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Analysis of the impact of selected hydrometeorological conditions on the accuracy of oil spill simulations on the PISCES II simulator

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Abstract

Computer simulations used for predicting the behavior of oil spills at sea allow optimizing the deployment of oil spill response personnel and resources, and using the backtracking method to identify the polluter in cases where spills are sighted some time after they occurred. Predicting the direction and speed of oil slick spreading is of fundamental importance. An attempt was made to verify the influence of selected simulation parameters, related to hydrometeorological conditions, on the behavior of the resulting oil pollution. Different responses were obtained under the same simulated weather conditions, depending on the type of spilled oil. The experiment was conducted on a PISCES II oil spill simulator.

Crude oil characterization

Crude oil is the product of various chemical, biochemical, and geological processes; although dead plant and animal organisms are also present in low amounts, its main components are carbon, hydrogen, oxygen, sulfur, and nitrogen (wiedza.diaboli.pl, 2015).Crude oil is made up of many types of hydrocarbons, such as alkanes, cycloalkanes, aromatics and other hydrocarbons with mixed structures, as well as heterocompounds with sulfur, oxygen, and metals.

The dominant group is represented by cycloparaffinic hydrocarbons, also referred to as cycloalkanes, or naphthenes. They represent an average of 50% of the total mass. Cycloparaffins are less volatile substances than paraffins, as they have a higher boiling point. Their density is greater than that of paraffin analogs, and therefore their content in oil is significant. Paraffinic hydrocarbons, or alkanes, are the second largest group present in crude oil, prevailing in the low-boiling point (petrol) oil fractions. Aromatic hydrocarbons are present in crude oil in amounts up to 15% by mass, usually concentrated in high-boiling point oil fractions, such as oil distillates and in vacuum distillation residues (Total, 2003; Politechnika Wrocławska, 2015).

Depending on its age, crude oil may contain resins and asphaltenes; trace amounts of the latter are found in oils of older geological ages, whereas their concentration, by mass, in younger oils may reach a few percentage points. Sulfur compounds, occurring in all types of crude oil, range from 0.01 to 8% by mass. Oils with high sulfur concentrations are characterized by a higher density (węglowodory.pl, 2010; Politechnika Gdańska, 2015).

In terms of sulfur content, the following types of crude oil are distinguished:

- low-sulfur;
- medium-sulfur;

- sulfur;
- high-sulfur.

The classification of crude oil is based on the results of laboratory tests, in which its physical and chemical properties are determined. Some of these properties are:

- **density**;
- **sulfur content**;
- chloride content;
- water and particulate matter content;
- trace elements content;
- **viscosity** and pour point;
- **fractional composition** (characteristic distillation);
- vapor pressure;
- acid number;
- carbon residue;
- asphaltene content;
- paraffin content;
- total nitrogen content.

The most important parameters characterizing the properties of the oil are: density, viscosity, pour point, volatility, and sulfur content (Politechnika Wrocławska, 2015).

Density

Density is one of the basic physical properties, expressed as the ratio between mass and volume of the substance and measured in kg/m^3 or g/cm^3. Relative density is the most commonly used concept, and is defined as the ratio, at a fixed temperature, between the densities of a given substance and a reference material. Water is normally taken as reference, at temperatures of 4, 15, or 200ºC. Relative density is a dimensionless quantity (Total, 2003; Politechnika Wrocławska, 2015).

The unit of density commonly used in the oil industry is the API degree (*American Petroleum Institute*). The scale is based on measurements of relative liquid density, measured at 60 ºF (15.6°C) and with reference to water.

Density is a function of the chemical composition of crude oil. A high content of paraffinic hydrocarbons, for example, leads to a liquid with a lower density compared to one with high content of aromatic hydrocarbons. Density also increases with the content of sulfur, nitrogen, and asphaltenes. Crude oils traded on the world market tend to have a density in the range of 0.8–1.0 g/cm^3 (Nafta polska, 2015; wiedza.diaboli.pl, 2015).

