An innovative offshore oil skimming system for operations in harsh seas

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ABSTRACT: Despite continuous progress in tanker safety and decreasing oil spills, severe accidents due to human failure can never be excluded. Currently deployed oil recovery systems have to abandon operations in wave heights exceeding 1.5 m. To prevent emulsification and weathering processes, the oil has to be skimmed off the sea surface as soon as possible after the accident. This can only be achieved by an oil recovery system with high transit velocities and the capability of operating in rough seas.

A Sea state-independent Oil Skimming system (*SOS*) that satisfies these requirements has been developed and gradually optimized in various numerical and experimental analyses. For the investigations, the *SOS* is integrated into the carrier vessels *MPOSS* and *FUTURA TANKER* at model scale. The optimized system of *MPOSS* and *SOS* yields an efficiency of up to $\eta = 95$ % at wave heights $H_s < 1$ m. In higher seas (up to $H_{max} = 4.6$ m), $\eta = 59$ % is attained at a cruising speed of $v = 2.25$ kn. The multi-purpose system consisting of *FUTURA TANKER* and *SOS* yields $\eta > 90$ % for diesel as well as heavy fuel oil in still water at $v = 3$ kn.

1 INTRODUCTION

International and national efforts on tanker safety have been made, resulting in improved regulations and high standards. As a result, the quantity of oil spilled in tanker accidents is notably decreasing over the last years (see Figure 1, top and ITOPF, 2008). Despite this progress, the factor of human failure can never be excluded. Major oil spills like the *Erika* disaster in 1998 and the loss of the *Prestige* off the coast of Spain in 2002 (see Figure 1, bottom) show that each individual accident leads to catastrophical ecological as well as economical consequences for the abutting countries.

Currently operating oil recovery systems are able to operate in calm water and wave heights up to 1.5 m. In severe weather they have to wait until conditions are improving. After a spill occurs, the oil film continuously spreads over wide areas of the water surface and changes its chemical characteristics (emulsification). To prevent these processes, it is necessary to skim the oil film off the sea surface very quickly after the accident. This can only be achieved by an oil recovery system that is

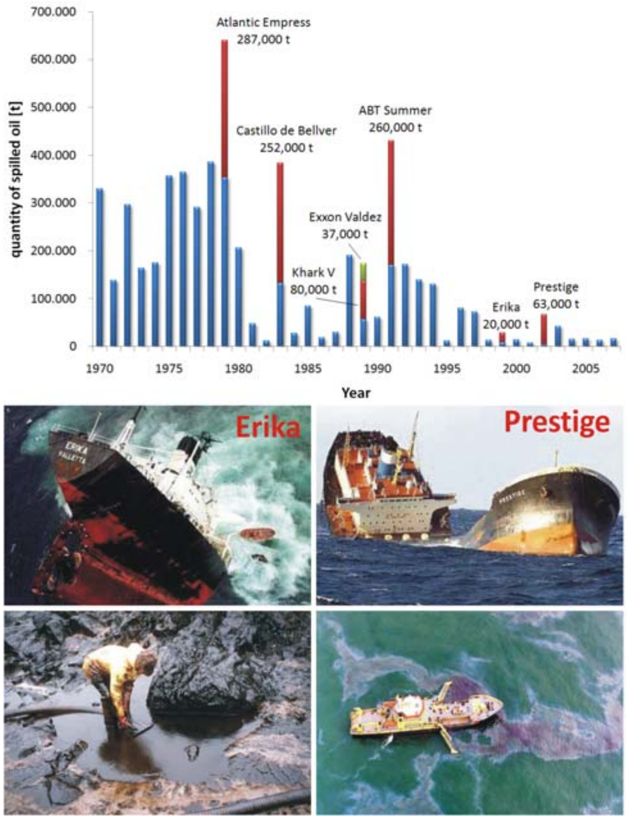

Figure 1. Quantities of oil spilled in the last decades (top), last major oil spills and common response techniques (bottom)

capable of operating in calm water as well as in rough seas (Clauss et al., 2001).

A new Sea state-independent Oil Skimming System (*SOS*) that satisfies these requirements has been developed at the Technical University Berlin (Clauss et al., 2002). In various numerical and experimental analyses, the system has been gradually optimized in three main steps as shown in Figure 2 (Abu Amro & Sprenger, 2008). For these investigations, the *SOS* is integrated into the carrier vessel *MPOSS* at model scales of 1:15 and 1:9, as well as into a *FUTURA TANKER* at model scale 1:36.

