses from oil viscosity and water drag, respectively.

The two first factors on the right hand side are the transfer of momentum across the boundaries. Note that the momentum in x-direction is transferred over all four boundaries. Following a similar procedure as before by assuming both U, V, P, S, M_{oil} and M_{water} to be differentiable in suitable variables, one can write

$$(\rho_o hU)_t + (h\rho_o U^2)_x + (h\rho_o UV)_y + P_x + S_x + M_{\text{oil}} + M_{\text{water}} = 0. \tag{7}$$

Now, the question is: What do the functions P, S, M_{oil} and M_{water} look like?

2.1. Viscosity

Assuming the oil to be a Newtonian fluid, the horizontal acting viscous stresses inside the oil will be given by the following components for the x-direction:

$$\tau^{xx} = 2\mu_o \frac{\partial u}{\partial x}, \qquad \tau^{xy} = \mu_o\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \qquad \text{and}$$
$$\tau^{xz} = \mu_o\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right),$$

where μ_o is the absolute viscosity of oil. The first superscript denoted the direction of the stress, the second which plane it is working on. Now, for an oil slick, the vertical dimensions will be small while the horizontal dimensions are large. In addition, one can assume that the vertical velocity is much smaller than the horizontal velocity. When retaining only the largest parts of the stresses above, the horizontal stress can be approximated to

$$\tau^{xz} = \mu_o \frac{\partial u}{\partial z}. \tag{8}$$

Let the velocity at the bottom and the top of the slick be denoted u_b and u_t, respectively. Now, approximate the derivative and write

$$\tau^{xz} \approx \mu_o\left(\frac{u_b - u_t}{h}\right) \tag{9}$$

A flow parameter ψ is defined in the same manner as in Venkatesh and El-Tahan(1992) to be

$$\Psi = \frac{u_b - u_t}{2U}. \tag{10}$$

By combining Eqs. (9) and (10) one obtain

$$M_{\text{oil}=}\tau^{xz} \approx \mu_o 2U\Psi\frac{1}{h}. \tag{11}$$

A suitable value for ψ is needed, which is not easy to find. The values of u_b or u_t are not known, and the precise shape of the velocity profile is also unknown. However, there is some knowledge about limiting behaviour. If the viscosity μ_{oil} is approaching zero, the connection between the different layers in the oil will influence each other to a small degree. This creates a situation where large differences in the top and bottom velocity can occur. At the other hand, as viscosity increases, the oil will behave more as a solid slug, and the vertical variation in velocity will be small. It is not possible to point out a clear connection between ψ and μ_{oil}, but from Eq. (10), it is reasonable to assume that ψ increase when μ_{oil} decrease, and the opposite way around. Formally, this reads:

$$\lim_{\mu_o \to 0} \Psi = 1 \qquad \text{and} \qquad \lim_{\mu_o \to \infty} \Psi = 0.$$

It is also required that ψ is steadily decreasing, while $\psi\mu_o$ is steadily increasing, at least in the relevant interval of μ_o. The last assumption ensures that the viscous stress increases when the oil viscosity does. In a compact way, this can be expressed as:

$$\frac{\mathrm{d}}{\mathrm{d}\mu_o}\Psi \leq 0 \qquad \text{and} \qquad \frac{\mathrm{d}}{\mathrm{d}\mu_o}(\Psi\mu_o) \geq 0.$$

Now, the question is how to connect ψ and μ_o. There are a lot of different choices, and the equation suggested below should be quite flexible. The two coefficients should be adjusted using experimental data.

$$\Psi(\mu_o) = \frac{K_1^{K_2}}{(K_1 + \mu_o)^{K_2}} \quad \text{given} \quad 0 < K_2 < 1. \tag{12}$$

It should be made perfectly clear that the flow factor ψ is an aid introduced to describe the problem in a convenient way. It may turn out that there are better ways of doing it. Here, it is assumed that the flow factor and viscosity are closely linked, but there might be other factors of importance.