Density is one of the criteria for the classification of crude oil. In this respect, crude oils are divided into:

- light;
- medium;
- heavy.

According to the API criterion, light oils have an API gravity above 38°, although some sources consider the threshold to be 47° API; medium crude oils have an API gravity ranging from 22 to 38°; and heavy crudes have a gravity below 22 or 20° (Total, 2003; Jewulski, 2006; IMO, 2015; Politechnika Gdańska, 2015; Politechnika Wrocławska, 2015).

Viscosity

Viscosity is another major property of crude oil. In some respects, it is the most important parameter because it determines the mobility of oil during transport, pumping, and after spillage into the ground or water.

Viscosity is a measure of liquid flow resistance and may be distinguished in dynamic and kinematic, also referred to as kinetic or absolute. The SI units of measurement for viscosity are:

- dynamic viscosity – 1 Pas, 1 mPas;
- kinematic viscosity – 1 mm^2/s.

In the CGS system, the unit of dynamic viscosity is the poise (P).

$$1\ \mathrm{P} = 1\ \mathrm{dyn{\cdot}sec/cm^2} = 1\ \mathrm{g{\cdot}cm^{-1}{\cdot}s^{-1}} = 0.1\ \mathrm{Pa{\cdot}s},$$

while kinematic viscosity is expressed in stokes (St), although the use of centistokes (cSt) is widespread. The correlations between these units are as follows:

$$1\ \mathrm{St} = 10^{-4}\ \mathrm{m^2/s};$$

$$1\ \mathrm{cSt} = 1\ \mathrm{mm^2/s}$$

(1 cSt: viscosity of water at temp. 4ºC).

Similarly to density, crude oils with a greater proportion of paraffinic hydrocarbons have lower viscosity, while higher viscosity is characteristic of crude oils with a large amount of aromatic hydrocarbons. The viscosity of crude oil varies widely depending on its grade (Total, 2003; Politechnika Gdańska, 2015; Politechnika Wrocławska, 2015).

Pour point

Pour point is the lowest temperature at which fluidity of a material is still observed, in standard conditions. The value of pour point depends on the composition of the oil. Aromatics and cycloparaffinic hydrocarbons have a higher pour point than their paraffinic counterparts (Politechnika Wrocławska, 2015).

Volatility

Volatility of crude oil is another important technological parameter. The assessment of an oil's volatility is carried out using three parameters: fractional composition, content of gaseous hydrocarbons (C1–C5), and vapor pressure. In order to characterize the composition of volatile products (liquid fuels, solvents, and other operational liquids), their fractional composition is often tested. Fractional composition is the relationship between the distillation temperature and the share of distilling components in the product at that temperature, under standard conditions. This relationship is identified by choosing a number of temperatures in correspondence of which a specific volume percentage of the product will be distilled, or by determining the percentage of product volume that will be distilled until a specific temperature is reached (Total, 2003; Politechnika Wrocławska, 2015).

The distillation temperatures of crude oil offered on the global markets start and end around 25–30ºC and 520–560ºC, respectively. The fractions of oil boiling in the range 30–360ºC (fuel fractions: naphtha, kerosene, diesel oil) are distilled at atmospheric pressure; the others, boiling at 360–560ºC, are distilled under reduced pressure.

In the process of distillation, crude oil is generally divided into the following fractions (boiling ranges are approximate):

1. During distillation at atmospheric pressure
   - light naphtha (C5): 80°C;
   - heavy naphtha: 80–180°C;
   - kerosene (jet fuel): 180–250°C;
   - diesel oil: 250–360°C;
   - atmospheric residue (heavy fuel oil) > 360°C.
2. During vacuum distillation
   - vacuum distillate: 360–550°C;
   - vacuum residue: > 550°C.

The classification of crude oil based on the content of light fractions (distilling up to 360ºC) is bead on four levels (Politechnika Wrocławska, 2015):

- low content of light fractions: < 25%;
- average content in the light fractions: 25–50%;
- high content of light fractions: 50–70%;
- very high content of light fractions: > 75%.