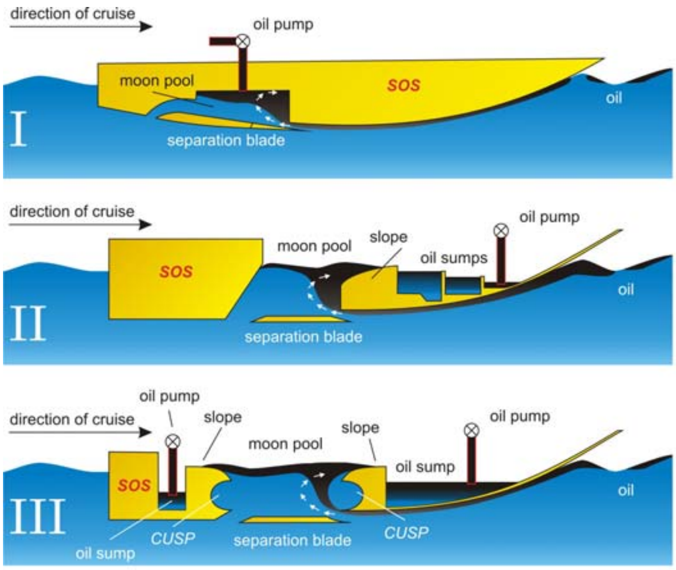

Figure 2. Optimization steps of the *SOS* concept

2 FUNCTIONAL PRINCIPLE OF THE *SOS*

The sea state-independent oil skimming system has already been patented in Germany (German Patent and Trademark Office, 2006) and the United States (United States Patent and Trademark Office, 2007). The skimming concept is based on purely hydrodynamic principles and is extremely robust since it works without moving parts. Figure 2 (bottom), illustrates the layout of the optimized system. A specially shaped bow segment glides on the water surface, damping the waves. The oil layer flows underneath the *SOS* bow towards a transverse blade, which separates oil from water. At the trailing edge of the bow segment, a vortex develops and accelerates the oil particles in addition to their positive buoyancy to the free water surface of the moon pool. Wave-induced sloshing effects convey the oil over adjustable slopes into oil sumps from where it is pumped off. As shown in Figure 2 (bottom), the moon pool is equipped with so-called CUSP designs. This particular geometry is utilized to reduce resistance at the stern of vehicles (Hucho, 2005). In case of the *SOS*, the CUSP serves the purpose of stabilizing the vortex behind the bow segment as well as retaining the skimmed oil in the moon pool. The main objective of the optimization procedure is to improve the skimming efficiency

$$\eta = \frac{flux\ of\ skimmed\ oil}{total\ discharge\ of\ oil}, \quad (1)$$

especially in high waves by numerical and experimental analyses.

3 INTEGRATION OF THE *SOS* INTO THE CARRIER VESSEL *MPOSS*

The *MS MPOSS* (Multi-Purpose Oil Skimming System) is an oil response vessel of the German *Central Command for Maritime Emergencies*, designed for coastal operations and currently based at the port of Hamburg.

Within the catamaran-shaped bow region of *MPOSS*, a skimming unit with floater-flaps is installed at present. This system is based on the ERNO concept and was also developed at Technical University Berlin (Clauss & Kühnlein, 1994). For the following investigations, this system is replaced by a *SOS* unit (see Figure 3).

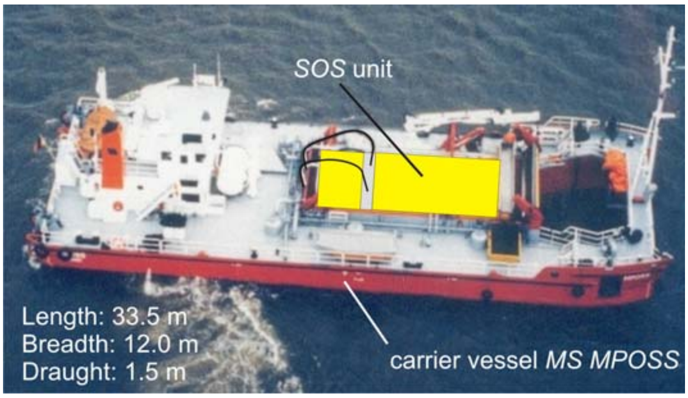

Figure 3. Schematical illustration of *MPOSS* with integrated *SOS* unit

3.1 *Numerical Analyses*

CFD (Computational Fluid Dynamics) simulations provide a powerful tool for predicting potentials as well as the operational range of oil skimming systems. One of the key advantages is the possibility of cost- and time-effective geometrical variation. Also, the global as well as the local flow phenomena, including mixing processes in front of the skimmer bow and inside the moon pool, can be analyzed for arbitrary wave conditions and oil types of different density and viscosity – without ecological restrictions.

For analyzing the *SOS*, the commercial CFD solver FLUENT is enhanced by specially developed User Defined Functions (UDF), e.g. for generating arbitrary irregular sea states (Fluent Inc., 2006). The nonlinear calculation of the viscous multi-phase flow is based on the coupling of the Reynolds-

Averaged Navier-Stokes Equations (RANSE) and the Volume of Fluid method (VOF, Hirt & Nichols, 1981).

Optimization of the discharge rate

In order to achieve an optimum efficiency of the *SOS*, a constant discharge rate

$$q = \frac{Q}{Q_0} = \frac{Q}{v\,D} \tag{2}$$

at the inlet opening D of the moon pool is critical. Here, the effective volume flow through the inlet opening is denoted by Q, whereas $Q_0 = v \cdot D$ describes the total influx, both quantities are normalized for the breadth. The dependency of the discharge rate from the height of the inlet opening D and and the length of the outlet opening l_a can be expressed by the coefficient

$$\lambda = \frac{l_a}{D}, \tag{3}$$

describing the ratio of the size of the openings. Assuming a constant inlet height of $D = 20$ mm (resulting from the size of the boundary layer at a model scale of 1:15), two-phase flow simulations (water/air) are conducted, varying λ by the length of the outlet opening l_a. Figure 4 illustrates the results of these calculations, clearly showing that for $\lambda = 4$ an optimum constant discharge rate is achieved, where about 80 % of the total flux Q_0 enters the moon pool.

