TWO- AND THREE-PHASE FLOW COMPUTATION FOR THE OPTIMIZATION OF OIL SKIMMING SYSTEMS

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ABSTRACT

After tanker catastrophes in high seas (Erika, Prestige) a new seaway independent oil skimming device has been developed at the Technical University of Berlin. The system consists of a streamlined displacement vessel (inverse ramp) with an integrated adjustable separation blade. The incoming waves are rolled out by the vessel, and the oil slick is guided under the bow within the boundary layer to the separation blade which diverts the oil to the collection pool. Numerical two- and three-phase flow simulations are conducted for a wide spectrum of operating conditions. The results are confirmed by experimental investigations including tests with oil layers. The nonlinear numerical methods used for stationary and unsteady viscous computation are based on the coupling of the Reynolds Averaged Navier Stokes Equations (RANSE) and a Volume of Fluid (VOF) method. Calculation of oil skimming efficiency in 2D and 3D flow are presented including grid generation as well as the simulation of the two-phase-flow (water and air) with and without oil particles (third phase). The flow simulation including the free surface is systematically validated. The analysis of local nonlinear flow phenomena are the basis for the development of an optimized oil skimming vessel in high seas. In addition the CFD results (Computational Fluid Dynamics) help to get valuable information about the possibilities and limits of such new oil skimming systems.

KEY WORDS

Oil spill, Oil Skimming, CFD-Analysis, VOF Method, Multi-Phase flow simulation, 3D numerical simulation, Grid generation

INTRODUCTION

Tanker catastrophes like the sinking of the "Erika" off the coast of Brittany and the "Prestige" off the coast of Spain revealed the shortcomings of existing oil combating systems to operate in open seas during severe weather. The risk of future oil spills is present every day. Even the use of double hull tankers can not exclude the risk of major accidents. Table 1 documents the largest tanker catastrophes as well as their devastating consequences for the marine environment and the local fishing industry and tourism.

Oil skimming is a highly delicate operation especially if the thin oil film has to be recovered from the churned up ocean surface at high irregular sea states. In this case the skimming mechanism must follow the wave motion otherwise the waves are breaking into the skimming device. As a consequence, the operational availability of existing oil skimming vessels is limited to wave heights of less than 1 m with an associated wave length of 25 m. Beyond these seaway conditions a safe oil recovery operation cannot be accomplished since the occurring motions as well as structural stresses and loads could result in severe damage of the vessel and its subsystems, and the associated skimming efficiency is low (Clauss et al. (2001)).

<table>
<thead>
<tr>
<th>Accident</th>
<th>Cost</th>
<th>Amount [t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967 Torrey Canyon, England</td>
<td>117,000</td>
<td></td>
</tr>
<tr>
<td>1970 Othello, Sweden</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>1972 Sea Star, Gulf of Oman</td>
<td>115,000</td>
<td></td>
</tr>
<tr>
<td>1974 Metula, South Chile</td>
<td>53,000</td>
<td></td>
</tr>
<tr>
<td>1976 La Urquiola, Spain</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>1977 Hawaiian Patriot, North Pacific</td>
<td>99,000</td>
<td></td>
</tr>
<tr>
<td>1978 Amoco Cadiz, France</td>
<td>$ 750 Mio.</td>
<td>223,000</td>
</tr>
<tr>
<td>1979 Atlantic Empress, Caribbean</td>
<td>276,000</td>
<td></td>
</tr>
<tr>
<td>1980 Torio, France</td>
<td>27,000</td>
<td></td>
</tr>
<tr>
<td>1983 Castillo de Bellever</td>
<td>250,000</td>
<td></td>
</tr>
<tr>
<td>1989 Exxon Valdez, Alaska</td>
<td>$ 1.9 Bil.</td>
<td>40,000</td>
</tr>
<tr>
<td>1990 Mega Borg, Kill-v.-Kull-Waterstr.</td>
<td>12,000</td>
<td></td>
</tr>
<tr>
<td>1991 Kiri, Indian Ocean</td>
<td>22,000</td>
<td></td>
</tr>
<tr>
<td>1992 Gerol Tschernomorjor, Gais</td>
<td>4,000</td>
<td></td>
</tr>
<tr>
<td>20.09.1992 Nagasaki Spirit, Malakka</td>
<td>2,000</td>
<td></td>
</tr>
<tr>
<td>03.12.1992 Agean Sea, Spain</td>
<td>81,000</td>
<td></td>
</tr>
<tr>
<td>05.01.1993 Braer, Shetland Islands</td>
<td>98,000</td>
<td></td>
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<tr>
<td>1993 Maersk Navigator, Malakka</td>
<td>2,000</td>
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<tr>
<td>1994 Morris J. Berman, Puerto Ricos</td>
<td>3440</td>
<td></td>
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<tr>
<td>25.01.1994 Cosma A, Hong Kong</td>
<td>23,000</td>
<td></td>
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<tr>
<td>1996 Sea Empress, Wales</td>
<td>70,000</td>
<td></td>
</tr>
<tr>
<td>1997 Nachodka, Japan</td>
<td>20,000</td>
<td></td>
</tr>
<tr>
<td>1999 Erika, Bretagne</td>
<td>17,000</td>
<td></td>
</tr>
<tr>
<td>20.03.2002 Balu, Spain</td>
<td>8,000</td>
<td></td>
</tr>
<tr>
<td>13.11.2002 Prestige, Spain</td>
<td>£ 10 Bil.</td>
<td>50,000</td>
</tr>
</tbody>
</table>