Simulations

Simulations were performed on a PISCES II oil spill simulator (Transas, 2008). The simulator allows modelling of oil pollution, including: dispersion in the water, evaporation, and sinking under the influence of simulated hydrometeorological conditions. We can conduct simulations of oil clearance operations in which the use of personnel and resources, available for combating oil pollution, is envisaged. The meteorological conditions that can be simulated include air and water temperatures, wind direction and speed, sea state, and parameters of currents. All of these data can be dynamically modelled during the simulation. The results can be recorded and then analyzed.

During the experiment, three types of oil were tested: light Bent Horn, medium Arabian, and heavy Belridge, with the aim of determining their behavior in different weather conditions. The characteristics of these oils are presented in Table 1.

Table 1. Characteristics of the types of oil used during the experiment (data from the simulator PISCES II (Transas, 2008)

Fuel Feature	Bent Horn	Arabian	Belridge
group	II	3.	4.
density	41.3 [API]	27.4 [API]	13.6 [API]
surface tension	53.5 [dyne/cm]	20 [dyne/cm]	20 [dyne/cm]
viscosity	29.3 [cSt]	271 [cSt]	12 931 [cSt]
maximum content	70%	70%	70%
emulsification constant	0%	0%	0%
pour point	–18 [ºC]	–28 [ºC]	2 [ºC]
flash point	–9 [ºC]	36 [ºC]	90 [ºC]

The experiment consisted in the simulation of a spillage of 400 tons of crude oil with wind at a constant speed of 15 m/s and a direction of 180º. The variable was represented by the sea state, for which the values of 0, 3, 5, and 8ºB were studied over 72 hours. Four simulations were made for each type of oil, for a total of 12 simulations.

Simulation 1 – sea state 0ºB (Table 2 and Figure 1)

The simulations were performed over 72 hours and the oil spill was considered to take place gradually, releasing to the sea 40 tons of oil every 0.5 hours, for 5 hours. During the time following the spill, movement, evaporation, and dispersion of oil slicks were observed. The spillage data were recorded automatically every 15 minutes.

The recorded data (Table 2) shows that at sea state 0ºB the evaporation of light oil fractions was

Table 2. Summary of simulated spill of oil after 72 hours, at sea state 0°B

Indicator name		Type of spilled oil					
		Bent Horn (light)		Arabian (medium)		Belridge (heavy)	
		Quantity	Percentage	Quantity	Percentage	Quantity	Percentage
1	amount of spilled oil	394 [t]	100%	394 [t]	100%	394 [t]	100%
2	amount of floating oil	73.4 [t]	18.7%	147 [t]	37.30%	266 [t]	67.60%
3	amount of evaporated oil	92.1 [t]	23.4%	126 [t]	32%	51.6 [t]	13.10%
4	amount of dispersed oil	228 [t]	57.9%	121 [t]	30.70%	75.8 [t]	19.30%
5	amount of emulsified oil	270 [t]		517 [t]		905 [t]	
6	maximum thickness of the slicks	1.0 [mm]		1.3 [mm]		3.6 [mm]	
7	area of spilled oil slick	1.5 [km^2]		2.2 [km^2]		2.6 [km^2]	
8	viscosity	4276 [cSt]		119 153 [cSt]		758 756 [cSt]	

Table 3. Summary of simulated spill of oil after 72 hours, at sea state 3°B

Indicator name		Type of spilled oil					
		Bent Horn (light)		Arabian (medium)		Belridge (heavy)	
		Quantity	Percentage	Quantity	Percentage	Quantity	Percentage
1	amount of spilled oil	394 [t]	100%	394 [t]	100%	394 [t]	100%
2	amount of floating oil	68.3 [t]	17.4%	147 [t]	37.50%	266 [t]	67.60%
3	amount of evaporated oil	90.2 [t]	22.9%	126 [t]	32%	51.3 [t]	13%
4	amount of dispersed oil	235 [t]	59.7%	120 [t]	30.50%	76.2 [t]	19.40%
5	amount of emulsified oil	251 [t]		519 [t]		905 [t]	
6	maximum thickness of the slicks	1.1 [mm]		1.3 [mm]		6.1 [mm]	
7	area of spilled oil slick	1.3 [km^2]		2.2 [km^2]		2.5 [km^2]	
8	viscosity	4072 [cSt]		118 730 [cSt]		752 589 [cSt]	