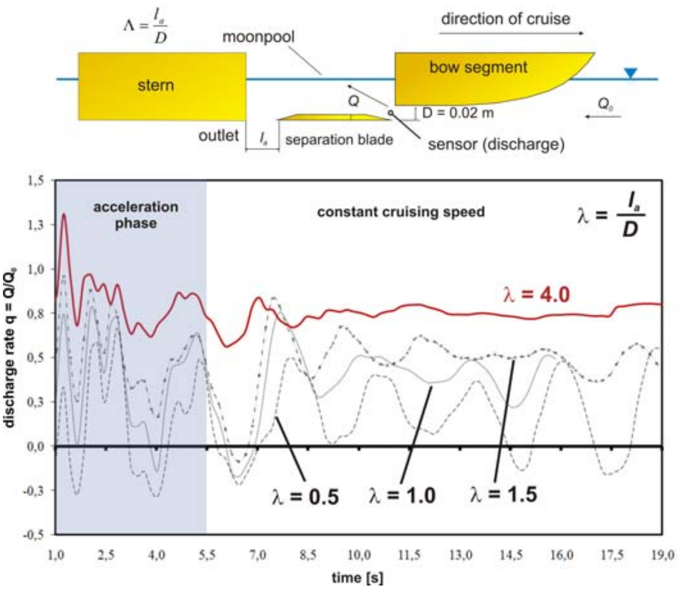

Figure 4. Visualization of the discharge rate q at the moon pool entrance at a scale of 1:15

For lower ratios ($\lambda << 4$), strong oscillations of the discharge rate q can be observed. When choosing $\lambda = 0.5$, even backflow through the inlet opening can be observed at $t = 6$ s, $t = 14.8$ s and $t = 17.3$ s, indicated by negative flow velocities.

Minimization of sloshing effects

Wave-induced ship motions cause sloshing effects at the free surface of the moon pool, which interfere with the stability of the vortex at the trailing edge of the bow segment and also influence the ship motions.

Here, the focus lies on the impact of sloshing on the discharge rate q. In order to simulate sloshing without computationally expensive consideration of the surrounding sea state, the *SOS* is initialized directly with the final velocity at $t = 0$ in a two-phase (water/air) domain at a model scale of 1:15. This leads to an abrupt shift of the water masses inside the moon pool ('numerical' sloshing), causing a destabilization of the vortex above the inlet opening. In order to avoid the disturbance of the vortex, a so-called CUSP design with slope is integrated into the moon pool. The slope reduces sloshing while the CUSP stabilizes the vortex and hence significantly decreases oscillations in the discharge rate (see Figure 5).

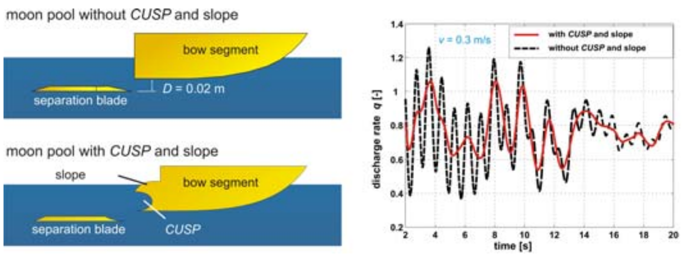

Figure 5. Influence of CUSP and slope on the discharge rate at a scale of 1:15

The effect of the optimized moon pool becomes clearly visible at low cruising speeds ($v = 0.3$ m/s, model scale 1:15 – i.e. 2.25 kn at full scale), since the influence of sloshing on the discharge rate is particularly pronounced for the corresponding low influx. But also at higher velocities, a further reduction of oscillations due to the optimized geometry can be observed.

3.2 *Experimental Analyses*

All model tests are conducted in the wave tank of Technical University Berlin. On the one hand, the test series are conducted to validate the numerical models and on the other hand to determine the seakeeping behaviour as well as the skimming efficiency η for different moon pool and stern geometries at various random sea states and cruising speeds. For these tests, coloured edible oil as well as mineral oil is applied on the water surface of the wave tank. The model of the *SOS* integrated into the carrier vessel *MPOSS* is constructed on basis of the numerical results at a scale of 1:15.

Seakeeping behaviour

In order to investigate whether a fixed or a pin-jointed coupling between *MPOSS* and *SOS* is to be preferred, the absolute value of the response amplitude operator (RAO)

$$\left|H(\omega)\right| = \frac{motion\ amplitude}{excitation\ ampliutde}, \qquad (4)$$

is experimentally determined. The results from tests with the pin-jointed system show high heave and pitch motions in a range of 1.5 rad/s < ω < 2.0 rad/s (full scale), strongly delimitating the operational range of this concept. This effect can be ascribed to reflection and superposition of waves in the funnel-shaped region between the two hulls of the carrier vessel.

