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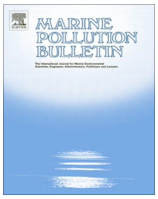

Water–oil separation performance of technical textiles used for marine pollution disasters

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ABSTRACT

Oil is principally one of the most important energy sources in the world. However, as long as oil is explored and transported for being used, there will be the risk of the spillage into the marine environment. The use of technical textiles, i.e. fibrous beds, is a conventional separation technique for oil/water emulsion since it is efficient and easy to design. In this paper, the recovery of oil by technical textiles was mathematically modeled based on the structural parameters of textile and the capillary mechanism. Eleven types of commercial technical textiles with different properties were prepared for the experimental program. The experimental design included fiber type (polypropylene and polyester), fabric type (woven and/or nonwoven), fabric thickness and fabric areal density. Consequently, the absorption capacities of different technical textile samples were derived by the use of theoretical and experimental methods. The results show that there is a well fitness between theoretical outputs and experimental data.

1. Introduction

Oil is one of the most important energy sources in the world. However, as long as oil is being explored and transported for different uses, there will be the risk of the spillage into a marine environment. Consequently, the spilled oil is subject to several processes including spreading, drifting, evaporation, dissolution, photolysis, biodegradation and/or formation of water–oil emulsions (Daling and Strøm, 1999). Nowadays, conventional separation techniques for oil/water emulsion include gravity settlers (Sadeghi et al., 2011), chemical methods (Yuan et al., 2011) and physical approaches. The physical methods are involved with using electric field (Ichikawa et al., 2004), acoustical (Pangu and Feke, 2004), centrifugal (Cambiella et al., 2006), air flotation (Al-Shamrani et al., 2002), porous medium filtration and coalescence including porous beds (Huang and Lim, 2006) and membranes (Chakrabarty et al., 2010). Coalescence of oil droplets in fibrous beds and membranes is efficient and easy to design (Shuo et al., 2012).

The application of natural fibers, such as cotton (Deschamps et al., 2003), cotton grass fiber (Suni et al., 2004), milkweed, kenaf (Choi and Cloud, 1992), vegetable fibers (Annunciado et al., 2005), silk (Moriwaki et al., 2009) and wool (Radetic et al., 2003, 2008), as the material for the removal of oil from the sea water has so far been investigated by different researchers. Nonwoven Textiles contain small pores which facilitate the transport of liquids into the sorbents and retain the liquids after sorption (Nederveen, 1994). On the whole, natural fibers have been generally used for oil-spill cleanups (Choi and Cloud, 1992), but they also possess high water sorption, when used in the marine environment. By contrast, polypropylene (PP) fibers have higher oil-sorption capacity with very much lower uptake of water (Schrader, 1993). Moreover, PP fiber is lighter than fresh or sea water and will float on it. Polypropylene is the ideal material for marine oil-spill recovery due to its low density, low water uptake and excellent physical and chemical resistance.

Wei et al. (2003) evaluated different forms of PP nonwoven sorbents in terms of initial oil-sorption capacities and oil-retention properties. They found that fiber diameter, sorbent porosity and oil property are the most important factors in the oil-sorption performance of PP nonwoven sorbents.

Brochard (1986) derived a critical spreading parameter for complete fiber wetting transition. He proved that liquids are more willing to wet planes than to individual fibers of the same material, due to the cylindrical shape of a fiber.

Konishi et al. (2005) examined performance of a hydrophobic Polytetrafluoroethylene (PTFE) tubular membrane for the separation of oil which was mixed with a kind of bacteria. Their microscopic observation confirmed that the recovered oil was essentially free of bacterial cells.

Moriwaki et al. (2009) concluded that waste silk fibers show a high performance as a low cost and environmental friendly sorbent

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for the removal of oil from water. Their results show the high sorption capacity of silk fibers, e.g. 42–52 $g_{oil}/g_{sorbent}$ for motor oil and 37–60 $g_{oil}/g_{sorbent}$ for vegetable oil.

It has been proved that recycled wool shows high sorption capacity for different kinds of oil. This material also exhibited excellent buoyancy after 24 h of sorption as well as a good reusability, and this was because the decrease in sorption capacity did not exceed 50% of the initial value after five sorption cycles in oil without water (Radetic et al., 2008). Zhang et al. (2012) demonstrated that non-woven textiles and polyurethane sponges, functionalized by grafting a block copolymer as a smart surface can be used for highly controllable oil/water separation processes.

Recently, Kulkarni et al. (2012) have used glass and polyester fibers to fabricate oil–water separator filters. The experimental results show that the hybrid glass/polyester layers reduce the pressure drop significantly and improve the filter performance compared to media fabricated with only glass fibers.

As it can be seen a brief literature review shows that although broad research has been carried out on technical textiles used for oil–water separation, a comprehensive model to simulate capillary flow through textile based on constructive parameters is still lacking.