Table 1: Significant oil accidents

In general, moving components endanger the operability of skimming systems and should be avoided. In addition, it is favourable to protect the skimming process against wave effects. Based on these requirements a new skimming system – the Seaway Independent Oil Skimmer (SOS) – has been developed which detaches wave damping and oil skimming.
The working principle of the skimmer unit is shown in Figure 1. The surface waves are rolled out by a streamlined displacement vessel (inverse ramp) which is integrated in a parent ship (Figure 2). The oil film is then guided within the boundary layer to the adjustable separation blade, and finally into the moon pool, where the recovered oil is accumulated, and pumped off to separation tanks (Clauss et al. (2002) and Clauss (2003)).

Figure 1: Working principle of the seaway independent oil skimming system (SOS)

$$\rho \left[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right] = -\frac{\partial \mathbf{p}}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho \cdot f_x,$$

$$\rho \left[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right] = -\frac{\partial \mathbf{p}}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho \cdot f_y,$$

$$\rho \left[ \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right] = -\frac{\partial \mathbf{p}}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + \rho \cdot f_z,$$

where $\rho$ is fluid density, $\mu$ dynamic viscosity, $p$ pressure. $f_{x,y,z}$ are accelerations due to volume forces.

With the assumption that the stochastic velocity fluctuations $u', v', w'$ represent the Reynolds stresses following from turbulence; $u', v', w'$ etc. denote time averaged quantities.

Figure 2: Integration of skimming unit into carrier vessel MPOSS

The correlations between the fluctuations $u'$, $v'$, $w'$ represent the Reynolds stresses following from turbulence; $u', v', w'$ etc. denote time averaged quantities.

The model is based on Boussinesq's eddy-viscosity concept, where the molecular viscosity is replaced by turbulent eddy-viscosity $\mu_T$.

In analogy to the viscous stresses in laminar flow, the turbulent stresses are assumed proportional to the mean velocity gradients.

Assuming isotropic turbulence $\overline{u'^2} = \overline{v'^2} = \overline{w'^2}$ in all directions the Boussinesq-formulation of the Reynolds-tensor yields

$$\rho \begin{bmatrix}
\overline{u'^2} & \overline{u'v'} & \overline{u'w'} \\
\overline{v'u'} & \overline{v'^2} & \overline{v'w'} \\
\overline{w'u'} & \overline{w'v'} & \overline{w'^2}
\end{bmatrix} = \begin{bmatrix}
2\mu_T\overline{u'^2} - \frac{2}{3} \rho' k & \mu_T(\overline{w'u'} + \overline{v'u'}) & \mu_T(\overline{w'u'} + \overline{w'^2}) \\
\mu_T(\overline{w'u'} + \overline{v'u'}) & 2\mu_T\overline{v'^2} - \frac{2}{3} \rho' k & \mu_T(\overline{w'^2} + \overline{v'^2}) \\
\mu_T(\overline{w'u'} + \overline{w'^2}) & \mu_T(\overline{w'^2} + \overline{v'^2}) & 2\mu_T\overline{w'^2} - \frac{2}{3} \rho' k
\end{bmatrix}$$

The kinetic energy of the fluctuation motion, i.e. the turbulent kinetic energy, is the sum of the turbulent normal stresses

$$k = \frac{1}{2} \left( \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right)$$

The eddy-viscosity $\mu_T$ for the standard $k-\varepsilon$ turbulence model (prevailent model) is related to the turbulent kinetic energy $k$ and its rate of dissipation $\varepsilon$ by

$$\mu_T = c_\mu \frac{k^2}{\varepsilon},$$

usually with the constant $c_\mu = 0.09$.

NUMERICAL ANALYSIS

The numerical model is based on a transient viscous simulation of the flow around the oil skimming system including free surface and oil layer.

- Governing equations

In the Cartesian coordinate system the governing equations for incompressible Newtonian fluids are as follows:

Conservation of mass

$$\Delta V = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0,$$

with the velocity vector $V(u,v,w)$.

