Fuel 234 (2018) 464–472

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

# Experimental study on burning behavior of crude oil pool fire in annular ice cavities

Depeng Kong[a,*], Zhen Zhang[a], Ping Ping[b], Guoming Chen[a], Xu He[a], Hanbing Yang[a]

[a] Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao, Shandong 266580, China
[b] College of Chemical Engineering, China University of Petroleum (East China), Qingdao, Shandong 266580, China

ARTICLE INFO

*Keywords:*
*In-situ* burning
Annular ice cavity
Double lateral cavity
Burning rate
Flame height

ABSTRACT

A series of experiments with different pool sizes and moisture contents were conducted to study the combustion behavior of pool fires in annular ice cavity. The initial pool area of 78.5 $cm^2$ and the initial oil thickness of 10 mm were determined in the each experiment. The results show that the double lateral cavity is formed after the pool fire in an annular ice cavity and the decrease of inner diameter is about 1.1 times as much as increase of outer diameter. Compared with circular ice cavity pool fires, fire merging, a unique phenomenon in annular ice cavity pool fires, was observed. The burning rate exhibits three stages: initial growth stage, merged growth stage and decay stage. Increasing pool diameters and moisture contents reduce the burning rate and flame height. The merged intensity ($I_m$) increases as the increase of pool diameters and moisture content, while the influence coefficient of merged fire ($\varphi$) has a contrary trend. A new correlation for predicting the flame height is proposed.

## 1. Introduction

Increased exploration and development of oil and gas in the Arctic region has prompted a risk of the accidental leakage of liquid fuel in the process of exploitation, storage and transportation [1,2]. The emergence of spilled oil has a long-term damage to the marine ecosystem, economy and environment. Oil spill cleanup at Arctic regions are encountering substantial difficulties such as oil on ice, in brash ice and between blocks of ice [3], as shown in Fig. 1. At present, the general ways to deal with spilled oil are physical treatment, chemical treatment and biological treatment [4,5]. *In situ* burning, as a method of chemical treatment, is especially suited in Arctic region where mechanical cleanup equipment cannot reach the spill area [3,6,7]. ISB has proved to be economical and effective during the Gulf of Mexico Deepwater Horizon [8,9] and Gulf of Finland [10] oil spills response.

In real oil spill scenario, oil leaked on the ice may not be covered the whole surface because of the variable topography. Gaps and cracks between ice sheets or holes created naturally are places to store spilled oil, that is to say, spilled oil exists in the ice chamber of different shapes and sizes in the actual environment. Therefore, in relation to treatment of spilled oil in the Arctic region by ISB, several works have been made on the study of pool fires bounded by ice walls. When spilled oil occurs on land, many realistic scenario of oil spills treatment are described as pool fires in rigid vessel [11–18]. Similarly, previous studies simplified the irregular ice chamber into a cylindrical ice cavity for pool fire experiments while varying factors such as oil type, initial diameter, fuel thickness, ullage and fuel temperature [19–26]. Farahani [20] found that the burning rate of crude oil pool fires in ice cavities is mainly strengthened by the ice cavity diameter and is restricted by the fuel thickness. He also pointed out that the natural convection is superior in the former half combustion period and Marangoni convection occupies the most important part in the final half of the burning [19]. For exploring this assumption, additional tests were carried out to know the thermal and flow field of n-octane combustion beside an ice wall by a 2-dimensional PIV system [22]. Kong [26] carried out the circular ice cavity crude oil pool fire experiments and thought that the initial fuel temperature has a considerable impact on initial decrease stage. Another typical environment where spilled oil appears in ice is an ice channel. Shi [21] investigated the regression rate and flame heat flux in a square ice cavity and an ice channel with three fuel thicknesses. Bellino [27] found that the burning rate is mainly restricted by ullage height and oil depth, however, the channel width has a slight influence on it. The other study of Bellino [28] is about the spreading behavior of crude oil in ice channels. The results demonstrate how a low Reynolds number fluid travels along an ice channel, and variations of the ice channel width influence the spread rate.

One thing that should be noted is that the spilled oil may exist between the ice channels or cracks, as shown in Fig. 1. Spilled oil will

* Corresponding author.
*E-mail address:* kongdepeng@upc.edu.cn (D. Kong).

https://doi.org/10.1016/j.fuel.2018.07.049
Received 19 May 2018; Received in revised form 3 July 2018; Accepted 11 July 2018
0016-2361/ 

