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Towards developing numerical methods for the modelling of oil slick behaviour on the vegetated coastal areas of Caspian Sea in western Kazakhstan

B. E. Bekmukhamedov[1], A. Sattarova[2*], I. V. Kaipov[1], Zh. Sh. Zhantayev[1]

[1]*National Center of Space Research and Technology, Almaty, 050010, Kazakhstan*
[2]*M. Auezov South Kazakhstan State University, Shymkent, 160012, Kazakhstan*

In case of emergency oil spills, we must be ready to understand how and in which direction oil slicks will move. Since remote sensing or tracking these spills from satellite at every hour is expensive, most reliable tool becomes mathematical modeling. The current paper, considers mathematical modeling of advection-diffusion of oil slicks within the vegetated water zones, which also takes into account significant chemical and physical processes that change the properties and the behavior of the oil slick in marine environment.

Keywords: oil spill, vegetation, wetlands, Caspian Sea, modelling, numerical simulation

INTRODUCTION

While extracting crude oil from offshore reserves or transporting it from one place to another though water by tankers or by underwater pipelines, there is a risk of oil spills to the marine environment. There is also risk of natural seepage of oil or gas from reservoirs to the environment. However, the latter is usually less harmful and is at small scales compared to the first one, which is caused by human interference. If marine oil spill is at large scale and is close to a shoreline, it affects ecosystem of coastal wetlands. Pollution of coastal wetlands by oil spills is considered as serious environmental disaster since wetlands are important for the ecosystem by storm and flood protection, good water quality, faunal support, recharge groundwater, carbon sequestration and stabilize climate conditions and control pests [1, 2].

Not all types of crude oil are buoyant. Whether spilled oil floats or not is defined by a scale developed by the American Petroleum Institute (API scale). The scale is inversely proportional to the specific gravity of the oil at 15.60°C. API of freshwater is 10 and most of the crude oil has higher API than 10, therefore, they float in freshwater. But, there are also some heavier refined products which have lower API. Such types of products are referred also as Group V oils. Oils of Group V are not dangerous to vegetation unless oil spill occurred very close to coastal wetlands. Once this type of oil is spilled it starts to sink immediately, thus, presenting different clean up challenges. In the current paper we consider buoyant oil, and how air and water flow influence to its movement in vegetated wetlands [3]. The study was carried out using numerical analysis. Such studies are very important, since they help to predict oil slick behavior near shorelines with vegetation or plants. One of the potential places for applications of the numerical modeling techniques is the coastal areas of Caspian Sea in western Kazakhstan where oil contamination takes place as a result of emergency situations such as crude oil discharge from abandoned oil wells, damaged underwater pipelines, or the transportation of crude oil by tankers or ships.

Fig.1. Consequence of the oil spill in the Gulf of Mexico. *Photo by Lee Celano*

* To whom all correspondence should be sent:
aigul_01_09@mail.ru

Fig.2 shows the oilfields in the Caspian Sea, the western part of [4, 5] Kazakhstan. Some of the oil places are very close to the shoreline. Therefore, there is a risk of oil spills to the coastal flora and fauna.

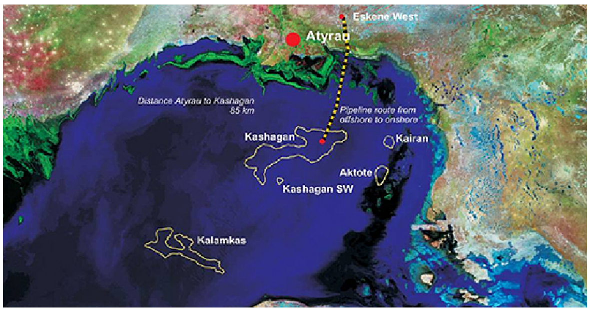

Fig.2. Oilfields in western Kazakhstan: Kashagan, Kalamkas, and Kairan

Although, results in this paper does not completely describe the process, it is considered as the first step towards developing efficient numerical tool for prediction of oil slick advection in vegetated coastal areas. The model also takes into account physical and chemical processes affecting to oil slick properties which are different from the open-air case.