Conservation of momentum (3D Navier-Stokes equation)

To analyse and optimize this new oil skimming system two-
• Free surface simulation

Methods for the simulation of the free surface and the computational fluid interface are classified into two groups (Ferziger and Peric (1996)), namely:

- surface methods (surface fitting)
- volume methods (surface capturing)

With surface fitting methods only two phases are calculated. The phases are represented by marking with special marker points (Figure 3), or by attaching it to a mesh surface which is forced to move with the interface. A detailed description of the implementation of these methods is given in Hyman (1984) and Ubbink (1997).

![Figure 3: Marker particles on the interface](image)

With surface capturing methods the free surface is marked by either massless particles (Marker-and Cell (MAC), Takizawa et al. (1992)) or an indicator function (Volume of Fluid Method (VOF)). In this investigation the VOF method is applied for the simulation of the free surface. The VOF method introduces a scalar indicator function between zero and one (Figure 4). The value “1” indicates the presence of a specified fluid (e.g. water) and the value “0” the second fluid (e.g. air). Partial filling is characterized by intermediate values (Hirt and Nichols (1981), Ubbink (1997)).

![Figure 4: Indicator function on a discrete mesh](image)

Using volume methods such as VOF or MAC it is possible to handle flows with a highly deformed free surface. Even phenomena of breaking waves can be analysed.

• Euler-Lagrange-method for oil modelling

In STAR-CD program oil particles are modelled by the Euler-Lagrange-method (third phase), in which the fluids are characterised by a primary and a secondary phase. The primary phase is defined as water or air (Euler-approach), the secondary phase as oil or other (Lagrange-approach).

Interaction between the primary and the secondary phase is determined by conservation equations of momentum, mass and energy.

The momentum equation for a droplet of mass $m_d$ is

$$ m_d \frac{d \mathbf{u}_d}{dt} = \mathbf{F}_{dr} + \mathbf{F}_p + \mathbf{F}_{am} + \mathbf{F}_b. $$

Here $\mathbf{F}_{dr}$ is the drag force (Figure 5), $\mathbf{F}_p$ the pressure force, $\mathbf{F}_{am}$ the so-called “added mass” force, $\mathbf{F}_b$ a general force, $\mathbf{u}_d$ droplet velocity, $A_d$ the cross-section area, and $x_d$ is the droplet position vector.

![Figure 5: Lagrangian droplet motion](image)

Details of mass and energy equations as well as of modelling practices and solution algorithms are given in the STAR-CD (1999) manual.

TWO-PHASE OPTIMIZATION OF SEAWEY INDEPENDENT OIL SKIMMER (SOS)

The Prestige disaster in the Atlantic revealed that seakeeping requirements for oil recovery vessels by far exceed the operational limitations of the present oil combating fleet. The analysis of operational problems and skimming efficiency of existing oil recovery vessels lead to the following perspectives and design criteria for future oil skimming systems:

- High transit speed in rough seas
- High skimming efficiency at operational speeds
- Operation in shallow water and harsh sea states
- Docking on disabled vessels
CFD methods allow to analyze and optimize the above design of the new oil skimmer. Global and local flow phenomena are of special interest. The analysis starts with the optimisation of 2D skimmer geometries. Not only the flow field near the separation blade is highly susceptible to unfavourable disturbances, but also the pressure field around the entire vessel is decisive for an efficient skimming process. Figure 6 illustrates that the primary design of the oil skimmer (see Figure 1) is not operating because of high flow resistance (stagnation pressure) at the moon pool entrance and outlet.

Figure 6: Velocity field with closed moon pool

As a consequence, the parametric study of the skimmer unit has been performed, and a systematic optimization procedure has been accomplished. In order to dissolve the transition of density and viscosity between the phases as accurate as possible, the cells of the grid must be small, particularly at the interface, since large cells lead to convergence problems. Figure 7 presents the geometry and the grid structure of the oil skimmer for RANSE-based CFD simulations.

Figure 7: Grid structure for the CFD analysis (scale 1:15)

To improve the oil-water flow into the moon pool the width of the outlet $l_o$ and the intake blade slit $D$ is varied systematically. A key parameter is the ratio $\Lambda = l_o/D$.

As shown in Figure 8 the ratio $\Lambda$ is decisive for a stable, stationary flow into the moon pool. At low values the flow shows strong fluctuations. At $\Lambda = 4$ stable discharge rates are observed.

Figure 8: Discharge rate at moon pool entrance

Figure 9 illustrates that this favourable influx follows from the action of a strong stationary vortex at the sharp trailing edge of the bow segment.

Figure 9: High discharge rate into the moon pool due to vortex activity behind bow segment

MODELLING OF OIL PARTICLES (THIRD PHASE)

To analyze the oil particles trajectories into the moon pool and in front of the bow segment, droplets are introduced in the flow (Euler-Lagrange-method). These droplets have the same density $\rho$ as the oil, and are approaching the bow segment at the free surface (Figure 10).