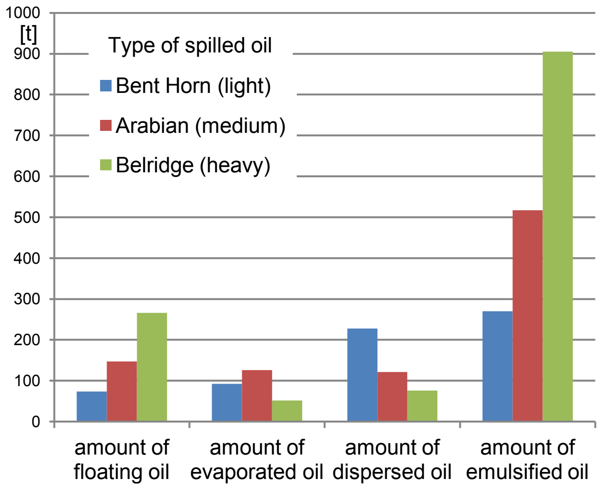

Figure 1. The simulation results for spills of different type oils at sea state 0°B

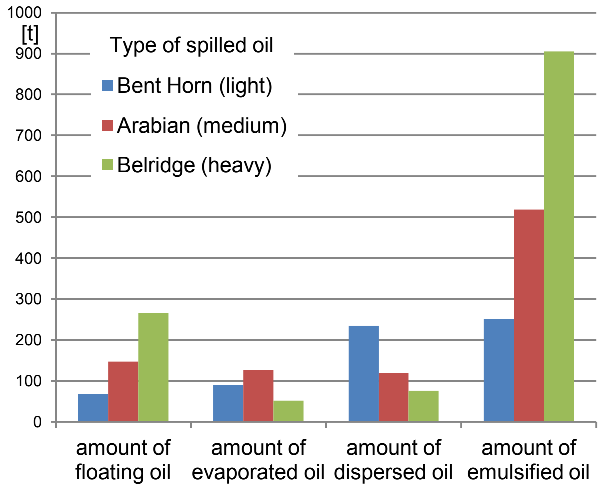

Figure 2. The simulation results for spills of different types of oil, sea state 3°B

most significant for the medium crude, and least significant for heavy crude. The medium weight crude oil was characterized by more extensive dispersion in comparison to the other crudes. The maximum thickness was observed in a slick of heavy crude oil, while light crude oil presented the thinnest slick. The comparison of oil slick areas gave similar results for all the three crudes tested.

Simulation 2 – sea state 3°B (Table 3 and Figure 2)

The simulation conditions adopted here were the same as those previously described, with the only difference of having studied the condition of a 3°B sea state. As it follows from Table 3, light crude oil was subject to the largest evaporation and dispersion, similarly to the case discussed above.

Table 4. Summary of simulated spills of oil after 72 hours, at sea state 5°B

	Indicator name	Type of spilled oil					
		Bent Horn (light)		Arabian (medium)		Belridge (heavy)	
		Quantity	Percentage	Quantity	Percentage	Quantity	Percentage
1	amount of spilled oil	394 [t]	100%	394 [t]	100%	394 [t]	100%
2	amount of floating oil	69.6 [t]	17.7%	151 [t]	38.40%	268 [t]	68%
3	amount of evaporated oil	90.9 [t]	23.1%	125 [t]	31.80%	50.8 [t]	12.90%
4	amount of dispersed oil	233 [t]	59.2%	117 [t]	29.80%	74.7 [t]	19.10%
5	amount of emulsified oil	256 [t]		532 [t]		912 [t]	
6	maximum thickness of the slicks	0.8 [mm]		1.3 [mm]		4.4 [mm]	
7	area of spilled oil slick	1.4 [km^2]		2.2 [km^2]		2.6 [km^2]	
8	viscosity	4148 [cSt]		116 648 [cSt]		741 555 [cSt]	

