Environmental spill modelling and risk assessment of Orimulsion 400 and Heavy Fuel Oil

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Abstract

An integrated oil spill modelling system was set up for I/S Sjællandske Kraftværker (SK Power). The purpose of the project was to carry out a risk assessment for accidents during transport of Orimulsion 400 and Heavy Fuel Oil (HFO) to the Asnæs Power Plant and a subsequent assessment of the environmental effects. The project dealt with oil spill modelling and assessment of environmental risks to the aquatic ecosystem, to seabirds and to the coastal environment.

Two fuel products were considered, Orimulsion 400 and Heavy Fuel Oil (HFO), with the purpose of comparing the environmental risk associated with the transportation through Danish waters to the Asnæs Power Plant and in Kalundborg Fjord. Two spill positions in the northern part of the Great Belt were considered and the fate and effects were modelled for three different seasons.

Three different models were combined for modelling of the fate of Orimulsion 400 and HFO spills. A hydrodynamic model was used to provide the basis for the oil spill model, a particle model described the transport of “imaginary” particles and an oil spill fate model described the physico-chemical processes affecting the oil, such as evaporation, dispersion and solubility in the water column. For the two positions (Hatter Barn & Asnæs) the fate of a 17,000 tonnes spill during spring, summer and autumn/winter was modelled for both products.

In conclusion the simulations showed that the model is capable of producing realistic scenarios including a comparative assessment of the environmental risks associated with the spill of different oil types.
1 Introduction

An increasing amount of oil products are being introduced into the biosphere. Estimates of the amount of oil spill in oceans range from 1 to 10 million metric tones per year, with the most probable rate being close to the middle of this range. The majority of the oil spills are due to small but continuous quantities from tanker operations, industrial discharge and on-shore waste disposal practices. The large accidental oil spills produce less effluent but disproportionately more public attention and research effort. The prospect for the immediate future is that the two types of pollution will increase with the increasing transport tonnage and offshore exploration efforts.

No matter which type of water body receives the oil products the effects on the aquatic ecology will invariably be destructive. The consequences are fish kills, smothering of sea birds, mortality of juvenile larvae and destruction of eggs, poisoning of vascular plants, reduced population and productivity of benthic fauna and flora. Adding to this, the human health problems, impaired aesthetics and general ecological imbalance.

In this study the emphasis was to have a holistic approach to the effects of an oil spill. This includes an assessment of the possible spill situation and place first, second a numerical modelling of the spill scenarios and third an environmental impact assessment of the consequences to the aquatic environment.

The study area is Kalundborg Fjord, which is an important area in relation to social, commercial and industrial points of view. The fjord accommodates Kalundborg harbour, the City of Kalundborg, a refinery and a power plant as well as other large industrial plants. The surrounding areas are used for agriculture and for recreational purposes. Both the pelagic and the benthic compartments function as habitats for fauna and flora, including invertebrates, fish, algae and vegetation.

2 Definition of the oil spill

With the aim of assessing the environmental consequences of a potential oil spill, different spill scenarios were defined. Only spills caused by navigational accidents were considered as the risk of spills caused by port accidents are considered controlled. As a reasonable worst case, a spill of 17.000 tones of Orimulsion and Heavy fuel oil, respectively, was considered. Spills of this size are assumed to take place less than once per more than 500 years.

Two positions were selected as being representative; Hatter Barn representing a risk for powered grounding and north of Asnæs is a position with the potential for drifted grounding.

Due to the seasonal changes in the environmental conditions, three different periods were selected:

- Spring, representing a period with outflow of water from the Baltic Sea, seabirds preparing for migration and with increasing growth of planktonic algae.
• Summer, representing a period with calm weather and low currents, relatively few seabirds and a high turnover in the water column.
• Autumn/winter, representing a period with inflow of water to the Baltic, arrival of large numbers of migrating birds and with decreasing activity in the water masses.

The modelled time periods were set to 45 days.

3 Numerical modelling

The MIKE 21 model system was used to perform the simulations. More specifically the following modules were used:

• The hydrodynamic module (HD), which is the basic module in the package. It provides the hydrodynamic basis for the computations performed in the modules for particle transport and oil transformation. The HD module simulates the water level variations and flows in response to a variety of forcing functions such as wind and water level variations.
• The Particle module (PA), which is based on the results from the HD module, simulates the non-reactive spread/dispersion processes of particles from an oil spill.
• The oil spill analysis module (SA) simulating the spreading and the weathering of hydrocarbons in the aquatic environment under the influence of the fluid transport and the associated physical and chemical dispersion processes such as advection/dispersion, evaporation, mechanical spreading, dissolution and emulsification. The processes are calculated on the basis of the chemical and physical properties for the oil constituents, which are specified by the user. The module can separate the oil component into eight fractions with different chemical and physical characteristics.