For the fixed coupled variant, the motions of the skimming unit are correlated to the carrier vessel motions, significantly improving the seakeeping behaviour. All further analyses are conducted with the fixed coupled system.

Reduction of sloshing

Sloshing causes a destabilization of the vortex at the inlet opening of the moon pool, leading to a reduction of the system efficiency. A series of towing tests at various irregular sea states and towing velocities is targeted on the investigation of design features for sloshing minimization. The oil skimming efficiency is determined with ecologically sensitive coloured edible oil (ρ = 922 kg/m^3, μ = 0.06 Pa s). The experimental results agree with the numerical analyses, showing a prevention of backflow through the inlet and a stabilization of the vortex by integration of a CUSP design with slope.

Further improvement can be observed when the slope is adjusted to the current wave height of the surrounding sea. As Figure 6 is showing, an efficiency of 70-88 % is achieved by this concept in calm water and wave heights up to H_s = 1 m.

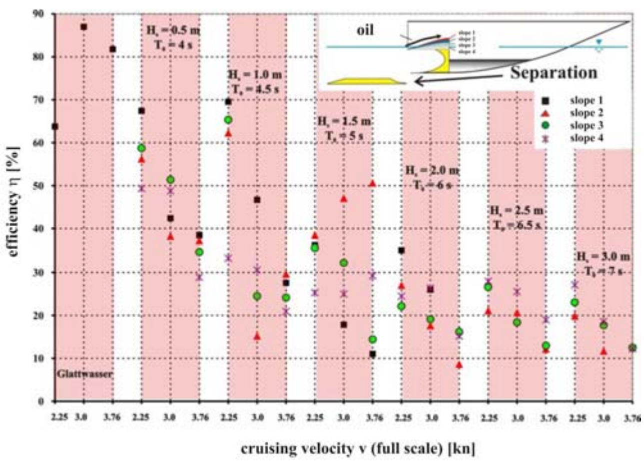

Figure 6. Efficiency in dependency of the slope position for different sea states and cruising v

For higher sea states (H_s up to 3 m), higher slope positions prove to be effective. Nevertheless, the system efficiency continuously decreases for increasing wave heights, reaching 12-20 % for high operational velocities.

Scaling effects

All model tests are conducted in compliance with Froude's law. Since viscous effects cannot be scaled correctly at the same time, the influence of different scales on the efficiency of the *SOS* is analyzed in a model test series. For this purpose, the *SOS* is integrated into the carrier vessel *MPOSS* at scales of 1:15 and 1:9 (see Figure 7).

For both model scales, the *SOS* is investigated at v = 2.25 kn and v = 3 kn (full scale) in calm water as well as five different random sea states with a layer of edible oil. The respective results, i.e. the efficiency η obtained from these tests, are compared in Figure 7.

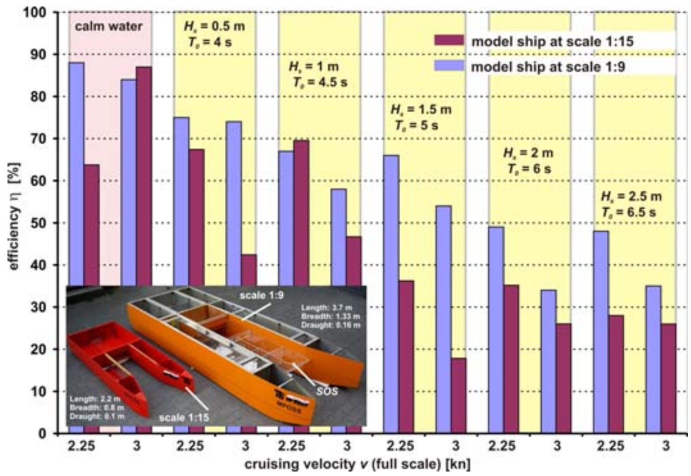

Figure 7. Comparison of the efficiencies obtained for the small (1:15) and the large model scale (1:9) at different cruising velocities and sea states (full scale)

It can be observed that the efficiencies obtained for the model at a scale of 1:9 are better than for the model at a scale of 1:15 at all times. This is due to the fact that the model at a scale of 1:9 features a larger moon pool. Since the physical properties of the oil particles – and hence their ascending characteristics – are not scaled, more oil is able to ascend to the free water surface of the moon pool and therefore less oil than at scale 1:15 is flowing through the outlet opening back into the main flow.

Optimization of the outlet shape

For further investigations, edible oil is replaced by mineral oil. This hydraulic oil features similar characteristics to diesel oil (Renolin DTA 10: ρ = 852 kg/m^3, μ = 0.0188 Pa s). In this experimental series, the influence of different outlet configurations on the flow patterns inside the moon pool – and hence the efficiency of the *SOS* is analyzed at a scale of 1:9. The first design is based on the original *MPOSS* geometry (see Figure 8, top left), the second outlet configuration is an improved variant of the first one (see Figure 8, top centre) and finally a third alternative is investigated where the layout including CUSP and slope is 'mirrored' from the inlet of the moon pool to the outlet (see Figure 8, top right). The different configurations are tested in light hydraulic oil Renolin DTA 10 at three different cruising speeds.