MODEL FORMULATOIN

Once oil spilled to a marine environment, it is influenced by physical and chemical processes caused by the environment. They are spreading, advection, evaporation, dissolution, natural dispersion, emulsification, photo-oxidation, sedimentation, and biodegradation [6, 7]. Most of the previous studies related to oil slick advection with above listed physical and chemical processes taken into account, were carried out without considering any hydrodynamic interaction between oil slicks and vegetation in coastal areas, but only in an open sea.

We decided to study this process in a simple way with the purpose of developing complex mathematical model later which describes oil slick movement in vegetated coastal areas. Therefore, it is assumed that there is vegetation established in a channel with flow direction as described in Fig.3. The leaves and shoots of the vegetation are not fully submerged to the water. Therefore, it is assumed that air flow also takes place together with water flow through the vegetation. If oil slicks are presented in the channel flow, the physics of the process become similar to Fig.1. In order to numerically model this process, two dimensional modelling approach is considered to be enough to evaluate the process of oil slick movement through the vegetated water, otherwise, three dimensional modelling is computationally expensive for such processes.

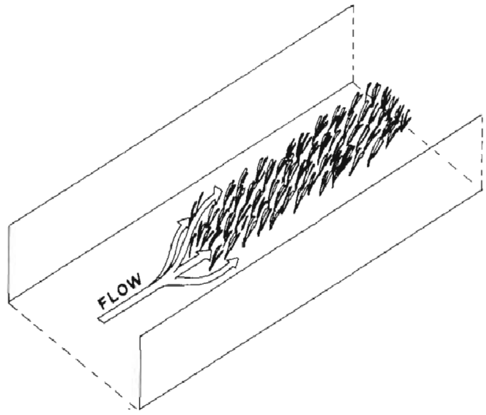

Fig.3. Visualization of the physics of the problem

Fig.4 illustrates the computational domain, where flow direction is along positive *x* direction. The vegetation is located in the center of the domain in 1m^2 area and the cross section of the vegetation is considered as a circular shape with the diameter of 1 cm. The number of the circles are 256 which are evenly distributed in the 1m^2 area and the oil slick will flow through the vegetation with the velocity determined from the water flow velocity.

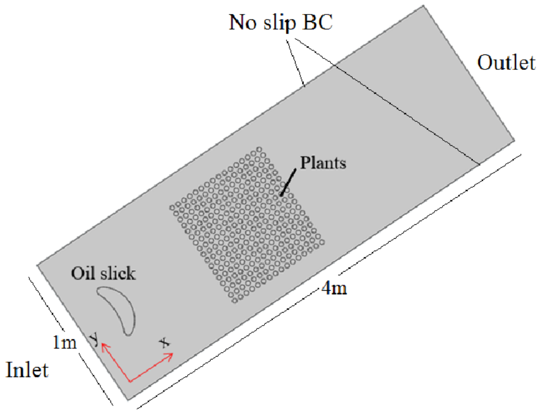

Fig.4. Visualization of the computational domain

Water flow is described using Navier-Stokes equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (1)$$

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

where *u, v*- velocity components, m/s; V - kinematic viscosity, m^2/s; *x, y*- coordinates, m and *t*- time, s. Eqn. (1) is solved numerically using non-slip boundary conditions (BC) at the side walls of the channel, and inlet velocity is 1 m/sec. Moreover, BC at the outlet is set up in terms of the pressure. Thus, based on the solution of Eqn. (1) velocity field is determined. Velocity field, in its turn, is used to calculate advection-diffusion process of the oil slick:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right) \quad (2)$$

where C is oil concentration which equals to 100 mol/m^3 at initial time and D is the diffusion coefficient (m^2/sec). Boundary conditions for oil concentration along sidewalls are Neumann type:

$$\frac{\partial C}{\partial n}=0 \quad (3)$$

where n - normal vector to the side wall, m. At the inlet there is no entering oil concentration, and at the outlet, outflow boundary condition is set up for the oil slick movement.