3.1 Modelling of the hydrodynamic conditions

The applied modelling system is based on 2D and 3D regional hydrodynamic models of the North Sea, the Danish waters and the entire Baltic Sea (Farvandsmodellen) developed and operated by DHI - Water & Environment for the Danish Ministry of Environment and Energy. The model is forced by astronomical tide and meteorological data provided by the Danish Meteorological Institute.

All simulations were made with 2D-model set-up. The Danish waters are in general stratified, but for the study of large-scale surface layer transports – such as those arising from oil spills – 2D models are quite satisfactory and arguably better suited than 3D models. For any fixed amount of computing capacity, the 2D models will allow for a better horizontal resolution of results.

3.2 Modelling of fate of the oil spill

The modelling of the fate of an oil spill was, as mentioned before, performed using the particle (PA) in combination with an Oil Spill Analysis Module (SA).
The particle module PA simulates the non-reactive spreading/dispersion processes of particles from an oil spill, while the SA module simulates the spreading and weathering of hydrocarbons in the aquatic environment under the influence of the fluid transport and the associated physical and chemical processes such as advection/dispersion, evaporation, mechanical spreading, dissolution and emulsification.

The quantification of the differences between an Orimulsion 400 spill and a normal heavy fuel oil spill was carried out by specifying different parameters. Orimulsion 400 is much more dispersible than HFO. Tests have shown that initially approx. 80% is dispersed in the water column and the remaining 20% will float on the surface. When HFO is spilled, the major part will remain on the surface. The present SA model is designed for modelling the fate of oil spills directly to the surface. The modelling of Orimulsion required the introduction of a high initial vertical dispersion rate for the first 2 days of the simulation.

The simulated material transport is based on calculated movements of particles floating on the water surface, which are influenced by the direction of both the currents and the predominate winds. For each time step in the model, the model keeps track of the distribution of the material between floating, dispersed and dissolved phases as well as the amount of evaporated or biodegraded material. Initially the wind will dominate the fate of the material, where increasing parts of the material eventually is dispersed into the water column as a result of an estimated net transport into the water phase and therefore the current velocity will become increasingly important.

For this study it has been assumed that the dispersed and dissolved material is evenly distributed in the upper 6.5 meters of the water column. Naturally, higher concentrations will be found in the uppermost layers and lower concentration in the deeper layers.

In shallow areas with water depths below 6.5 meters, the model calculates concentrations above the average concentration, which means that we might have a sudden overestimation of the concentrations in these areas.

4 Results

For all scenarios, the drift of the plume was followed for a period of 45 days. At the end of this simulation period the simulations indicate that only minor effects can be expected.

From the different simulated scenarios it was possible to track the oil plumes path and get a hypothesis of where the oil will be located at a certain time.

The hypothesis of the placement and the calculated concentrations then makes it possible to assess the environmental risk associated with the spill.
5 Environmental risk assessment

5.1 Risk to aquatic organisms

The risk to aquatic organisms in the pelagic part of the marine ecosystem was assessed for each one of the up to eight model components selected for the two products by comparing the Predicted Environmental Concentration (PECs) of components dissolved in the water column with the predicted No-effect-Concentration (PNECs). In general, it is assumed that when the long-time average PEC is higher than PNEC, there may be risks of chronic ecotoxicological effects on the ecosystem and on the organisms constituting it. Moreover, it is assumed that acute ecotoxicological effects can be expected when PEC is more than 10 or 100 times higher than PNEC.

However, as more than one component are present at the same time, any species will be exposed to more than one toxic component, therefore the risks associated with each of the component were added, i.e. the total risk is estimated as risk ratios defined as:

\[
TRR (Total \ Risk \ Ratio) = \sum_{i} \frac{PEC_i}{PNEC_i}
\]

\(i = \) number of oil component

The simulations showed that for all positions and periods the estimated risks to aquatic organisms and to the ecosystem were considerably higher for HFO than for Orimulsion 400. Typical results are shown in Figure 1.

As can be observed from the figure considerable higher risk ratios are found for HFO than for Orimulsion 400. Table 1 gives a summary of the results.