The efficiencies obtained for the respective outlet configurations are presented in Figure 8 (bottom). Each coloured area represents a certain sea state where three cruising speeds are considered.

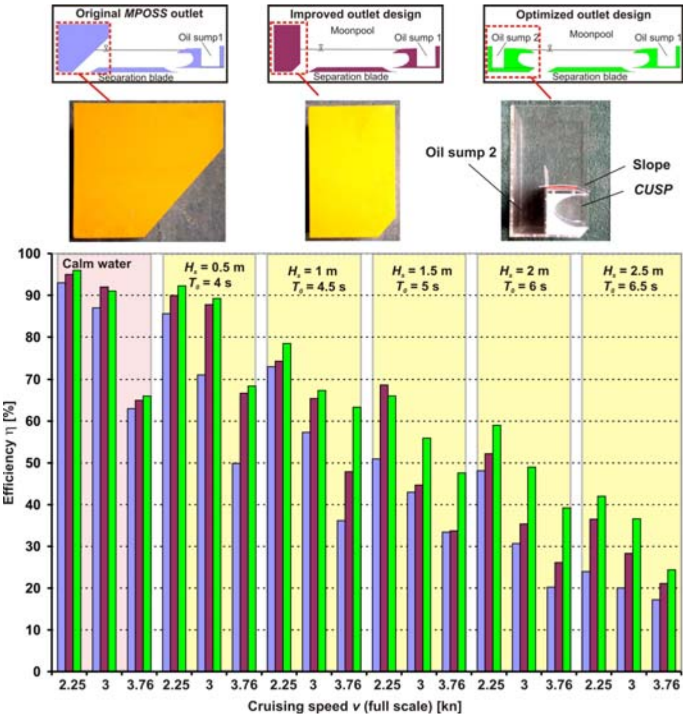

Figure 8. The three different outlet configurations (top), comparison of results of the model tests conducted at a scale of 1:9 with a light hydraulic oil (bottom)

The optimum operating speed for all three outlet shapes is $v = 2.25$ kn (full scale), where η reaches 96 % in calm water. With increasing sea states, efficiency continuously decreases for all variants. In comparison, the outlet layout with the 'mirrored' CUSP and slope design yields the best results for all conditions investigated. While the advantage of this configuration is negligible for operations in slight sea states, it becomes evident for $H_s \geq 1$ m. Comparing the efficiencies for the original *MPOSS* configuration to the optimized design at $H_s = 2$ m and $v = 2.25$ kn, an improvement of 12 % from $\eta = 47$ % to 59 % can be observed.

The reason for these differing results is the flow pattern inside the moon pool. In order to visualize these processes, two cameras are installed on the *SOS* model as indicated by Figure 9 (top): camera 1 at the inlet and camera 2 at the outlet of the moon pool.

The video stills of camera 1 show that for $v = 3$ kn, a vortex develops at the trailing edge of the bow segment. This vortex accelerates the oil particles towards the free water surface of the moon pool. In case of the original *MPOSS* outlet configuration (Figure 9, centre) a large part of the oil flows through the outlet back into the main flow along the vessel's hull – leading to a decrease of the efficiency η.

While the disadvantages of the original outlet configuration become obvious from these images, the advantages of the optimized layout is also observable (see Figure 9, bottom). The 'mirrored' CUSP and slope geometry stabilizes a second vortex above the outlet of the moon pool and leads to improved damping of sloshing effects. This second vortex prevents most of the oil particles that have not reached the free water surface of the moon pool from flowing through the outlet.

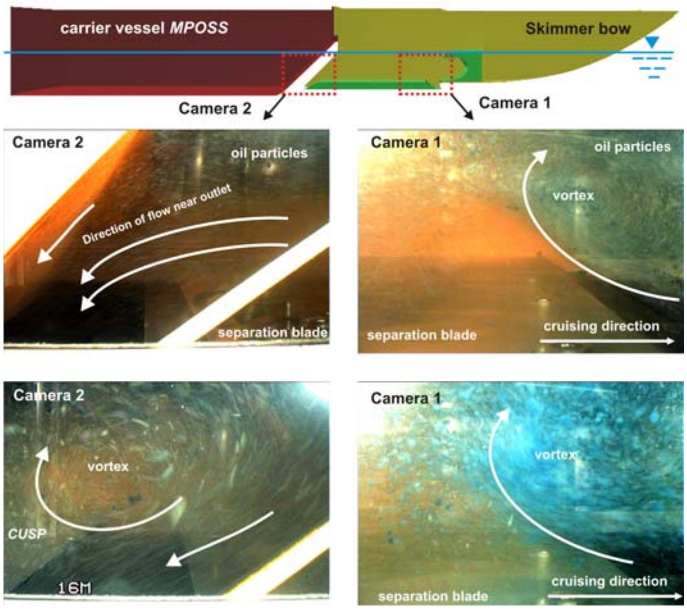

Figure 9. Position of the cameras on the model (top), video stills showing the flow inside the moon pool for the original *MPOSS* outlet (centre) and the optimized outlet configuration (bottom) at $H_s = 2$ m, $T_0 = 6$ s and $v = 3$ kn (full scale)

The optimized outlet configuration is also tested in a mixture of 20 % Renolin DTA 10 and 80 % Valona MS 8015 D, the latter featuring similar characteristics to heavy fuel oil ($\rho = 923$ kg/m^3 and $\mu = 0.0415$ Pa s). In these experiments $\eta = 90$ % is achieved in calm water and $\eta = 40$ % at $H_s = 2.5$ m – leading to the conclusion that the *SOS* with the optimized outlet configuration is capable of effective oil recovery operations for a wide range of oil types in calm water as well as in rough seas.