Table 5. Summary of simulated oil spill after 72 hours, at sea state 8°B

	Indicator name	Type of spilled oil					
		Bent Horn (light)		Arabian (medium)		Belridge (heavy)	
		Quantity	Percentage	Quantity	Percentage	Quantity	Percentage
1	amount of spilled oil	394 [t]	100%	394 [t]	100%	394 [t]	100%
2	amount of floating oil	71.1 [t]	18.1%	154 [t]	39.20%	268 [t]	68%
3	amount of evaporated oil	91.7 [t]	23.3%	125 [t]	31.80%	50.7 [t]	12.9%
4	amount of dispersed oil	231 [t]	58.6%	114 [t]	29%	75.4 [t]	19.1%
5	amount of emulsified oil	261 [t]		543 [t]		910 [t]	
6	maximum thickness of the slicks	0.7 [mm]		1.7 [mm]		4.2 [mm]	
7	area of spilled oil slick	1.5 [km^2]		2.1 [km^2]		2.4 [km^2]	
8	viscosity	4230 [cSt]		116 825 [cSt]		739 363 [cSt]	

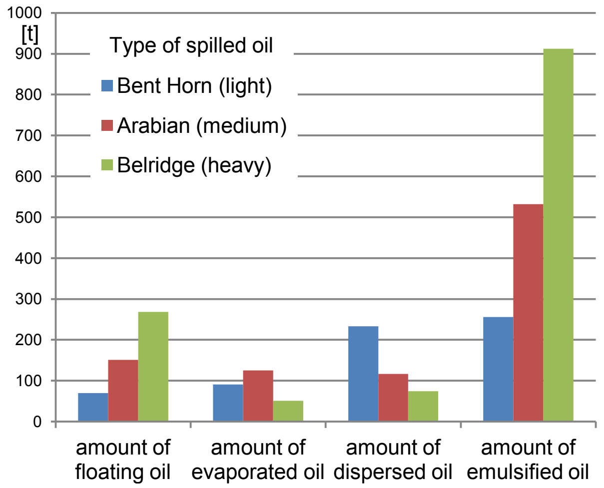

Figure 3. The simulation results for spills of different types of oil at sea state 5°B

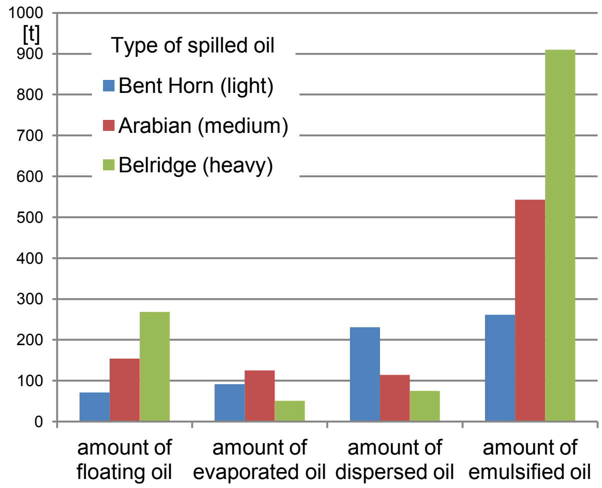

Figure 4. The simulation results for spills of different types of oil at sea state 8°B

The other parameters also behaved similarly to simulation 1.

Simulation 3 – sea state 5°B (Table 4 and Figure 3)

The simulation was conducted for sea state 5°B. As Table 4 shows, despite the changed state of the sea, all the measured phenome yielded results in line with those obtained in the previous simulations.

Simulation 4 – sea state 8°B (Table 5 and Figure 4)

The simulation was performed for the sea state 8°B. All the tested parameters remained similar to those of the previous simulations.