RESULTS AND DISCUSSIONS

Modelling results

Once water starts to flow, vortices are formed after the vegetations. Such vortices can be seen from Fig.5 based on velocity streamlines.

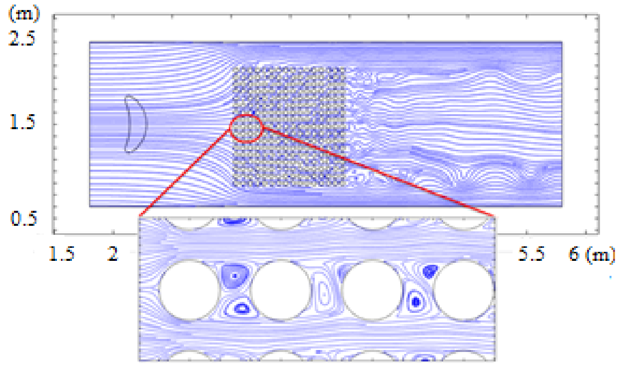

Fig.5. Velocity streamlines and vortices around the vegetations

The oil concentration movement is calculated after finding the velocity field. The resulting oil slick spread thought the vegetations after 1 sec is shown in Fig.6. It can be noticed that oil slick consternation spreads over large area while passing thought the vegetations. The spreading area depends on the density of the vegetations. Such behaviour of the oil slick thought the vegetations directly influence to physical and chemical processes that affect to the oil slick composition and properties. Indeed, these processes dominate at different times following the oil spill and thus leading to the loss of the oil mass.

