Dispersion of Contaminants in the Ocean

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Abstract

The present work describes the simulation of contaminants in open ocean waters. An aqueous mixture of contaminants is released from off-shore oil platforms through submerged headers several meters below the surface. The discharge results in the development of a submerged plume due to the presence of moderate currents. Plume behavior is influenced by its initial momentum, concentrations, temperature and, specially, the gradients of temperature and concentration in the ocean layer, to which the plume trajectory and leveling depth showed to be extremely sensitive. Three classes of components were considered: dissolved salts, floating particles and sinking particles. A simplified approach for phase slipping was introduced in GROUND thus avoiding the use of less flexible internal models such as the algebraic slip model (ASLP) or more complex ones such as the inter phase slip algorithm (IPSA). Contaminant turbulent dispersion, velocity and temperature profiles of the current, sea water density and boundary conditions for the exit of the domain were programmed in GROUND with the aid of PLANT. Preliminary tuning of the models was achieved in comparison to data reported in literature with good agreement between described characteristic behavior and simulation results.

1. INTRODUCTION

The increasing environmental awareness has motivated remarkable advances in industrial practices during the last years. Although opportunities for advances could be easily spotted in many situations, in others the possibilities of improvement were still limited by the lack of information on the effective extents of the eventual impacts caused by the activities. In that matter, the benefits from actions were also difficult to evaluate.

Computational fluid dynamics (CFD) has been applied successfully in many situations related to environmental studies. In fact, any work oriented to optimization of resources (energy, raw materials, etc.) can be acknowledged as environmentally friendly, no matter the much this factor has effectively oriented the solution. Specifically in the area of risk management and consequence analysis, CFD has made possible the systematic approach to situations which could never be experimented, e.g. toxic spills and major fires or explosions. Comparing to

other types of mathematical models based mainly in statistical regressions or empirical correlations, CFD proved to be a much more realistic approach.

Operations in the petroleum exploitation and refining industry are undoubtedly among the greatest concerns of environment protection entities. This is justified by the huge amounts of potentially hazardous materials being handled in the most diverse areas on land and sea. Investments in safety and mitigating actions receive therefore a major attention from companies in this industry as a way of minimizing impacts and assuring sustainable operation.

This work was dedicated to the development of a model for assessing the potential impact of operations in off-shore oil platforms. The focus of these simulations was the release of an aqueous solution resulting from the pre-treatment of petroleum. The expected results will allow a systematic analysis of the problem and the evaluation of the need and options for solutions.

2. DESCRIPTION OF THE SYSTEM AND MODELLING

2.1. Geometry and Grid

The region of interest was the ocean layer downstream the release point. It was considered for the development of the model that the ocean floor was flat and at constant depth. The submerged fraction of the platform was disregarded for the sake of simplicity, being the header the only structure reproduced in the simulation because of its great influence in the near-field of the release.

Figure 1 illustrates the simulation geometry.
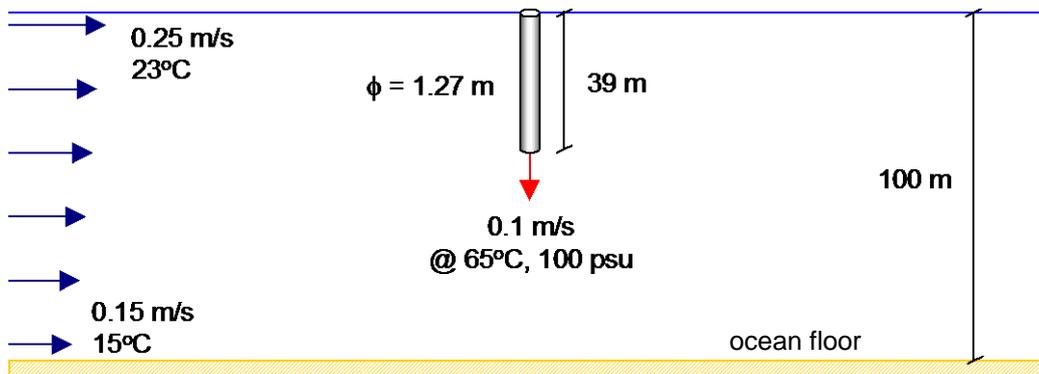
Figure 1 – Geometry of the release

Simulation was assumed to be symmetric in the plane defined by the header centerline and stream direction, allowing the domain size to be cut by half.

The domain was composed by very distinct regions. In the near-field (i.e. closer to the source) the grid should be well refined in order to cope with the dimensions of the header and the aggressive shifts in plume behavior and turbulence effects. In the far-field the grid could be coarser to save computational effort. Increasing cell sizes from the release point to the limits of the domain was set therein.

2.2. Properties

Density

The liquid released consists of a mixture of salt water, lighter and heavier than seawater oils dispersed in small concentrations. The salinity of the effluent is much higher than that of the sea and so is its temperature.

The influences of these properties on the density of the mixture were modeled and implemented in GROUND. Because of its low concentrations, it was considered that the oil fractions would not interfere in this calculation, resulting in an expression for the density depending only on the temperature and concentration of salt.