Analysis of the results of simulation

The presented simulation results show that the volatile components of crude oil are lost very quickly through evaporation. The highest percentage of components evaporates within the first hours of the oil spill, which could be seen by analyzing statistical data from simulations and diagrams, observing the relationships between evaporation and dispersion of spills. With the assumptions made (sea state, wind force and direction), medium crude oil (Arabian) featured the highest amount of evaporated light fractions (about 32%), Bent Horn oil evaporation reached approximately 23%, whereas only a little over 13 % of heavy Belridge oil evaporated.

In the course of time, after evaporation of its more volatile components, part of the spilled oil sinks into the sea. This part of the oil spreads on the surface of water at a speed that depends on the type and properties of the chemical compounds and on environmental conditions (wind force, sea state, ambient temperature, etc.). Light petroleum fractions spread rapidly, whereas heavy oils tend to aggregate into lumps. The speed with which oil spreads is greatest in the initial phase, and decreases significantly when the thickness of the layer decreases to a few millimeters (Politechnika Wrocławska, 2015). The simulation data show that the fastest spreading oil was Bent Horn light oil, of which approximately 59% was scattered. Heavy oil slowly scattered in the water and its amount fluctuated around 19%.

Evaporation of lighter oil fractions is proportional to slick area size and shear forces. The oil slick surface area in the simulations was greatest in case of heavy crude oil − 2.4 to 2.6 km^2, and lowest for light crude oil, varying from 1.3 to 1.5 km^2.

Examples of recorded oil dispersion and evaporation processes on the sea surface are shown in Figures 5 and 6. These examples refer to sea state 0ºB, but for all other test conditions these two phenomena were found to have similar behavior. It can be concluded that both the dispersion and evaporation of oil depend, to a small extent, on the sea conditions that can be considered using the PISCES II simulator.

After evaporation of light components, the viscosity of residual fractions increases. The highest viscosity was recorded in the simulations at sea state 0°B for each type of crude oil. Light crude oil had the lowest viscosity at sea state 3°B, medium crude oil at sea state 5°B, and heavy crude oil at 8°B.

The rate of spreading is also affected by the formation of and oil-in-water emulsion, having a viscosity greater than the one of the oil. Spilled oil can quickly be dispersed in seawater, forming a hard breakable emulsion with a water content of 40–80%. The formation of the emulsion is accompanied by a significant increase in viscosity. Emulsification is a result of shear forces: rougher sea conditions lead to faster (IMO, 2015; Politechnika Wrocławska, 2015).

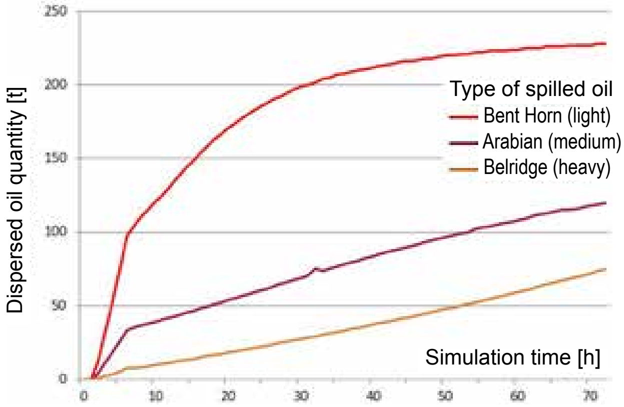

Figure 5. Rate of dispersion of oil in the simulation depending on oil type at sea state 0ºB

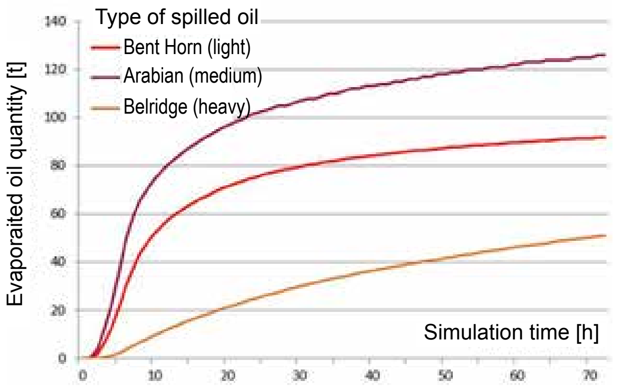

Figure 6. Rate of evaporation of oil in the simulation depending on oil type at sea state 0ºB

