Special aspects of modeling on accidental oil spills in inland sea waters

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Abstract. Intensive development of marine oil fields is characterized by significant pollution of sea environment, linked with leaks of diesel fuel and oil products during production activities on ships, or as a result of technical means accidents. To assess the potential scale of environmental impact mathematical modeling of hypothetical spills is required. The main processes of distribution and physico-chemical transformation of diesel fuel determined. The spreading of diesel fuel slicks on sea surface in case of accidental spills in storm conditions evaluated. Assessment of spatial-temporal picture of emergency development allows to select and prove a strategy for spills control during a storm wind.

1. Introduction
The behavior of oil spills (diesel fuel) in the sea is determined by both the physico-chemical properties of oil and the state of marine environment. Schematically, the process of oil distribution is described below. At initial stage of a spill, a rather rapid spreading of oil over surface of water body occurs, due to its positive floatability. The spreading rate can vary widely and depends mainly on physical oil properties under given hydro-meteorological conditions. Depending on oil volume, this process can last from several minutes to several hours and even days in case of particularly large spills. Further spread of oil over surface of a water body is due to surface tension and turbulent diffusion, or more precisely the turbulent nature of tangential stresses at oil-water and air-oil interfaces. Deformation and transport of surface contamination field is determined by combined activity of wind and streams at oil slick location. Almost from the moment of spill, volatile oil fractions evaporate, and physico-chemical properties of oil spreading oil (density, viscosity) change. Since the amount of evaporated oil is determined by both the evaporation area and the hydro-meteorological conditions (wind, temperature), the processes of spreading and evaporation are rather closely related. With sufficiently strong winds and developed waves, part of oil enters to water in form of drops, forming intra-mass pollution, or forms water-in-oil emulsions. The further fate of mass pollution is mainly determined by the dynamic structure of stream field. Emulsion transfer is determined by practically the same factors as film oil.

When a spill occurs on a solid ice cover, the spreading is determined by filtration properties of ice (or snow) cover in addition to oil physical properties. Depending on these factors, the contaminated area will vary widely. The most difficult and little-studied is behavior of oil in broken ice of various concentration. In this situation, the behavior is significantly determined by dynamics of ice cover, its
structure and properties, and can vary from spreading close to spreading on open water (with small ice concentration) to almost complete absence of spreading with big concentrations.

Thus, the behavior of oil in the sea is determined by many processes occurring both in oil itself and in marine environment. Some of these processes are studied quite well and can be modeled, some processes can be described by simple correlations based on experimental data.

2. Methodology of mathematical modeling of diesel fuel distribution during accidental spills

The simulation is based on calculation of distribution and transformation of diesel fuel, taking into account the operating characteristics of used hydro-meteorological fields.

Each calculated scenario of diesel fuel distribution contains information about location, geometrical dimensions and degree of weathering, corresponding to specific hydro-meteorological conditions, scale and mode of fuel discharge due an accident.

For each specific scenario of diesel fuel distribution, the time dependences of main spill characteristics (coordinates and film thickness) are calculated.

In modeling, assessment also includes:

- identification of risk areas for diesel fuel spreading at different moments since an accident, when risk areas are the areas beyond boundary of which none of possible scenarios for diesel fuel spreading go;
- calculation of probability of damage to special significance areas in water area and coast, depending on the time since an accident;
- identification of diesel fuel distribution scenarios leading to damage of special importance areas as spill propagation paths.

The monitoring the drift of diesel fuel slick by an imitation method (the method of wandering particle markers) is the most rational method [1,2]. This technique has been used in calculations of hydrocarbon transfer in recent years [3,4].

By using the simulation method of wandering marker particles, the contaminant field (oil slick) is given by a combination of a large number of individual particles, each of which contains one conventional contaminant unit. The number of particles in a unit square of the sea determines the concentration of contaminant in a given area. Particles participate in two types of motions: they are transferred by existing sea streams and fluctuate due to turbulent "additions" to the field of these streams and waves. Contaminant source can be given instantaneously or continuously for a certain period of time. The weight of a substance emitted into the sea at one time or distributed in time with a known intensity is proportional to amount of emitted marker particles. Markers coordinates are described by system of equations:

\[
\frac{\partial x}{\partial t} = u_w(x, y, t) + u_p(x, y, t) + u_{pr}(x, y, t) + u'(x, y, t),
\]