2.2. Water drag

For water drag, the equation

$$M_{\text{water}} = \tau_w = \frac{1}{2} C_s \rho_w U^2, \tag{13}$$

is used, where ρ_w is density of water and C_s is a shear stress coefficient with values

$$C_s = 0.074 Re^{-1/5}$$
(turbulent boundary layer, $Re > 5 \cdot 10^5$)

$$C_s = 1.328 Re^{-1/2} \quad \text{(laminar boundary layer)}$$

where $Re = UL\rho/\mu$ is a Reynolds number, depending on characteristic values for velocity, length, density and viscosity. The coefficients are offered by Schlichting (1960) for boundary layers above a plate, based on Blasius equation for the laminar case, and a velocity power law for the turbulent case.

2.3. Surface tension

The net surface tension, σ_n acting at the outermost border of the slick, could in principle be calculated by

$$\sigma_n = \sigma_{o/w} + \sigma_{o/a} - \sigma_{w/a}, \tag{14}$$

where $\sigma_{o/a}$ and $\sigma_{w/a}$ are surface tensions at the oil–atmosphere and water–atmosphere boundaries, respectively, while $\sigma_{o/w}$ is the interfacial tension at the oil–water boundary. In general, this will result in a negative σ_n that will work to spread the oil. To describe the surface tension in an alternative way, an equilibrium thickness h_{eq} of oil is introduced, which is the thickness when oil spreading will cease at a calm sea. When all the time derivatives in Eq. (7) are ignored the effective net surface tension can expressed as

$$\sigma_n = h_{eq}^2 \frac{g\Delta\rho\rho_o}{2\rho_w}, \tag{15}$$

where $\Delta\rho$ is the difference in density for oil and water.

It may seem a bit odd to assume surface tension to be differentiable, knowing that it works only at the boundary of the slick. Applying it as a boundary condition seems more reasonable. However, we are interested in a general parcel of oil, be it at the edge or in the interior. This means that either the edge of the slick must be treated in a different way than the interior, or an artificial tension that will mainly act at the boundary can be imposed. The latter is our choice, and we will elaborate further on this in Section 3.2.

2.4. Pressure

When neglecting the atmospheric pressure, there will be a static pressure inside the oil at depth z

$$p(x, y, z, t) = \rho_o g z, \tag{16}$$

where g is the acceleration of gravity. The total integrated pressure from depth h_1 to h_2 is given by

$$P(x, y, t) = \int_{h_1}^{h_2} \rho_o g z \, \mathrm{d}z \tag{17}$$

The forces coming from pressure are always acting in all directions. For a parcel of oil on top of water, consider the boundary between the two fluids. It will be attacked by two forces of opposite direction: the pressure from the oil and from the water. As long as the boundary is horizontal, it will experience forces only in the vertical direction. In all other situations, there will be both a vertical and a horizontal component. This means that pressure differences in the oil and the water will lead to a horizontal motion or spreading of the oil.

3. Numerical details

As this is the first implementation of the model, it was decided to emphasise simplicity in numerics and programming. First-order explicit methods were applied. In short, a forward Euler method is used for time derivatives, and first-order approximations for the spatial derivatives. For a general function f, the spatial derivative is

$$f_x(i,j) = \frac{f(i+1/2,j) - f(i-1/2,j)}{\Delta x}, \tag{18}$$

and corresponding for the y-direction. Details concerning the implementation of the equations are described below. The model operates on a ordinary square grid, with Uh, Vh and h being calculated in the center of the cells. It is also valid for grids with different spatial spacing, but this makes little sense for this application, as there is no reason to believe that one spatial direction will need more or less detailed description.

3.1. Velocity and impulse

The velocity at the border of the cells is needed. There is no general rule to apply, concerning which of the two velocities or impulses that is valid on the border between two cells. The direction of both velocities have to be checked, and the correct one chosen in the following manner:

$$U_{i+1/2} = \begin{cases} U_i & \text{if } U_i > 0 \text{ and } U_{i+1} > 0 \\ U_{i+1} & \text{if } U_i < 0 \text{ and } U_{i+1} < 0 \\ U_i + U_{i+1} & \text{if } U_i > 0 \text{ and } U_{i+1} < 0 \\ 0 & \text{if } U_i < 0 \text{ and } U_{i+1} > 0 \end{cases} \tag{19}$$

See (Fig. 2) for illustration.

