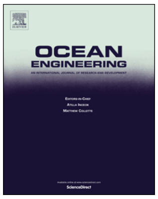
Ocean Engineering ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



A state-of-the-art review of fate and transport of oil spills in open and ice-covered water

Mawuli Afenyo, Brian Veitch, Faisal Khan*

Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Canada, A1B 3X5

ARTICLE INFO

Article history:
Received 4 July 2015
Accepted 8 October 2015

Keywords:
Ice-covered waters
Oil weathering
Oil spill models
Oil spill

ABSTRACT

A state-of-the-art review of fate and transport modelling of oil spills is presented. Emphasis is placed on oil spills in ice-covered waters. The review encompasses advection, spreading, evaporation, dissolution, dispersion, emulsification, biodegradation, encapsulation, sedimentation and photo-oxidation processes. The current understanding of these processes and algorithms to describe and model them are discussed. Quantitative studies of oil spills in open and dynamic ice conditions are also reviewed. The review identifies the current knowledge gaps and future research directions.

1. Introduction

Accidental releases of oil over the years have resulted in the pollution of the marine environment. Notable among them are the collision of the Atlantic Empress and Aegean Captain vessels that resulted in the release of 287,000 tonnes of oil (Hooke, 1997), ABT Summer's explosion that produced a large slick covering a 208 km^2 area (Hooke, 1997), Castillo de Bellver's fire accident that released 60,000 tonnes of light crude oil (Moldan et al., 1985; Wardley-Smith, 1983), the grounding of Amoco Cadiz that released 223,000 tonnes of light crude oil and 4,000 tonnes of bunker oil into heavy seas (Bellier and Massart,1979; Anon., 1978; Spooner, 1978; Conan et al., 1978), and the grounding of the Exxon Valdez that released 37,000 tonnes of Alaska North Slope crude (Rice et al., 1996; Wells et al., 1995; Galt et al., 1991; Loughlin, 1994). During the three months of the BP oil spill in the Gulf of Mexico, approximately 486,000 tonnes of crude oil was released at a water depth of 1520 m (McNutt et al., 2011) and resulted in the pollution of 9900 km^2 of water surface (Wei et al., 2014). BP spent over $30 billion to manage the spill (Visser, 2011).

Traffic in the arctic has increased recently (Arrigo, 2013). Increased traffic may increase the probability of an oil spill in arctic waters (Johansson et al., 2013). To better prepare for emergency response and mitigation of such spills, there is a need to predict the fate and transport of different oil types (Brandvik et al., 2006).

Fate and transport of spilled oil is a complex process and the presence of ice makes it more complicated. It is governed by spreading, evaporation, emulsification, dispersion, advection, photo-oxidation, biodegradation, dissolution, encapsulation and sedimentation, which take place simultaneously after an oil spill (Bobra and Fingas, 1986; Spaulding, 1988; Sebastiao and Guedes, 1995; Reed et al. 1999; Yang et al., 2015).

Understanding the processes involved in the fate and transport of oil spills is key to good modelling, particularly in developing emergency spill response models (Anon., 2003). These composite models are used to predict where the spill will go, and how it will weather. This information is important to determine response priorities (Anon., 2003), help make better predictions of the possible impact of petroleum related developments, and prepare contingency and mitigating measures (Mackay and McAuliffe, 1988; Fingas, 2015).

Compared to the knowledge that exists for fate and transport of oil spills in open water, knowledge regarding oil spills in ice-covered waters is more limited and at an adhoc level (Brandvik et al., 2006; Reed et al., 1999). The goal of this paper is to present a state-of- the art review of fate and transport modelling of oil spills in ice-covered waters. This paper builds upon earlier works by Spaulding (1988), Reed et al. (1999), and Fingas and Hollebone, (2003).

2. Oil characteristics

Fate and transport of spilled oil and refined petroleum are influenced by their chemical and physical properties (Buist et al., 2013). The influence of chemical properties is attributed to the composition of crude oil, as it is made up of hundreds of different organic compounds (Lehr, 2001). Each of these compounds has unique characteristics (Lehr, 2001). The constituents of crude oil

---

* Corresponding author. Tel.: +1 709 864 8939.
E-mail address: fikhan@mun.ca (F. Khan).

http://dx.doi.org/10.1016/j.oceaneng.2015.10.014
0029-8018/© 2015 Elsevier Ltd. All rights reserved.

Please cite this article as: Afenyo, M., et al., A state-of-the-art review of fate and transport of oil spills in open and ice-covered water. Ocean Eng. (2015), http://dx.doi.org/10.1016/j.oceaneng.2015.10.014

are saturates, aromatics, resins and asphaltenes. Light crude contains a higher percentage of saturated hydrocarbons and aromatics, while heavy oil contains more resins and asphaltenes (Fan and Buckley, 2002).

From a spill perspective, volatility, insolubility, spreadability, and the tendency of oil to form emulsions are the most important physical properties for consideration (Buist et al., 2013). Crude oil is made up of a high percentage of light and volatile hydrocarbons that evaporate quickly once exposed (Buist et al., 2013; Fingas, 2011). Studies have shown that crude oil is generally insoluble in water except for alkanes and aromatics, which are slightly soluble in water (Buist et al., 2013; Reed et al., 1999). Apart from highly viscous oils and oils with a pour point above ambient temperature, oil will generally spread because of its unique surface tension. The presence of natural surfactants (asphaltenes and resins) in the right proportions creates the condition for emulsion formation (Buist et al., 2013; Reed et al., 1999). These physical and chemical properties are important inputs for oil spill models (Reed et al., 1999).