(1)

\[
\frac{\partial y}{\partial t} = v_w(x, y, t) + v_p(x, y, t) + v_{pr}(x, y, t) + v'(x, y, t),
\]

(2)

\[
\frac{\partial z}{\partial t} = w(x, y, t) + w'(x, y, t),
\]

(3)

when \(u_w, u_p, u_{pr}, v_w, v_p, v_{pr}\) - horizontal components of average contaminant transfer velocity, including wind, constant and tidal streams, obtained from measurements or calculations;

\(u'(x,y,t), v'(x,y,t), w'(x,y,t)\) - corresponding pulsation "additions" to average speeds, causing turbulent dissipation;

\(w\) - lowering speed of contaminant components under gravity.
The system of equations is solved according to a numerical scheme with linear interpolation of stream rates between nodes of computational grid.

The scattering of particles under pulsation velocities in their calculations is given by a random vector \( u', v' \), the components of which are described by amplitudes of the vector of orbital velocities of wind waves [5] and the amplitude of turbulent (diffusion) particles scattering, the components of which are described by normal law [2]. This task is carried out by a random number sensor with a given dispersion. Dispersion value is determined by data of pulsations of stream velocities measured in considered area.

When experimental data are absent or insufficient, the dispersions of stream rates are determined on the basis of shear instability theory linking the dispersion of velocity components with the Richardson criteria. In the simplest case, turbulence is associated with stream rate by equation used in practice when nature measurements of velocity dispersion are absent [6]. Based on this ratio, the following engineering equations are used to calculate the speed of turbulent pulsations:

\[
\sigma_u = (1 + 0.196u + 0.076v)^{1/2},
\]
\[
\sigma_v = (1 + 0.196v + 0.076u)^{1/2},
\]
\[
\sigma_w = (\sigma_u^2 + \sigma_v^2)^{1/2},
\]

when \( u, v \) – components of average velocity.

3. Assessment of diesel fuel slick spreading on the sea surface during accidental spills and storm wind

For assessment of environmental risks acceptability, can also use accident risk criteria by probability together with classification of emergency situations by categories [7].

The probability of diesel fuel spills getting into different points of water area is estimated by incident frequency of ingression the markers particles into cell of grid computational area by imitation method.

Figure 1 shows risk areas are conditional probabilities of damage to objects in water area by spill of 32.6 tons of diesel fuel under storm conditions over period of spill stain (less than a day). The risk zones in open and coastal areas of the sea are determined by spatial-temporal structure of wind field, corresponding fields of streams and waves, taking into account a depth and configuration of coastline.

The concept of conditional probability means the probability of water area damage provided that accident occurred. To determine the risk of objects damage in water area and on coast, multiply the incident probability associated with emergency situation (in this case, from \( 10^{-8} \) to \( 10^{-6} \)), by conditional probability of objects damage presented in figure 1. According to classification of accidents and probability of their occurrence [7], this incident can be evaluating as an “almost impossible incident” that almost never happened, but is not excluded at all.

Assessment results of spread trajectory of an emergency spill in area of work show that fuel spots can reach the coastal zone in first days after the accident (figure 2).

According to assessment of spread trajectory of an emergency spill, taking into account the evolution of diesel fuel, only slicks from thin films of diesel fuel (less than 0.0001 mm thick) and only in small quantities and volumes can reach the coast.

The scale of potential damage to objects in water area and on coast depends primarily on volume of emergency diesel fuel discharge. For large fuel spills, the formation of a surface contamination zone takes a long time due to hydrodynamic spreading. In case of small spills, the contamination zone is formed due to turbulent diffusion processes.
Figure 1. Conditional probability of objects damage in inland sea area at place of assumed accidental discharge of 32.6 tons of diesel fuel in stormy conditions over period of spill slick existence (scale in kilometers).

Figure 2. Diesel fuel film thickness (m^6) on water surface of inland sea area after a ship accident in storm wind (discharge of 32.6 tons, duration 1 hour) in: 6 hours from start of discharge (scale in kilometers).
4. Conclusion
Obtained estimates of spreading of diesel fuel slicks on water surface of inland sea during accidental spills by storm wind showed that the spreading scales of diesel fuel slicks will be small, and the thickness of diesel fuel film on sea surface will generally not exceed 0.001 mm and will not be dangerous to the environment. This circumstance and specific features of spatial-temporal picture of predicted emergency situation development will allow to choose and prove the strategy to diesel fuel slicks control.

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