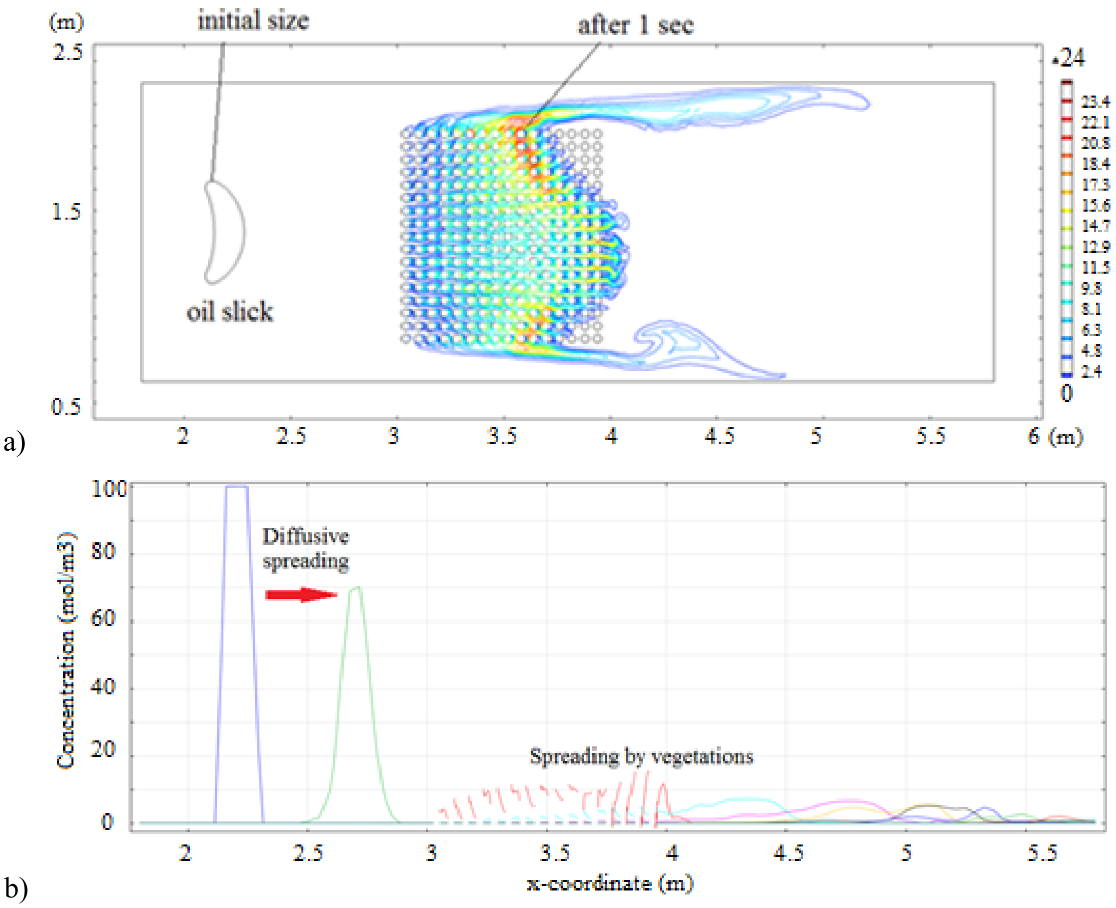

Fig.6. Oil slick spreading: a) after 1 sec; and b) oil slick spreading with time interval 0.2 s

It can be seen from Fig.7 that processes such as evaporation, dispersion, emulsification and spreading affect to the oil slick right after it spilled to the sea, and have more influence to change the oil properties than dissolution, oxidation, biodegradation and sedimentation.

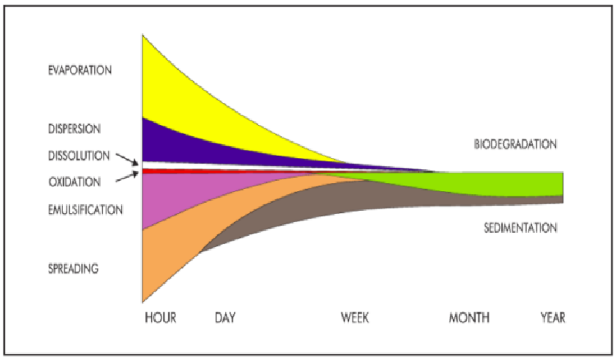

Fig.7. Time dependence of the physical and chemical processes that affect to oil slick properties

Spreading

Once oil spilled, it spreads while floating over the water surface. The rate of surface area change of the oil slicks has been studied by Fay [7], Hault [8], and later modified by Mackay at al. [12]. Thus, the rate of surface area change of the oil slick is calculated by the following formula:

$$\frac{dA_S}{dt} = K_{Spread} \cdot A_S^{\frac{1}{3}} \cdot \left[\frac{V}{A}\right]^{\frac{4}{3}} \qquad (4)$$

where A_S - area of the slick, m^2; $K_{Spread} = 150$ - constant, 1/s; V - volume of the spilled oil, m^3. But, in case of the absence of vegetation not fully submerged to the water, it influences to the rate of the surface area of the oil slick. Thus, it is concluded that surface area change of the oil slick should be proportional to the density of the vegetation. For instance, when vegetation density increases, surface area of the oil slick also increases. Therefore, eqn. (4) should be modified to the following form:

$$\frac{dA_S}{dt} = K_{Spread} \cdot A_S^{\frac{1}{3}} \cdot \left[\frac{V}{A}\right]^{\frac{4}{3}} \cdot \rho_{vegetation} \qquad (5)$$

Evaporation

It is one of the early time processes that causes significant mass loss in all kinds of oil which has API>10. Moreover, it can significantly change density, viscosity and other properties. Most of the time, evaporation is responsible up to 60 percent of spilled oil mass loss. As the lighter components of the oil slick evaporates faster than heavier components, chemical composition of the slick changes. There are two famous methods applied to calculate an evaporation rate: a) the pseudo-component method [9, 10], and b) the analytical approach [11]. The pseudo-component approach uses oil as a set of fractions grouped by boiling point and molecular weight. Consequently, for different components, there are different evaporation rates. On the other hand, in the analytical approach vapor pressure is a function of evaporated fraction. The analytical method developed by Stiver and Mackay [10] is applied to calculate volume fraction evaporated:

$$F_E = \ln[1 + B(T_G/T_E)(K_E \cdot A_S \cdot t/V_0) \cdot \exp(A - B(T_0/T_E))] \cdot [T_E/(BT_G)] \qquad (6)$$