For simplicity, U is equipped with only one index, omitting the other one which is identical all the time. Let the single index denote either of the two directions. Corresponding choice is made when spatial derivatives of Uh, $h\rho_o U^2$, $h\rho_o UV$, Vh, $h\rho_o V^2$ and $h\rho_o VU$ are needed.

3.2. Surface tension

Instead of imposing the surface tension on the outer boundary of the slick, an artificial tension working on the slick in general is created. Surface tension will act on all boundaries in a cell, the tension at the right side working towards left, and correspondingly for the other boundaries, as shown in Fig. 3. If the neighbouring cell has an oil thickness that is higher than equilibrium thickness, no tension will work at this boundary. This will restrict the surface tension to have effect mainly around the border of the slick. The tension is defined in the following manner

$$\sigma_i^r = \begin{cases} \max\left\{0, \left(1 - \frac{h_{i+1}}{h_{\text{eq}}}\right)\right\}\sigma_n & \text{if } h_{i+1} < h_i \leq h_{\text{eq}} \\ 0 & \text{else,} \end{cases}$$

superscript r denoting right boundary of cell i, and σ_n is the net surface tension. See Fig. 4 for further illustration. In practice, this states that the tension is zero at the border if the neighbouring cell contains more oil, i.e. $h_{i+1} > h_i$, or if the cell has an oil content that is larger than the equilibrium amount. When thickness is equal in both cells the tension is zero, and when there is no oil in the neighbouring cell tension is σ_n.

This way of interpreting the surface tension can cause an overestimation as long as there is dynamic motion in the slick. When equilibrium thickness is achieved, the surface tension will act only at the boundary, in the same manner as expected according to the physical understanding of the problem.

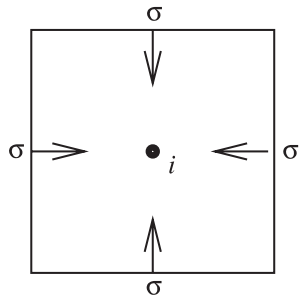

Fig. 3. Tension forces on the border of an oil cell.

3.3. Pressure

When calculating the pressure on cell i's right hand border, the pressure that cell $i+1$ is setting up is used. This will in general be of a different magnitude than the pressure which cell i sets up on cell $i+1$.

There are two different situations that can occur, which are both shown in Fig. 4. In the limit between the two scenarios, the oil thickness in both cells is equal. The pressure acting on the right side of cell i is calculated. In case a, oil thickness in cell $i+1$ is greater than in cell i. The pressure will then be given by

$$P_i^r = \int_{(h_{i+1}-h_i)\left(1-\frac{\rho_{\text{oil}}}{\rho_{\text{w}}}\right)}^{h_{i+1}\left(1-\frac{\rho_{\text{oil}}}{\rho_{\text{w}}}\right)+h_i\frac{\rho_{\text{oil}}}{\rho_{\text{w}}}} \rho_{\text{oil}} g z \, \mathrm{d}z$$

$$= \frac{1}{2}\rho_{\text{oil}} g \left\{ h_i^2 \left(2\frac{\rho_{\text{oil}}}{\rho_{\text{w}}} - 1 \right) + h_i h_{i+1} 2 \left(1 - \frac{\rho_{\text{oil}}}{\rho_{\text{w}}} \right) \right\}, \tag{20}$$

where superscript r denotes the right side of cell i. Case b is slightly different, as pressure both from neighbouring oil and water works on the wall of cell i.