Data from the literature [3] showed that the isolated effect of the concentration on the density could be linearly fitted, while the same approach for the temperature would lead to a third order polynomial. A reasonable accurate model could be obtained by combining those contributions over a reference state, set from seawater at 15°C, 35 psu (practical salinity units $\approx$ g/kg).

$$\rho(C3,T) = \rho^o + \Delta\rho(C3,T^o) + \Delta\rho(C3^o,T)$$

Eq. 2.1

$$\Delta\rho(C3,T^o) = \alpha + \beta \cdot C3 - \rho^o$$

Eq. 2.2

$$\Delta\rho(C3^o,T) = \alpha' + \beta' \cdot T + \gamma' \cdot T^2 + \delta \cdot T^3 - \rho^o$$

Eq. 2.3

Diffusion

Considering the nature of the flow and the dimensions of the domain, laminar diffusive effects could be neglected. Nevertheless, the diffusion variable was manipulated in order to achieve the expected spread of the contaminants due to turbulence and mixing in the edges of the plume. A model for the diffusion coefficients (PIL command `PRNDTL(phi) = - ###`) was set in GROUND as a function of the micro-mixing rate (EPKE). The parameters for this model were tuned in accordance with validation experiments as described below

2.3. Sources and Environmental conditions

Sinking and Floating

The oil droplets were not simulated as dispersed phases. Instead, they were introduced by means of the concentration variables C1 and C5, from which the diffusion effects were eliminated. The main reason for this decision was the need for a customized model for the density, which would not be possible if an internal module such as the Algebraic Slip Model was used, unless modifications to the original files were made.

Sinking and floating were therefore represented by a source equation resulting from the mass balance in each cell, as illustrated by the following figure and equation. This source was programmed in GROUND.
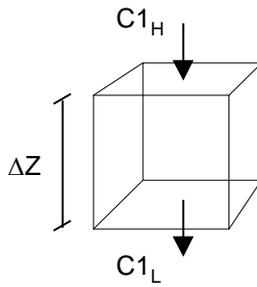
$$\frac{\partial C1}{\partial t} = \frac{V1^{o} \cdot (C1_{H} - C1_{L})}{\Delta Z} \qquad \text{Eq. 2.4}$$

Figure 2 – Mass balance for the finite volume due to sinking.

The terminal settling velocity, $V1^{o}$, was estimated using traditional models from the literature [2].

Turbulence

The standard k-ε model was used.

Stream Profile

The stream profile is an extremely important factor. It is know from oceanographic research that the temperature, salinity and velocity along a vertical line can vary substantially. This phenomena may lead to well know effects such as thermal inversion or thermocline. For the development of the model, a constant salinity was used, while temperature and velocity were assumed to have linear profiles from the bottom to the surface. This corresponds to a moderately stratified environment, i.e. reduced vertical streams and consequently reduced mixing of the plume (which is a conservative approach to the problem).

The equations for these profiles were set in GROUND and ought to be modified should different environmental conditions be desired.

Relaxation

Due to the wide range of cell sizes, relaxation for the velocity variables could not be kept as a single constant value. The false-time-step relaxation was therefore calculated in GROUND using the approximate in-cell characteristic time [4]:

$$TFAL \cong \frac{X^{2}}{X \cdot v + 10^{-5}} \qquad \text{Eq. 2.5}$$

3. RESULTS

Due to the difficulties in obtaining good experimental data with extensive concentration profiles along the dispersion region, the validation of the models, specifically for the diffusion, was achieved in reference to the dilution curve of the system. This curve represents the decaying ratio of the maximum concentration of the plume as a function of the distance from the release point.

A post processing software was used to interpret the PHI file and retrieve the maximum concentration points at each cross section of the plume. By dividing each of these values by the concentration of the effluent, the dilution curve for simulation is obtained.

Data from literature [1] was presented in two distinct environmental conditions: unstable density layers (greatest dilution) and stable-stratified layers (less dilution). Geometry from the related experiment is very similar to that described in Item 2.1. Figure 3 presents the validation simulation in comparison to experimental data.
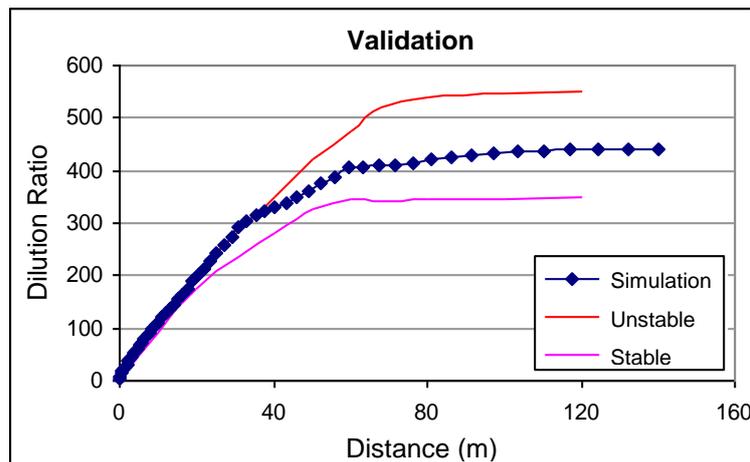
Figure 3 – Validation of the model with experimental data from literature

It can be seen that the simulation curve lays between the two experimental curves, what is totally reasonable considering the intermediate environmental condition used.