Analyses with a larger carrier vessel

For this test series with the *MPOSS* model at a scale of 1:9 (length 3.7 m, breadth 1.3 m, draught 0.16 m) in Renola DTA 10 oil, the sea states generated in the wave tank are scaled at 1:22 instead of 1:9 as hitherto. With this approach, the length of the carrier vessel corresponds to approx. 80 m instead of 33.5 m at full scale. The influence of the dimension of the carrier ship on the system efficiency is shown in Figure 10 for the optimized outlet shape at three different cruising velocities.

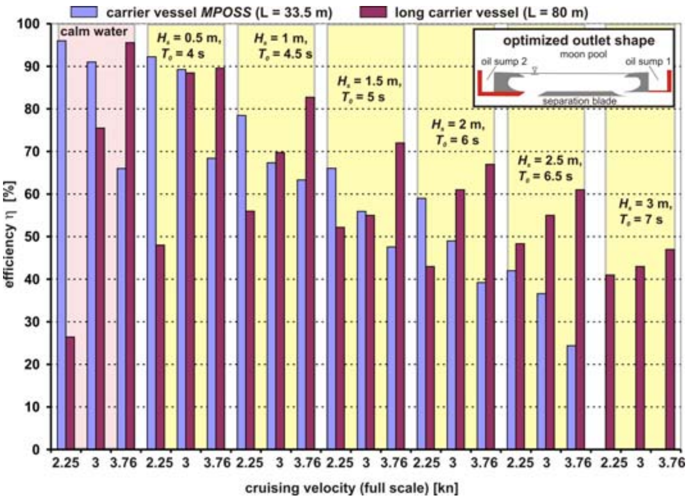

Figure 10. Comparison of the *SOS* efficiency for the carrier vessel *MPOSS* to a carrier vessel of 80 m length

The larger carrier vessel with its corresponding seakeeping characteristics is clearly yielding better efficiencies in higher sea states. At H_s = 2.5 m, an efficiency of 61 % is achieved and at H_s = 3 m (this and all subsequent properties are related to full scale) 47 % is observed. Due to the greater draught of the long carrier vessel (T = 3.5 m), backwater effects are occurring in front of the bow at cruising velocities of $v < 3$ kn, preventing the oil from flowing to the separation blade. Hence, the operating velocity for this configuration has to be higher – an optimum is observed at $v = 3.75$ kn. On basis of these results, the *SOS* is integrated into the carrier vessel *FUTURA TANKER* (length 109.8 m). The investigations conducted for this concept are presented in the following sections.

4 INTEGRATION OF THE *SOS* INTO A *FUTURA TANKER*

Figure 11 (right) shows an impression of a *FUTURA TANKER* (designed by *New-Logistics GmbH*, length 109.8 m, breadth 11.45 m, max. draught 3.75 m) with integrated *SOS*. The potentials of such a multi-purpose tankship – which could be operated e.g. as a bunkering vessel – are investigated in the following sections. Since the bow section of the *FUTURA TANKER* is similar to the *SOS* bow (see Figure 11, left), the integration of a skimmer unit would require minimum effort and costs. Further advantages follow from the similar safety regulations for tankers and oil response vessels (i.e. explosion and fire control, oil pumps, heatable oil tanks etc.).

Figure 11. Typical bow section of a *FUTURA TANKER* (left), impression of the *SOS* integrated into a *FUTURA TANKER* (right)

The multi-purpose *FUTURA-SOS* system can be applied for oil transportation as well as oil recovery. The enlarged first tank behind the bow serves as the moon pool with 'mirrored' CUSP design and slope. An adjustable hydraulic separation blade is intergrated into the bottom of the hull.

4.1 *Numerical Analyses*

In order to determine the operational range of the *FUTURA-SOS* system, numerical analyses for different oil types, cruising velocities and draughts are conducted at a model scale of 1:36. All calculations are based on the coupling of RANSE with the VOF method, as described in section 3.1.

Variation of the moon pool length and draught

The influence of the moon pool length on the skimming efficiency is numerically analyzed for a compact moon pool design (L_1 = 12 m, full scale) and an expanded moon pool design (L_2 = 17 m) for calm water conditions and different cruising velocities.

The comparison of both designs in Figure 12 shows consistently better results for the expanded moon pool version (L_2). This can be explained by the fact that for the compact design (L_1), the vortex stretches across the entire moon pool, transporting oil particles in large part back into the main flow. For the expanded design, the oil particles are already ascending towards the free surface in the fore region of the moon pool, from where they are subsequently transported to the slopes.