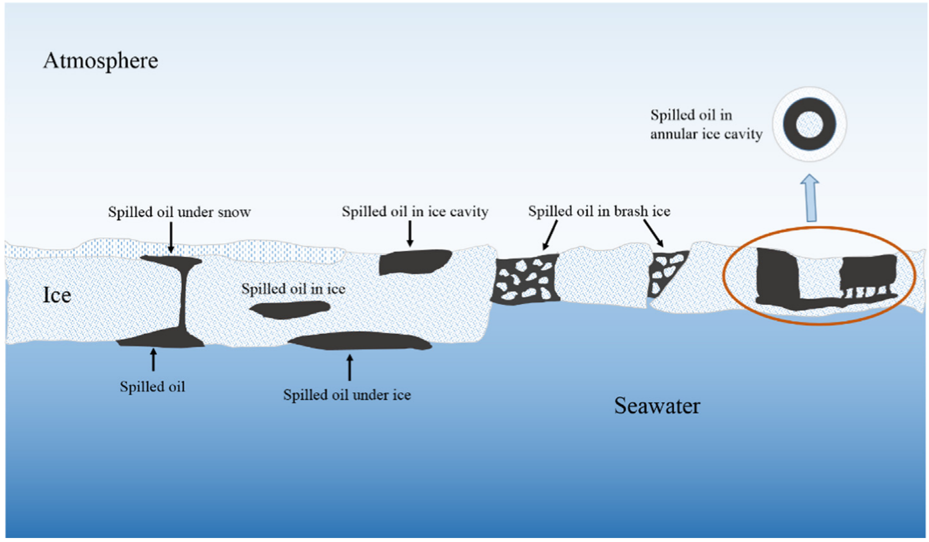


**Fig. 1.** Schematic diagram of oil spill distribution in ice area [3].

encounter icicles that protrude from the ice cavity during its spread in Arctic region, resulting in a fuel-free area in the oil pool. In such circumstances, the burning of the spilled oil can be simplified as a pool fire in an annular ice cavities. Many scholars have conducted some studies on the annular pool fires in the rigid vessel. Sun [29] studied the burning rate and flame height of n-heptane pool fire by using four annular pools and one circular pool with the same area of 0.071 $m^2$. Wang [30] found that fire merging obviously enhances the burning rate and flame height of pool fires on two hollow trays. Tao [31] conducted several experiments with the difference between the outside and inside diameter of 10 cm and found that the flame height of ethanol pool fire slightly changes with equivalent diameter, while the one of n-heptane pool fire evidently increases. However, when it comes to the pool fire in annular ice cavities, the ice wall will melt and the outside and inside diameters correspondingly change during the burning, making the burning behavior quite different from the previous study and need further exploration.

The purpose of this study is to investigate the influence of combustion characteristics in annular ice cavity pool fires with different pool sizes and moisture contents. In the current study, the differences of variation value of inner diameter and outer diameter are firstly discussed in details. The effects of annular sizes and moisture contents on combustion characteristics of annular ice cavity crude oil pool fire are then analyzed. Special attention is paid to the effects of fire merging on the combustion characteristics, including burning rate and flame height. Finally, a correlation of dimensionless flame height is developed.

## 2. Experimental setup

The overall experimental setup is shown in Fig. 2. An annular ice cavity was made before the experiment. The inner and outer diameters have five cases with the same pool area of 78.5 $cm^2$. The water and pure crude oil were mixed with different mass ratios to get the blended fuel with varying moisture contents. A series of preliminary experiments were carried out with the blended fuel to determine the suitable range of crude oil moisture contents. Starting from pure crude oil, the moisture content increased by 5% each test to confirm whether the blended fuel can be ignited. The ignition procedure was 5 s of heating with a propane torch. If the blended fuel did not ignite, the procedure was repeated after a 10 s break. When the blended fuel was not ignited with third effort, the one was considered as "not ignitable". It can be found that the blended fuel is hard to be ignited when the moisture content of crude oil is more than 25%, as shown in Table 1. Eventually,

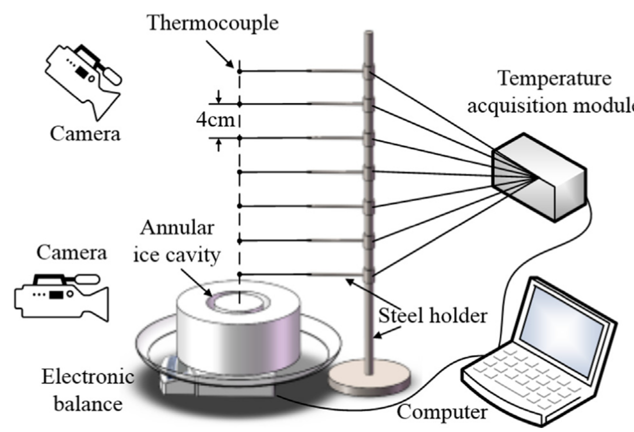


**Fig. 2.** Schematic of the experimental setup.

**Table 1**
Ignitability of blended fuels with different moisture contents.

| No. | Moisture content/% | First ignition | Second ignition | Third ignition | Ignitability |
|---|---|---|---|---|---|
| 1 | 0 | Yes | N/A | N/A | Yes |
| 2 | 5 | Yes | N/A | N/A | Yes |
| 3 | 10 | Yes | N/A | N/A | Yes |
| 4 | 15 | Yes | N/A | N/A | Yes |
| 5 | 20 | Yes | N/A | N/A | Yes |
| 6 | 25 | No | No | Yes | Yes |
| 7 | 30 | No | No | No | No |

five different crude oil moisture contents ($w$) of 0–20% were considered for each diameter.

There is a minimum critical thickness of crude oil when it ignites, so the initial thickness of the chosen fuel layer needs to ensure that the pool fire can maintain burning. On the other hand, due to the limitation of experimental conditions, the initial fuel thickness ($L_0$) of 1 cm is suitable for this experiment in order to avoid overflow. Detailed experimental parameters are shown in Table 2.

An electronic balance with an accuracy of 0.01 g was placed below the ice block to record the variations of mass. Two cameras were respectively placed on the different directions of the annular ice cavity. The horizontal camera was utilized to record the flame shape, and the vertical one was used to collect the geometry change of annular ice