Concentration profiles were similar for the three types of contaminants. This represents the reduced influence of sinking or floating of particulate matter, for the concentrations and density differences used. Below is the concentration profile for each contaminant, where the generic aspect of the plume can be noticed.
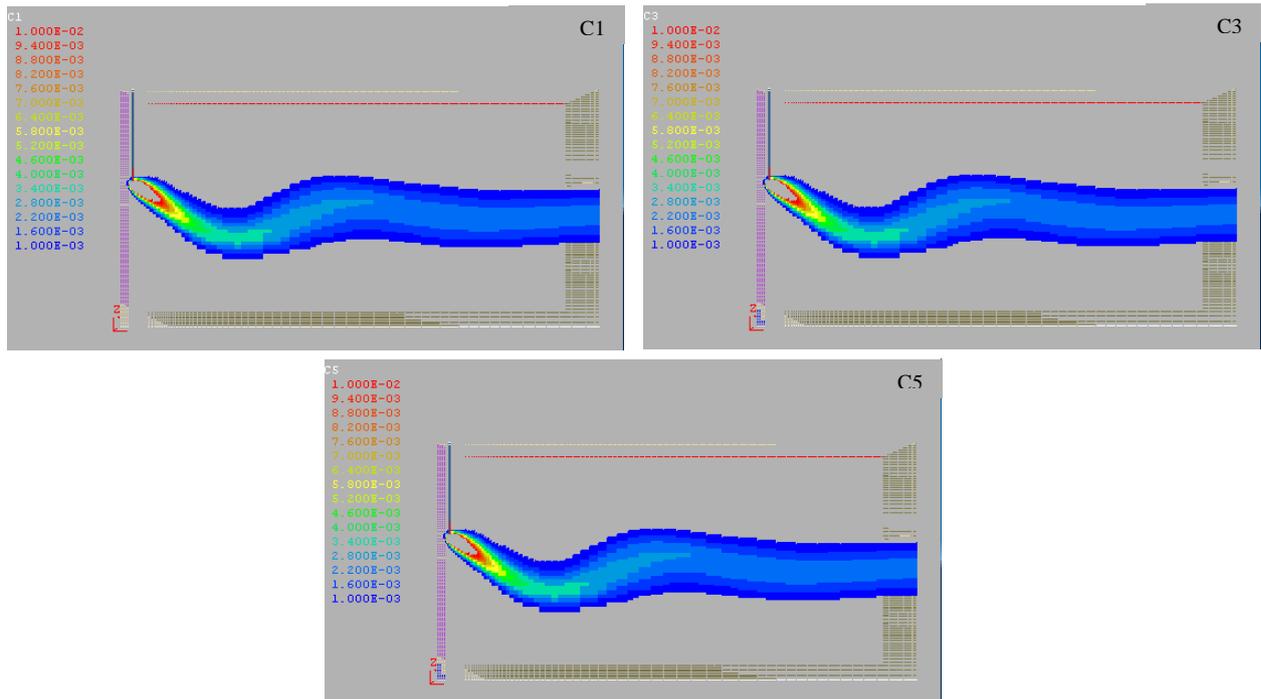
Figure 4 – Concentration profiles for each contaminant

The initial momentum ceases very soon after the release. The following sinking of the entire plume occurs because of its higher density comparing to the surroundings. As turbulent mixing vanishes, the dilution ratio tends to stabilize. At this moment, the plume will start seeking for the layer that can suit its own density better. This process may cause the plume to stabilize in different depths, depending on the density profile of the water body. Some more dilution may occur in this stage, after which concentration changes will tend to be diffusion driven only.

4. CONCLUSIONS

The simulation of a submerged contaminant plume in the ocean was presented. The development of this model involved several particular models, which were introduced in PHOENICS through GROUND.

The results showed reasonable quantitative agreement with experimental data and good qualitative behaviour. The simulation served as an important tool for understanding the sensibility of the plume to operational and environmental conditions. One of the most important conclusions of this study is that the maximum concentration falls to acceptable values very shortly after the source point.

5. BIBLIOGRAPHY

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6. NOMENCLATURE

C1   - normalized concentration of heavy oil droplets
C3   - normalized salinity
C5   - normalized concentration of light oil droplets
T   - temperature, ^{o}C
T^{o} - reference temperature, ^{o}C
TFAL   - false time step, s
$V1^{o}$ - terminal settling velocity for the heavy oil droplets, m/s
v   - resulting velocity of fluid in cell, m/s
X   - minimum dimension of the cell, m
ΔZ - thickness of the cell in vertical direction, m

$\alpha, \beta, \alpha', \beta', \delta', \gamma'$ - constants
ρ - density, kg/m^{3}
ρ^{o} - reference density, kg/m^{3}
$\Delta \rho$ - density variation, kg/m^{3}