where F_E - evaporated volume fraction, %; $K_E = 2.5 \cdot 10^{-3} \cdot U_{wind}^{0.78}$ mass transfer coefficient for evaporation, m/s; U_{wind} - wind speed, m/s; V_0 - initial volume of oil spill, m^3; T_0 - initial boiling point, K when F_E is zero I, T_E - environmental temperature, K; T_G - gradient of the boiling point, K/m; T_B и T_E line, K, A and B are constants which can be chosen from distillation data. According to Stiver and Makay's calculations where they used distillation data for five different types of crude oils, magnitude of A and B are 6.3 and 10.3 respectively.

It can be seen from Eqn. (6) that evaporated volume fraction F_E is the function of surface are of the slick which depends on the vegetation density. Moreover, U_{wind} - wind velocity, m/s and temperature profile inside the vegetation also depends on, $\rho_{vegetation}$ number of vegetation/m^2. Therefore, Eqn. (6) also must be modified in the way that it accounts for the presence of the vegetation and its height emerged from the water surface which influences to the temperature inside the vegetation, consequently, evaporation rate.

Emulsification

The process of emulsification is the inverse of dispersion where instead of oil droplets dispersing into the water column, water enters into the oil [13]. As a consequence of the emulsification, volume, density and especially viscosity of oil slick changes. Mackey et al. suggested the following formula to calculate the incorporation of water into oil slick:

$$\frac{dF_{wc}}{dt} = K_{wc}(U_{wind} + 1)^2(1 - F_{wc})/OC \qquad (7)$$

where F_{wc} - fraction of water in oil, %; OC - final fraction of water content, % and K_{wc} is taken as 2x10^{-6}, ms/m^2. Here, Eqn. (7) also needs to be modified because if oil slick is located in vegetated area, the rate of fraction of water in oil F_{wc} changes differently. It can be seen from the last formula that U_{wind} is different in case of vegetated area than the one where open water surface because inside vegetation wind speed changes depending on the density of the vegetation.

Density and viscosity

As already mentioned above, evaporation and emulsification are the main processes that change the density and viscosity of the oil slick, and they must be modified taking into account the presence of the vegetation and its density. The following formulas are broadly used to calculate density ρ, kg/m^3 and viscosity changes μ Pa/s [14]:

$$\rho = F_{wc}\rho_w + (1 - F_{wc})(\rho_{ref} + C_{E2}F_E) \qquad (8)$$

$$\mu = \mu_{ref} \exp(C_{E1}F_E + (C_{wc1}F_{wc})/(1 - C_{wc2}F_{wc}))$$

where ρ_{ref} and μ_{ref} are the viscosity and density of fresh oil at reference temperature, C_{E1}, C_{E2}, C_{wc1} and C_{wc2} are assigned values by the user based on the general oil type. Thus, from the formulas, it can be noticed that once evaporation and emulsification equations are modified in order to take into account the vegetation, Eqns. (8) will describe density and viscosity changes of the oil slicks inside the vegetation zones.

CONCLUSION

Oil contamination of water is hazardous to the environment. It happens naturally as well as with the interaction of humans. It is very important to predict how spilled oil behaves itself in the marine environment and what kind of environmental processes influence to the change of the oil properties.

The fluid and thermal properties of oil slicks change differently in vegetated coastal areas than the case where slicks are on an open sea. Therefore, in the current paper, we studies the hydrodynamics of oil slick in vegetated areas, using two dimensional modelling and the channel flow parameters. Results showed that the oil slick spreads faster while flowing thought the vegetated zone. Such behaviour of the oil slick assists in the changes of physical and chemical processes such as evaporation, emulsification, surface area change, density and viscosity changes which influence to the oil property. It was discussed that formulas used to describe these processes should be modified by taking into account the presence of the vegetation and its density. Our purpose in the future, is to carefully study the appropriate modification of these formulas based on experimental and numerical methods which will describe the changes of oil slick properties and its hydrodynamic behaviour in vegetated coastal areas.

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