Figure 10: Simulation of oil particles (far field)
Figure 11: Oil particle tracks behind bow segment (diesel oil, $\rho = 840$ kg/m$^3$)

Figure 12: Oil particle tracks behind bow segment (heavy oil, $\rho = 970$ kg/m$^3$)

Due to the pressure loss behind the bow segment of the skimmer a stationary vortex develops in the moon pool area with a stable flow rate at the separation blade (Figure 11 and Figure 12). This vortex transports oil particles to regions at the moon pool surface, from where the oil is pumped to separation tanks.

To investigate the difference between light (e.g. diesel oil) and heavy oil, flow conditions and oil trajectories into the moon pool are evaluated. Figure 11 and Figure 13 illustrates that diesel oil ascends immediately behind the moon pool entrance towards the surface, whereas heavy oil (Figure 12) rises quite slower. This effect may cause some oil leakage at the trailing edge of the separation blade as shown in Figure 14.

Figure 13: Outflow conditions with diesel oil

Figure 14: Outflow conditions with heavy oil

This leakage is avoided by reducing the flow velocity as illustrated in Figure 15: At $u = 0.5$ m/s even the heavy oil remains in the moon pool.

Figure 15: Oil trajectories

VALIDATION OF CFD SIMULATIONS

The CFD simulations have been validated by experimental tests in a small acrylic towing tank. The flow is visualized by plastic particles. Figure 16 and Figure 17 illustrate that the results of the model tests agree well with data of the numerical simulation. Similar to the computation at the ratio $\Lambda = 0.5$ it is observed that the particles are diverted under the separation blade. With the ratio $\Lambda = 4$ a stationary vortex behind the bow segment is generated as predicted by CFD computation.
Both, CFD simulations and 2D towing tests reveal that the oil is guided into the separation chamber and then - due to the influence of the vortex - is driven to the moon pool surface near the inverse ramp. This collection mechanism allows to pump the oil into the carrier vessel efficiently.

After validation of the CFD method at model scale the scale effect itself is investigated. Comparing model scale and full scale calculations (Figure 18 and Figure 19) it is obvious that heavy oil ascends quite earlier at full scale conditions if compared to model scale results.

**Figure 16**: Comparison of CFD results and 2D towing tests ($\Lambda = 0.5$)

**Figure 17**: Comparison of CFD results and 2D towing tests ($\Lambda = 4.0$)

**Figure 18**: Flow conditions at trailing edge - heavy oil - model scale 1:15

**Figure 19**: Flow conditions at trailing edge - heavy oil - full scale

**OIL AND SEA STATE INVESTIGATION**

So far our investigations have been accomplished with 2D models. After validation of the CFD procedure and optimization of the skimmer module a final test has been performed with the oil skimmer integrated in a parent ship (Figure 20).
The separation blade efficiently shields the moon pool from the action of the incident wave field, i.e. the fluid surface in the moon pool is scarcely sloshing and splashing. However, ship motions are inducing some wave motions in the moon pool. For this reason, wave dampers have been integrated. To complete the system also oil sumps are installed to further separate oil and water. The optimized skimming system is illustrated in Figure 23.

CONCLUSIONS AND OUTLOOK

CFD analyses show that the primary design of the oil skimmer is not operational due to the high flow resistance of the moon pool. After numerous steps of CFD calculations the system has been optimized successfully by variations of the ratio $\Lambda$ between the outlet $l_0$ and the intake blade slit $D$ of the moon pool. A geometrical ratio $\Lambda = 4.0$ is determined as “optimal”, with no reverse flow at the entrance of the moon pool and a high flow rate.

The CFD results have been validated by experimental tests. The optimized skimmer configuration is integrated into a parent ship, to analyze the influence of the seaway on the entire system. The system has been tested in waves at a scale of 1:15 sloshing a mixture of diesel and heavy oil (IFO30) from the water surface. The model test results in waves demonstrate the high efficiency of the separation principle.

In future CFD studies all three-phases will be simulated by VOF methods utilizing the program Fluent (2001). A goal of this analysis is the optimization of the ratio $\Lambda$ as a function of oil film thickness $d$ under the bow depending on vessel speed (Figure 24).

In addition, a large variety of irregular seas will be considered to investigate the wave influence on the oil skimming process in detail. Different types of oil and different cruising speeds will be investigated. Sloshing in the moon pool due to
the ship motion will be also evaluated in simulations. For the
minimization of sloshing in the moon pool different absorption
systems are investigated.
As a final goal the design of a new generation of multipur-
pose ships is envisaged. Such a vessel with an integrated SOS
module is drafted in Figure 25.

Figure 25: Integration of SOS into a new carrier

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