2. Modeling of mechanical recovery of oil by technical textiles

In this section, the mechanical recovery of oil by technical textiles will be investigated by the use of a mathematical model. The model has been developed based on the structural parameters of the textile and the capillary mechanism. Researchers have principally described the liquid transport through the textile by Darcy's law (Rahli et al., 1997) and/or capillary tube theory (Benltoufa et al., 2008). In capillary flow through the textile fabrics, the constituent yarns are responsible for the main portion of the wicking action (Hollies et al., 1956). Since textile materials are "porous media", wicking in textiles is really a very complicated, multi-faceted phenomenon (Benltoufa et al., 2008). A "porous media" means a solid of an unspecified form delimiting and including vacuums called "pores" filled with fluid (Benltoufa et al., 2008; Oxarango, 2004). It is clear that the wicking taking place in a textile material depends on the internal geometry of the structure. Therefore, a new index entitled "porosity" should be defined as being the volumetric ratio of the pores accessible V_a by total volume of the material V_t:

$$\varepsilon = V_a/V_t \tag{1}$$

Analyzing the technical textile structures, one can observe two porosity scales: macro pores and micro pores. The former means vacuums between yarns in the structure, while, the later includes vacuums between the fibers within the yarn as shown in Fig. 1.

It is important to know that the textile structures are divided in to two categories including woven and nonwoven fabrics. Woven (also includes knitted and braided) fabrics are made from yarns, while nonwovens are directly formed by entanglement of fibers. Therefore, both micro and macro pores exist in the woven fabrics. Nonwovens and/or fibrous bed structures are clearly comprised of macro pores. These two kinds of pores are discussed in the following.

2.1. Micro pore modeling

The micro pores cause micro porosity. The micro porosity ε_{mi} in the yarn is defined as:

$$\varepsilon_{mi} = 1 - (V_{Tf}/V_Y) \tag{2}$$

where V_{Tf} and V_Y are the total volume of fibers within the yarn and the volume of the yarn, respectively. Some simplifications are required for the purpose of geometrical modeling. Therefore, it is assumed that the yarn within a sample fabric ($L \times L$) has a circular cross section and uniform diameter d_Y. Moreover, the intrinsic voids can be neglected on the surface of the fibers. If N_f circular fibers with uniform diameter d_f exist within the yarn, V_{Tf} will be:

$$V_{Tf} = \pi N_f \times d_f^2 \times L/4 \tag{3}$$

In addition, V_Y can be obtained through:

$$V_Y = \pi d_Y^2 \times L/4 \tag{4}$$

It can be concluded from Fig. 2 that:

$$d_Y = T/2 \tag{5}$$

where T is the fabric thickness. Consequently, Eq. (4) changes to:

$$V_Y = \pi T^2 \times L/16 \tag{6}$$

As shown in Fig. 2, the fiber diameter d_f can be calculated based on fiber density ρ_f and fiber denier D_f in accordance with:

$$D_f = \pi \times d_f^2 \times 900000 \times \rho_f/4 \tag{7}$$

Fiber denier D_f is the mass (g) of 9000 m fiber and/or yarn. Thus:

$$d_f^2 = 4 \times D_f/\pi \times 900000 \times \rho_f \tag{8}$$

By substituting Eq. (8) in Eq. (3), we have:

$$V_{Tf} = N_f \times D_f \times L/900000 \times \rho_f \tag{9}$$

By merging Eqs. (6) and (9) with Eq. (2) we get:

$$\varepsilon_{mi} = 1 - (5.7 \times 10^{-6} \times N_f \times D_f/(\rho_f \times T^2)) \tag{10}$$

2.2. Macro pore modeling

As it was mentioned the macro pore includes the macro canals and/or voids within the fabric structure. To calculate the macro porosity ε_{ma} consider a fabric specimen with the thickness of T, surface area of A and mass of m. Using Eq. (1), ε_{ma} will be:

$$\varepsilon_{ma} = V_a/V_t = 1 - V_s/V_t \tag{11}$$

where V_s is the volume of the constitutive solid polymer. Consequently, V_s can be calculated through:

$$V_s = m/\rho_s \tag{12}$$

in which ρ_s is the density of solid polymer. In the same way, V_t would be obtained by:

$$V_t = A \times T \tag{13}$$

Substituting Eqs. (12) and (13) in Eq. (11) gives:

$$\varepsilon_{ma} = 1 - m/(A \times T \times \rho_s) \tag{14}$$

2.3. Oil–water separation performance of textile structures

The study of oil absorption in textile structures is possible by considering the capillary force and capillary kinetics of the liquid at equilibrium condition. Since a textile material is a porous media, the capillary progression of a liquid through a textile should be generally described by the Washburn law (Benltoufa et al., 2008). In this way, the channels within a textile structure should be regarded as tortuous capillary tubes with average radius of R and tortuosity τ as shown in Fig. 3. In other words, since the technical textiles used in water–oil separation process are generally nonwovens, i.e. fibrous beds, the capillary progression through the textile

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