3. Oil spill models

The goal of oil spill modelling is to predict where oil is likely to go after a spill. This is accomplished through the use of data on ocean currents, winds, waves and other environmental factors (Drozdowski et al., 2011). There are three major components of an oil spill model: (i) the input (ii) weathering and transport algorithms to quantify the processes involved, and (iii) the output, which produces the required results in an appropriate way (Sebastiao and Guedes, 1995; Yang et al., 2015; Spaulding, 1988). Fig. 1 attempts to capture different steps and processes involved in oil spill modelling.

Environmental data include wind, current, temperature, and ice in space and time. Oil type, physical and chemical properties of oil, release rates and location make up the oil data. (Reed et al., 1999). The output is a representation of the spatial extent of the spill and oil mass balance by environmental compartments, geographical distribution and properties as a function of time (Spaulding, 1988). Weathering and transport algorithms link the output and the input models (Spaulding, 1988; Reed et al., 1999). Individual processes act together to bring about weathering (Sebastiao and Guedes, 1995). The processes are dependent on each other as illustrated in Fig. 2. Linkages and dependencies among the weathering and transport processes are not limited to Fig. 2 as illustrated.

For instance, evaporation facilitates emulsification through the formation of mousse; lighter components of some oil types evaporate to yield the level of resin and asphaltenes required to stabilise emulsions (Buist et al., 2013; Reed et al., 1999). Emulsification and dispersion are series of batch processes. Both processes are controlled by hydrodynamic factors and oil properties. The hydrodynamic factors include frequency of breaking waves, mixing intensity and depth of mixing. Density, viscosity and interfacial tension are the important oil properties for emulsification and dispersion (SjÖblom, 2006; Daling et al., 2003; Fingas, 2015). Resins produced from photo-oxidation may cause the formation of water-in-oil emulsions (Fingas, 2015). Interdependencies of weathering processes imply that the algorithm describing the weathering processes may have common inputs and sometimes the output of one algorithm may be the input of another. The implementation of the model is important. Two models containing the same algorithm and receiving the same inputs may produce different results because of the difference in the implementation (Reed et al., 1999).

3.1. *Oil spill models for open waters*

Abascal et al. (2010) presented a study on the development of a statistical oil spill model and its validation. The validation was carried out using the oil slick observation during the Prestige accident. The model has been applied to the Bay of Biscay (Spain) to support spill response planning along the Cantabrian coast (Hānninen and Sassi., 2010; Abascal et al., 2010). The National Oceanic and Atmospheric Administration (NOAA) developed the Trajectory Analysis Planner (TAP) to statistically analyse the output from an oil spill trajectory model (Hānninen and Sassi., 2010). Automated Data Inquiry for Oil Spills (ADIOS) was developed by the National Oceanic and Atmospheric Administration Hazardous Material Response Division (NOAA/HAZMAT) to aid responders

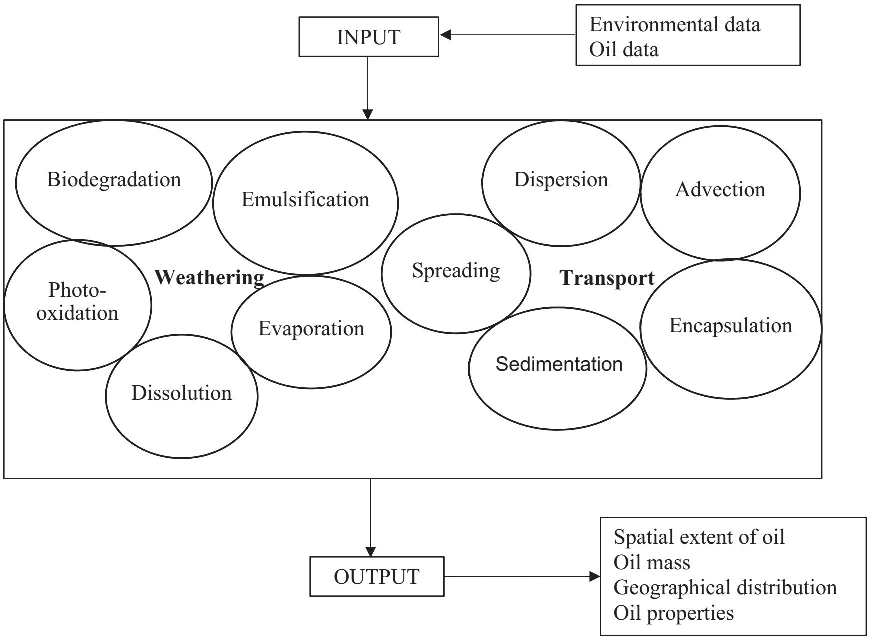


Fig. 1. General structure of an oil spill model (after Reed et al.,1999).

Please cite this article as: Afenyo, M., et al., A state-of-the-art review of fate and transport of oil spills in open and ice-covered water. Ocean Eng. (2015), http://dx.doi.org/10.1016/j.oceaneng.2015.10.014