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Proceedings of the Combustion Institute 35 (2015) 2699–2706

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

A study on burning of crude oil in ice cavities

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Abstract

In situ burning is a practical means of oil spill cleanup in icy conditions. This study considers one example of oil spill scenario: burning oil in an ice cavity. A new set of parameters to the classical problem of confined pool fires in vessels arises under these unique conditions. The icy walls of the cavity create a significant heat sink causing considerable lateral heat losses, especially for the small cavity sizes (5–10 cm). The melting of ice due to the heat from the flame causes the cavity geometry to change. Specifically, the diameter of the pool fire increases as the burning proceeds. This widening causes the fuel to stretch laterally thereby reducing its thickness at a faster rate. The melted ice water causes the oil layer to rise up, which causes the ullage (the distance from the oil surface to the top surface of ice block) to decrease. The reduction in the ullage and increase in the diameter counter-act the reduction in oil thickness due to the widening. This results in a strong coupling between the mass loss rate and the geometry change of the pool and cavity. To systematically explore this process, experiments were performed in cylindrical ice cavities of varying diameters. It was found that due to the cavity expansion the average mass loss rate of crude oil in the ice cavity is greater than the mass loss rate in a pan. For example, the mass loss rate of crude oil burning in a pan found to be 50% less than that of an ice cavity with similar initial diameter. A model was developed to estimate mass loss rates and efficiencies which are in reasonable agreement with the experimental results. Extension of the model to larger sizes, comparable to realistic situation in the Arctic is discussed.

Keywords: Crude oil; Ice; Cavity; Mass loss rate; Efficiency

1. Introduction

Oil spill cleanup in Arctic waters induces substantial difficulties because of the total or partial ice coverage for most of the year. When oil is released underneath the ice surface, it collects below the ice sheet. The spring break-up causes the hidden oil to emerge from lower ice sheets, forming melt pools of oil surrounded by ice walls [1–4].

In situ burning (ISB) is a practical countermeasure to oil spill incidents. This method gasifies the contaminant by burning the released oil in the spill site. Oil removal from the spill surface can

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http://dx.doi.org/10.1016/j.proci.2014.05.074

Nomenclature

C_P	specific heat of air (1.04 kJ/kg K)
D	diameter of cavity (m)
g	acceleration due to gravity (9.8 m/s^2)
L_v	latent heat of vaporization (kJ/kg)
L	fuel layer thickness (m)
$\dot{m}$	mass loss rate (g/s)
$\dot{m}''$	mass loss rate per unit area (g/s cm^2)
$\dot{Q}$	heat release rate (kW)
T	temperature (K)
V	volume (ml)

Greek symbols

ρ	density (kg/m^3)
χ	fraction of total heat feedback to fuel
λ_l	conductivity of crude oil (W/m K)

Subscripts

cd	conduction
cv	convection
f	flame
i	ice
l	fuel layer
rad	radiation
ref	reflection
rr	re-radiation
w	water

be remarkably efficient and at high rates under favorable condition. Removal efficiencies for thick slicks can easily exceed 90%. The method is ideally suited for remote places because of significant reduction in equipment and personnel needed to reach potentially high clean up efficiencies [5–10]. After burning, collection and transport of the residue reduce significantly because the liquid fuel is mostly converted to gas. In Arctic broken-ice, where oil spill cleanups are hindered and mechanical means of cleanup are not applicable, *in situ* burning may be the optimum solution. There have been extensive efforts to investigate *in situ* burning of oil in cold-climates since the late 1960s. These studies are mainly focused on burning of oil on open waters in presence of ice where oil is not confined by icy walls [2,11–14].

Ice and oil can interact in many configurations of different shapes and sizes i.e. channels and cracks between ice sheets or basins created naturally. However, there is no statistical data reported on the size and shape of these cavities. Perfect cylindrical cavities might be rare to find, yet, spill on a flat ice sheet can be directed to human-made cylindrical cavities for *in situ* burning. Nevertheless, using a symmetrical geometry will help to simplify the problem and facilitate modeling. Therefore, to achieve a better understanding on the burning of crude oil, a series of experiments were conducted in different sizes of cylindrical ice cavities to mimic burns of liquid fuels in icy conditions. An earlier study by Bellino et al. [15] reported mass loss rates of oil (3:1 mixture of motor oil and petroleum ether) burning in ice channels. The focus of the current study is to further explore the burning behavior of crude oil using a circular ice cavity where corner effects are eliminated. Unlike burning of an oil slick on open waters, burning of liquid fuel in an ice cavity shows unique characteristics. Melting of ice due to the heat from the flame causes the geometry of cavity to change. The icy walls of the cavity and cold water beneath the fuel layer create a significant heat sink causing considerable heat losses especially for smaller cavity sizes.

What is the role of the cavity dynamics on the burning of crude oil? What are the burning characteristics in ice cavities of varying sizes? Is it possible to model the mass loss rate of crude oil in this setting and how can it be generalized to larger scales? To answer these questions, the change in shape of the ice cavity and the oil layer thickness are measured experimentally using a combination of visual images, mass loss, and temperature data along the centerline of the cavity. The objective of this research was to study the role of cavity dynamics and determine burn efficiencies of crude oil for different sizes of ice cavities. In addition, a heat transfer model is developed to estimate mass loss rate and burning efficiency of crude oil. This model is a first attempt to analyze the controlling processes such as in-depth conduction losses, melting of ice, etc. and requires further developments in the future to be able to predict $\dot{m}$ and burning efficiency. Results from the model are then compared with experimental results.

2. Experimental setup and procedure

Figure 1 shows the experimental apparatus with crude oil in a 5 cm diameter ice cavity. Similar setups were used for diameters of 10, 15, and 25 cm. Three experiments at each diameter were conducted to form a data set of twelve experiments. Each experiment utilized an ice block with a cylindrical cavity excavated in its center.

Table 1 shows the initial ice cavity dimensions and crude oil volumes for each diameter. There are two possible extinction scenarios for burning