Further investigations with the expanded moon pool design reveal an efficiency of $\eta > 80$ % for diesel oil ($\rho = 830$ kg/m^3, $\mu = 0.0034$ Pa s) and operational velocities of $v > 2$ kn, while the efficiency for heavy fuel oil is decreasing below 35 % for higher velocities. Low operational velocities ($v < 2$ kn) in combination with great draughts (here: T_{max} = 3.75 m) are causing backwater effects, i.e. oil of low density is flowing sideways around the bow and cannot enter the moon pool. Due to these effects, the skimming efficiency for diesel oil and $v < 2$ kn is decreasing to $\eta = 5$ %. Thus, the operational velocity of the multi-purpose *FUTURA-SOS* system has to be greater than 2 kn in light oil types. From the numerical analyses with both oil types, an optimum velocity of v = 3 kn can be suggested. Nevertheless, the velocity should be adjusted to the respective type of oil in order to achieve a maximum efficiency.

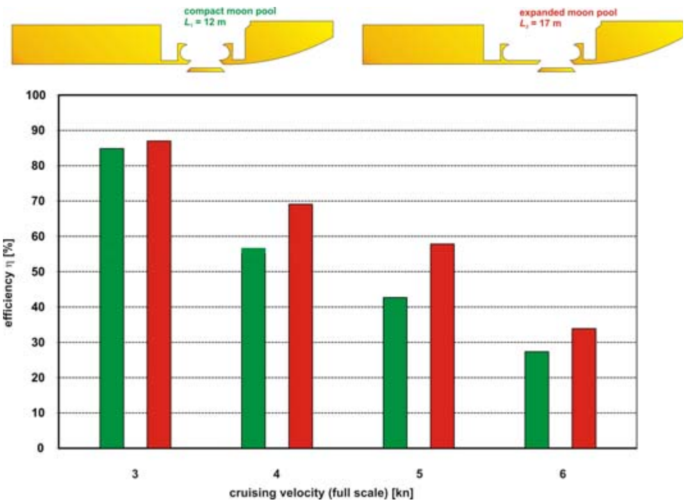

Figure 12. Comparison of the expanded (red) and the compact (green) moon pool variant for different cruising velocities in calm water

Inclination of the separation blade

Another parameter that is investigated is the inclination angle of the separation blade. So far, the planar blade ($\alpha = 0°$) was considered exclusively. Additional simulations with the separation blade inclined by 2.5° are conducted with the expanded moon pool design and heavy fuel oil as well as diesel oil at a draught of 3.75 m. A comparison of both blade variants in calm water is shown in Figure 13.

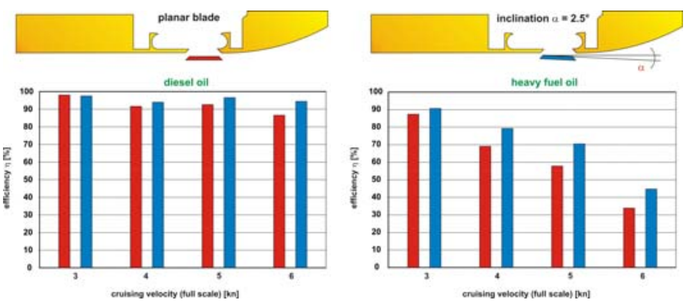

Figure 13. Comparison of the planar ($\alpha = 0°$, red) and the inclined ($\alpha = 2.5°$, blue) separation blade for diesel (left) and heavy fuel oil (right)

The advantages of the inclined blade are particularly articulated for heavy fuel oil, where the efficiency increases from 58 % for the planar design to $\eta = 70$ % for $\alpha = 2.5°$. The inclined blade deflects the heavy oil particles towards the free water surface of the moon pool, and thus they cannot be transported back into the main flow.

5 CONCLUSIONS

This paper presents the Sea state-independent Oil Skimming system (*SOS*) that has been developed at the Technical University Berlin. By various experimental and numerical analyses, the *SOS* unit has been gradually optimized and its performance is investigated for exemplarily integration into the carrier vessels *MPOSS* (model scales 1:15 and 1:9) and *FUTURA TANKER* (model scale 1:36).

The following conclusions can be drawn from the analyses with the *SOS* integrated into the carrier vessel *MPOSS* (see section 3):

- An optimum stable discharge rate at the moon pool inlet is achieved by a ratio of the size of the outlet to the size of the inlet opening of $\lambda = 4$
- A moon pool with 'mirrored' CUSP and slope designs significantly reduces sloshing and stabilizes the vortex
- A fixed coupling between *SOS* and carrier vessel is favourably
- The slope should be adjusted to the respective operational conditions
- For calm water and $H_s < 1$ m, an efficiency of $\eta = 92$-95 % is achieved. In higher sea states ($2 \text{ m} \leq H_s \leq 2.5$ m, $H_{max} = 4.6$ m) η decreases to 42-59 % for an optimum operational velocity of $v = 2.25$ kn

This reduction is caused by increasing wave-induced motions with associated sloshing inside the moon pool and has to be ascribed to the size of the carrier vessel *MPOSS*. A larger carrier vessel (length over all: 80 m, length of skimming unit: 36 m) still achieves $\eta = 47$-68 % in sea states with $2 \text{ m} \leq H_s \leq 3$ m ($H_{max} = 5.6$ m).