$$P_i^r = \int_0^{h_{i+1}} \rho_{\text{oil}} g z \, \mathrm{d}z + \int_{\frac{\rho_{\text{oil}}}{\rho_{\text{w}}}h_{i+1}}^{\frac{\rho_{\text{oil}}}{\rho_{\text{w}}}h_i} \rho_{\text{w}} g z \, \mathrm{d}z$$

$$= \frac{1}{2}\rho_{\text{oil}} g \left\{ \left(1 - \frac{\rho_{\text{oil}}}{\rho_{\text{w}}} \right) h_{i+1}^2 + \frac{\rho_{\text{oil}}}{\rho_{\text{w}}} h_i^2 \right\}. \tag{21}$$

4. Comparing experimental data and numerical calculations

To achieve an impression of how the model performs, it was decided to run some simulations that are similar to experiments performed by Sayed and Løset (1993). In short, they poured oil on top of a broken ice cover, and observed the spreading. The two crudes, Gullfaks and Oseberg, in addition to bunker IF-30 were used.

Three simulations were carried out, one for each type of oil. In all cases, 4 l of oil was poured at a constant rate. In the experiments, the oil was poured on top of slush ice, while the simulations described spreading in open, cold water. Otherwise, the simulations were identical to what was done in the experiments. The viscosity of Oseberg, Gullfaks and IF-30 are 0.024. 0.041 and 1.240 Pa s, respectively, given at 0 °C. The net surface tension σ_{n} was obtained from the experimentally found equilibrium thickness of the oil, according to Eq. (15) (Fig. 4).

The results of the simulations are shown in Fig. 5 along with results obtained from the experiments. For the experimental data, two diameters d_1 and d_2 are plotted. This is because the oil did not spread symmetrically, mainly due to the presence of the ice cover. Exact dimensions were not easy to obtain, and the authors believe there is a 0.1-m uncertainty. The upper and lower limit of this uncertainty is marked with dashed lines in the plots.

From the simulations, it is observed that the flow parameter ψ had a very small effect in the case of Oseberg oil. This is not surprising, as this oil is not very viscous. For Gullfaks, values ranging between 0.3 and 1 gave similar and reasonable results, while for IF-30, there was a small range of 0.01–0.05. In the plots presented, ψ has the values of 0.99, 0.80 and 0.05, respectively. Those values imply that the parameters of Eq. (12) should be approximately 0.1 for K_1 and K_2 should be close to 1.

In the experiments, the oil is spreading on top of slush ice. For IF-30, there are more distinct pieces. The simulations, however, assume open water. This may have different consequences. First, it would be expected that the spreading is slower over slush due to the rougher surface it spreads on top of. It will lead to a higher friction at the bottom of the slick. Secondly, the equilibrium thickness of oil is expected to be

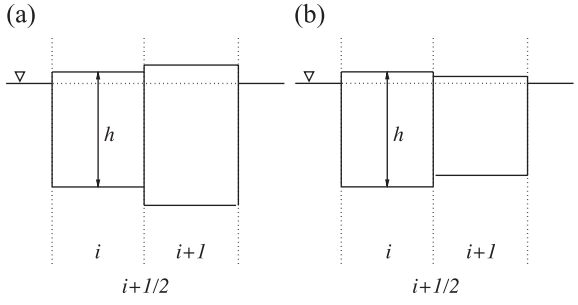

Fig. 4. Calculating the pressure on the border of two oil cells.