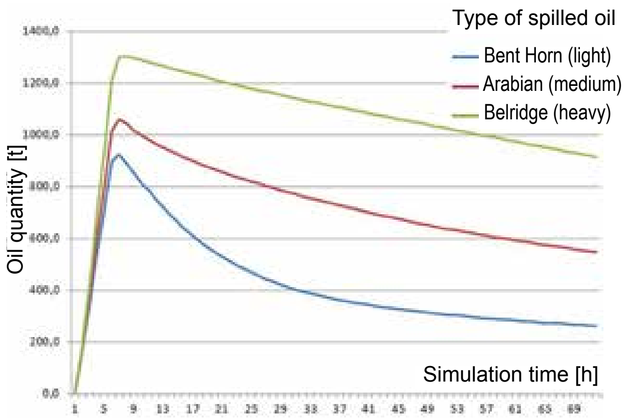

Figure 7. Emulsification of different types of oil spills at sea state 8ºB

Petroleum hydrocarbons may undergo biodegradation, which occurs a few days after spillage. The degree of biodegradation of oil depends on the complexity of its chemical structure; the presence of suitable nutrients, mainly nitrogen, phosphorus, oxygen; and temperature. Biodegradation occurs at the oil-water interface. The solubility of oil in water is very low, and therefore the amount of oil lost in this way is small. Part of the oil may, however, be dissolved by photo-oxidation. Factors promoting the process are sunlight and the presence of oxygen. The end result is directly proportional to the surface of the oil film itself, and the process itself is very slow (IMO, 2015; Politechnika Wrocławska, 2015).

The area of spilled oil coverage differs according to the type of oil used in the simulation. At the end of the simulation, the smallest surface area was covered by light crude oil for all simulated sea states, because comparably more of that oil had evaporated. Besides, the spill extends to its maximum surface area in the shortest amount of time (case shown in Figure 8), namely after about 28 hours of simulation.

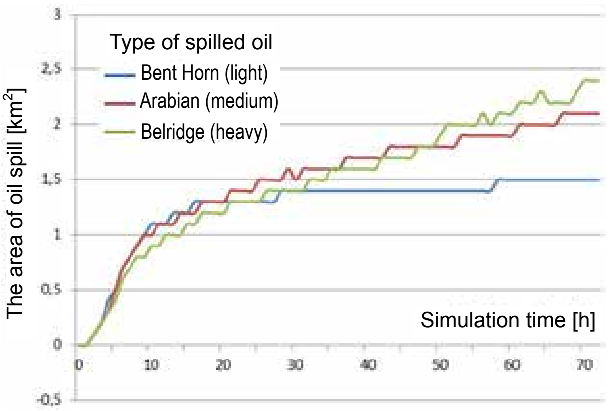

Figure 8. The water surface area covered with an oil slick during the simulation at sea state 0°B

Conclusions

The simulation results confirm the influence of the parameters such as density, viscosity, evaporation, dispersion, and volatility on the manner in which oil slick spreads on the sea surface. The study of the behavior of different types of crude oil during the simulation has revealed that the sea state had no significant effect on the way crude oil spreads on the water or on the evaporation of light fractions; however, we can observe that the sea state affects the viscosity of the tested oil. Emulsification becomes faster as wave action increases, which was most evident in simulations carried out on medium and heavy crude oil.

The shape and thickness distribution of an oil slick in the first stage (from a few to tens of hours) depends mainly on weather conditions, particularly wind and currents. The wind spread and elongated oil spills, finally divided into streaks that would further undergo fragmentation. At this stage the evaporation of light fractions of oil occurred, while on subsequent days biodegradation took place.

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