Based on these results, the *SOS* is integrated into a *FUTURA TANKER* at a model scale of 1:36. The potential of this multi-purpose concept (oil transport and oil spill response, see section 4) is analyzed numerically. The following conclusions can be drawn from these calculations:

- Due to the evolving flow patterns, the expanded moon pool design (length 17 m, full scale) performs better than the compact version (length 12 m, full scale)
- The operational velocity of the system has to be adapted to the density of the spilled oil

($v \geq 3$ kn) in order to avoid draught-dependent backwater effects

- Inclining the separation blade by $\alpha = 2.5°$ leads to a further enhancement of the efficiency – in particular for heavy fuel oil
- For an optimum operational velocity of $v = 3$ kn, an efficiency of $\eta > 90\ \%$ is achieved for diesel as well as heavy fuel oil in calm water.

In summary, it was shown that the optimized *SOS* – both integrated into the carrier vessels *MPOSS* and *FUTURA TANKER* – achieves excellent efficiencies in calm water and rough seas for light as well heavy oil types.

6 PERSPECTIVES

On the basis of the results from the investigations conducted so far, continuative experimental and numerical research is planned. The focus of this work is the development and optimization of an autonomous carrier system with integrated *SOS* unit (see Figure 14).

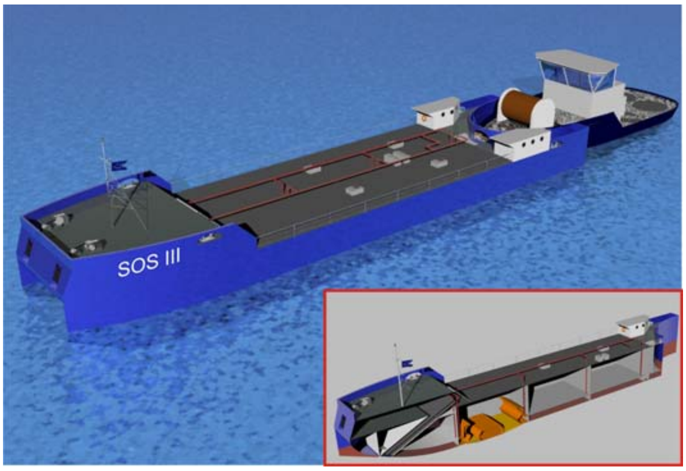

Figure 14. Impression of an autonomous carrier system with integrated *SOS*

Such a system could be powered by a tug or moored as an oil barrier e.g. in rivers. The central point of this concept is a new mechanism for minimizing the amount of water sloshing over the slope into the oil sumps and thus enhancing the efficient usage of the onboard storage tanks. So far this problem, as well as the issue of the dynamically changing draught during oil intake, was solved by height adjustment of the slopes. Dynamic ballasting systems could also be an appropriate measure, but the main drawback of these solutions is their technical complexity and the space that is required aboard the carrier vessel – at the cost of oil storage volume. Therefore, the new concept consists of a hermetically closed moon pool with pressure regulation and a flap system with separate inlet and outlet flaps (see Figure 15) – both features are already applied for German patents (German Patent and Trademark Office, 2008). The flaps can be designed hinged and either open outward or inward or they can be constructed to slide sideward. Their specially designed tips induce and stabilize the vortex inside the moon pool, making the complex CUSP structures redundant. Instead of the adjustable separation blade proposed so far, the new concept also comprises a fixed bottom plate as integral part of the hull structure.

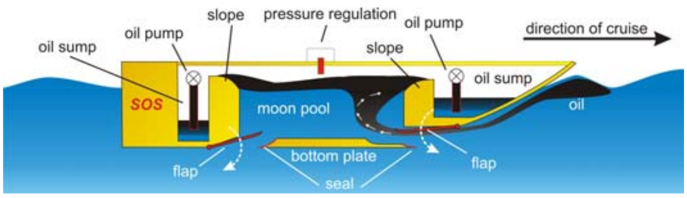

Figure 15. Schematic sketch of the new *SOS* concept featuring a hermetically closed moon pool and a flap system

When the pressure inside the enclosed moon pool is increased, the water level will be reduced by Δh and the draught of the carrier vessel by ΔT, where the magnitude of ΔT depends on the design of the vessel. Contrariwise the water level is going to rise when the pressure inside the moon pool is decreased. With this robust and economical approach, a controlled flow rate into the oil sumps, independent from operational conditions, is provided. The key advantages of the new system are:

- The completely encapsulation of the moon pool together with the hazardous oil layer and hence reduction of the risk of explosions or fires
- Additional space due to the continuous deck
- Video surveillance and remote controlling of the pressure level from the bridge
- Better discharge control by individual adjustment of the ratio λ (length of outlet to inlet opening)
- Less force required for opening and closing of inlet and outlet
- Fixed bottom plate shelters moon pool from hydrodynamic pressure of the sea
- Improved hull strength
- Simplified geometry (no CUSPs)
- Fast pressurization of the moon pool in survival mode

The consideration of viscous effects and the physical properties of the materials involved in the oil skimming process with the consequences on the economics of the *SOS* design (e.g. minimum dimensions required for the moon pool) provide further research potential.

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