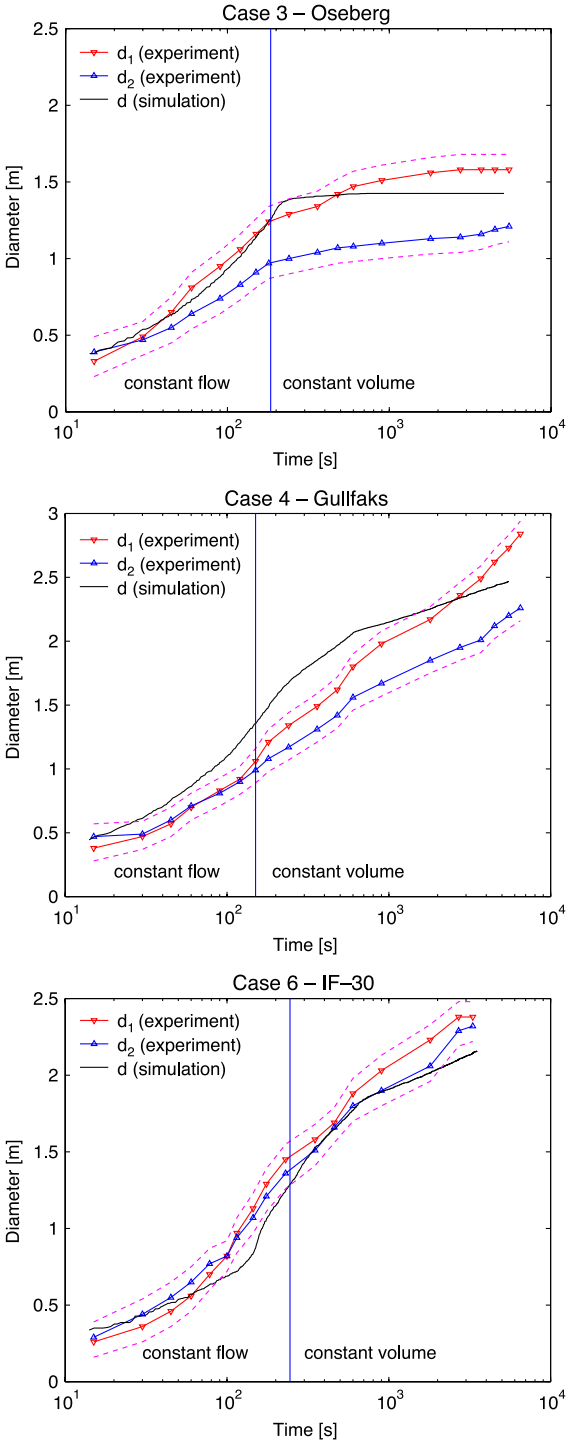

Fig. 5. Diameter of oil slick, simulations and laboratory experiments.

higher on slush than on water, as ice has a lower density than water. This latter effect is included in the simulations, as data from the experiment is used to estimate the net surface tension.

It is seen that the simulations suggest faster spreading than the experiments for the two upper cases. This tendency cannot be altered by changing the flow parameter. For the last case, the situation can be radically changed as the flow parameter is adjusted. Letting ψ be zero cause the oil to spread much faster than shown in the plot.

5. Discussion

Although the simulations describe a different case than the experiments, there are strong similarities and some conclusions can be drawn. It is expected that spreading will be slightly slower on slush compared to water. This matches the results for the Oseberg and Gullfaks case. For IF-30, the same will be observed if the flow parameter becomes small enough. These cases are not well suited to define the coefficients K_1 and K_2 in Eq. (12), and for this reason, it is strictly speaking not possible to suggest reasonable values for ψ. Even if the settings for the experiments and simulations were identical, the amount of data would be too sparse to define the coefficients in a decent manner.

The results indicate that the model can be used to simulate oil spreading on top of slush and not only in open water. This would require a changed description of stress at the bottom of the slick to match the friction between oil and slush.

A limitation of the model as of today is clearly the assumption of Newtonian behaviour of the oil. This implies that heavy emulsified oil cannot be simulated, as it performs more as a viscoelastic medium. When it comes to the time range, the model can be expected to be valid, the main limitation is the assumption of slow flow of the oil. One can hardly expect to simulate a bulk release in the initial phase, but a leakage at moderate rates can be simulated from the start.

6. Conclusions

A model for oil spreading is developed, suitable for cold waters. It is based on conservation laws of

momentum and mass, and is implemented by a finite difference approach.

As the model contains simplifications, it cannot be expected to simulate the real world in detail. However, it is shown to perform quite well for the cases that have been tested, some of which are included in this paper. Further validation is needed before a conclusion on the quality of the model can be made, but as this is written, the amount of suitable data is sparse.

The model is successfully coupled to a discrete element ice model which is provided by Hopkins (1996), but so far there is no data available to check the performance of this coupled model. Basin experiments are being planned, which will be reported and compared to model results later on.

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