Table 1 Risks to aquatic organisms and ecosystems.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Orimulsion 400</th>
<th>Heavy Fuel Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area with TRR &gt; 1 [km²]</td>
<td>Mean TRR</td>
</tr>
<tr>
<td><strong>Hatter Barn</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>198</td>
<td>27</td>
</tr>
<tr>
<td>Summer</td>
<td>310</td>
<td>27</td>
</tr>
<tr>
<td>Autumn/win.</td>
<td>316</td>
<td>4</td>
</tr>
<tr>
<td><strong>Asnæs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>246</td>
<td>7</td>
</tr>
<tr>
<td>Summer</td>
<td>89</td>
<td>42</td>
</tr>
<tr>
<td>Autumn/win.</td>
<td>180</td>
<td>8</td>
</tr>
</tbody>
</table>
8 Oil and Hydrocarbon Spills II: Modelling, Analysis and Control

From Table 1 it can be seen that the areas, which may be exposed to components of the two products after a spill, are around 4 to 6 times larger for HFO than for Orimulsion 400, when the chronic toxicity is considered, and from 7 to 115 times larger regarding acute toxicity.

![Figure 1. Total Risk Ratio from a HFO spill north of Asnæs.](gridspacing.png)

5.2 Risk to bird life

Kattegat is an important wintering area for a large number of sea birds. Thus, a spill of oil or of a similar product that floats on the surface may impact or even be fatal to birds that are exposed to the material. Even small quantities may be fatal for the birds when oil adheres to and penetrates into the plumage and thereby reducing the heat insulation and the water repellence. One of the main reasons for oil exhibiting high risk to seabirds is that the oil slick smoothenes the surface of the water, i.e. reduces the waves, whereby flying birds are attracted to the assumed smooth sea. It is assumed that this phenomenon requires a certain oil thickness.

Another parameter of importance is the relative stickiness of the oil, which decreases with increasing weathering. A measure for the degree of weathering is the viscosity. During a spill HFO will increase its viscosity from about 1 to 25,000 cS within a few days, while the viscosity of Orimulsion 400 is relatively constant at 10,000 cS because the main part of Orimulsion 400 is bitumen, which has a weathered character originally. No direct relationship between viscosity...
and thickness of the slick layer has been derived, but considering the relative quick increase in viscosity in comparison to the development of slick layer thickness in the scenarios, we assume that a threshold of 0.1 mm is applicable for identification of the maximum areas where surface slick causes risks to seabirds. Table 2 shows an overview of the typical thickness and the time period in which the affected waters are covered by slick of more than 0.1 mm.

### Table 2 Typical thickness of surface slick and duration with >0.1 mm.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Orimulsion 400</th>
<th>Heavy Fuel Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typical thick. of surface slick [mm]</td>
<td>Duration of thick.&gt;0.1mm [hours]</td>
</tr>
<tr>
<td></td>
<td>0.5-2</td>
<td>5-10</td>
</tr>
<tr>
<td>Hatter Barn</td>
<td>0.5-1</td>
<td>20-50</td>
</tr>
<tr>
<td>Autumn/win.</td>
<td>0.1-2</td>
<td>20-100</td>
</tr>
<tr>
<td></td>
<td>0.1-0.5</td>
<td>10-25</td>
</tr>
<tr>
<td>Asnæs</td>
<td>0.1-3</td>
<td>10-75</td>
</tr>
<tr>
<td>Autumn/win.</td>
<td>0.5-3</td>
<td>20-75</td>
</tr>
</tbody>
</table>

#### 5.3 Risk to coastal environment

Only a qualitative assessment of the risk to the coastal environments has been made in the study. The basic parameters are the modelling of the flow of the oil slick, which shorelines are in potential danger of exposure and how long time it will take before the slick reaches the shoreline.

For example the simulations indicate that a spill at Hatter Barn during the specific time period for the spring scenario, will reach the shoreline of Djursland (Århus) within a week. If the spill occurs north of Asnæs, it may reach the eastern coast of Samsø including Stavnsfjord, which is a very valuable wintering area for birds.

#### 6 Conclusions

The main objective of the study was to prepare a comparative assessment of the risks associated with transport of Orimulsion 400 and Heavy Fuel Oil (HFO) through Danish waters.

First the main risk of accidents leading to a spill was investigated. It was found that the most likely and harmful scenario would be a powered or drifted grounding in the narrow transit route in the northern part of the Great Belt.
Second, Predicted No-effect-Concentrations (PNEC) was derived for up to 8 main constituents of each of the two products. (This part is not mentioned in this article).

Third, the oil spill scenarios were simulated using the MIKE 21 software tools. Oil spills of 17.000 tonnes at two different locations, for three time periods (spring, summer, and autumn/winter) and for the two types of oil were simulated. Both the fate of the slick on the surface and the fate of the dispersed and dissolved part in the water column were considered.

Fourth, an environmental risk assessment was made based on the results from the simulations. For all scenarios the modelling of the risk to aquatic organisms showed that a spill of HFO results in considerably higher risks over a much greater area than a spill of Orimulsion 400. The potential risk to seabirds was considered to increase with increasing slick thickness. Comparing the thickness of the slick on the surface of the two products showed much thicker layers of HFO than of Orimulsion.

References