Application of Flame Refluxer^{TM} Concept to ISB – Experimental Results of 5 Field Trials in Mobile, Alabama

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Abstract
A new *in situ* burning (ISB) method, capable of enhanced combustion of oil slicks in containment booms, is analyzed. The concept named Flame Refluxer^{TM} is based on the use of immersed thermally conductive objects to transfer heat generated by the combustion back to the fuel to create a feedback loop. The resulting enhanced heat transfer from flame back to the fuel helps to sustain a significantly increased burning rate. The project spanned a period of two years ranging from bench scale to large-scale experiments in the laboratory and culminating in outdoor field experiments. Five large-scale field experiments were performed at the United States Coast Guard (USCG) test facility at Little Sand Island in Mobile Bay, Alabama. A confined liquid pool (1.4 m diameter) was continuously fed to maintain a constant oil layer thickness of 1 cm floating over water. A 0.5 cm thick copper blanket, 94% porous, was immersed in the oil and served as a heater for the oil slick. Conical shaped copper coils extending out into the fire were attached to the blanket and were used to collect the heat from the flame. Experiments resulted in three major outcomes: i) Additional heat transfer to the fuel lateral dissipation through the copper blanket increased mass loss rate by 6 times ii) Heat stored in the blanket facilitated burning of the heavier components of crude oil such as tar, resulting in negligible residue (15 times less than baseline). iii) Black smoke was reduced by 50%. The Flame Refluxer^{TM} is robust, easy and cheap to construct and has no moving parts. The field experiments demonstrated the feasibility of the technology to be used in efficient clean up of oil spills using ISB.

1 Introduction

In situ burning (ISB) is a feasible disposal option in offshore oil spills. It is a low cost response method that can help limit the spread of oil and thereby reduces the chance of shoreline contamination and poisoning of biota (Walton et al., 1993, Fingas, 2006, Fingas, 2016). However, the average regression rate for large burns on water is only about 1 mm/min (heavy oil) to 3.5 mm/min (light oil) (Fingas, 2006), which is low relative to the capacity needed to effectively burn off the quantities of oil recovered from catastrophic spills. For example, at 1 mm/min, 4 cm thick oil layer will take 7 hrs. to burn under ideal conditions. Obviously, an improvement in the burning rate can reduce the operation time for the response and reduce the cost and environmental impact. Further, as the oil layer thins during burning it looses heat to the water sub-layer because of which the burning slows and ultimately extinguishes when the oil layer reaches a thickness of around 2 – 3 mm (Garo et al., 1999, Wu et al., 1998, Torero et al., 2003, Ranellone et al., 2017, van Gelderen and Jomaas, 2017). This leaves a post burn tar-like residue of around 10 – 30 % on the water depending on the properties of the oil (Garo et al., 1999, Wu et al., 1998, Shi et al., 2015) which either sinks to the bottom or has to be picked up mechanically (Buist et al., 1999, Torero et al., 2003, van Gelderen et al., 2015a, van Gelderen et al., 2015b). The slow burning also leads to copious amounts of smoke released into the atmosphere posing a hazard to the safety of the response crew persisting kilometers downwind from the burn (Ghoneim et al., 1993, Mullin and Champ, 2003).

The reason for the slow burning during ISB is the limitation of the heat transfer from the flame to the oil surface. Torero et al. (2003) characterized the theoretical efficiency of heat transfer for burning oil slicks showing it could be as low as 0.3%. With such a small fraction of the total heat released actually returned to the fuel surface, the vaporization and consequently combustion is slow as all the heat is lost to the environment through the buoyant convection plume and thermal radiation (Brosmer and Tien, 1987, Gritzo et al., 1998, Torero et al., 2003, Shi et al., 2016). For large-scale oil slick pool fires, significant losses also take place through the water sub-layer on which the oil is floating further cooling the oil leading to early extinction and inability to burn off the heavier tar-like components.

A recent experimental study sponsored by the Bureau of Safety and Environmental Enforcement (Rangwala et al., 2015a) showed that a thermally conductive object (thin aluminum cylinders) exposed to the fire, and also immersed in the liquid pool can enhance the burning rate of a pool fire by 10 times. While, several studies have investigated the effect of metal objects immersed in the flame (Russell and Canfield, 1973, Gritzo and Nicollete, 1997), in these studies, the metal objects were only immersed inside the flame. But, when the metal object is in contact with both the flame and the liquid, a heat feedback loop is generated enabling increased heat transfer from the flame to the fuel surface. The experimental study (Rangwala et al., 2015a) showed that the metal object inside the liquid and the flame zone promoted higher mass loss rate (x10) of the liquid fuel. The increased burning rate also resulted in a reduction of smoke (Tukaew, 2017). Nucleate boiling (formation of bubbles on the surface of the metal immersed in the liquid) was the main reason of significant enhancement of mass burning rate. The metal object immersed in the flame zone creates a high-efficiency pathway for heat transfer from the hot flame zone (~800 – 1000 °C) to the cooler fuel layer (~200 – 400 °C). This is because the portion of the object immersed in the fuel can easily reach temperatures above the fuel boiling point resulting in sub-cooled nucleate boiling which increases the heat transfer rates by an order of magnitude (x100). This is the main reason for the faster evaporation of the fuel and corresponding increase in the burning rate (Sezer et al., 2017a).

The experimental study (Rangwala et al., 2015a) led to the development of a patented technology named Flame Refluxer^{TM} (Rangwala et al., 2015b, Arsava et al., 2016, Arava et al., 2018). The simple but effective design of the Flame Refluxer^{TM} requires no moving parts, atomizing nozzles, or compressed air, which makes it more reliable than existing burner technologies. The technology was developed over a span of 3 years through funding by the Bureau of Safety and Environmental Enforcement (BSEE) (Rangwala et al., 2015a, Arsava et al., 2017a). The technology has been featured on National Public Radio (NPR, 2017).

This paper describes a WPI - BSEE - US Coast Guard led experimental investigation and proof of concept analysis of the Flame Refluxer™ applied to outdoor field scale experiments comprised of a 1.4 m diameter oil slick of 1 cm thickness. In terms of Technology Readiness Level (TRL) advancement (Panetta and Potter, 2016) the outdoor field scale experiments demonstrate a TRL 5 capability showing prototype testing in relevant environments. The overall experimental program leading to TRL 5 spanned a period of three years ranging from bench scale (Sezer et al., 2017a, Arsava et al. 2018a) to large-scale experiments in the laboratory (Arsava et al. 2017b, Arsava et al., 2018b) and culminating in outdoor field experiments reported here. The fundamental questions addressed in the current paper are: (1) What is the improvement in heat transfer by the flame to the oil slick because of the Flame Refluxer™ and (2) What is the influence of the Flame Refluxer™ on the burning efficiency in terms of mass loss rate, post burn residue removal, and emissions in the atmosphere. The last question related to emissions is analyzed in a second paper also in this symposium (Tukaew et al., 2019).

2 Design Concept

Figure 1 shows a schematic of the *Flame Refluxer™* capable of collecting radiative and convective heat generated by a fire via conical copper coils and transferring it back to the fuel to create a feedback loop that sustains a significantly increased burning rate. With thin oil slicks on water, porous metal wool made of copper (blanket) immersed inside the fuel surface forms the heater component of the Flame Refluxer™. The blanket enables lateral heat transfer; increases volumetric heat capacity and increases mass transfer by nucleate boiling (shown as an inset in Fig. 1)

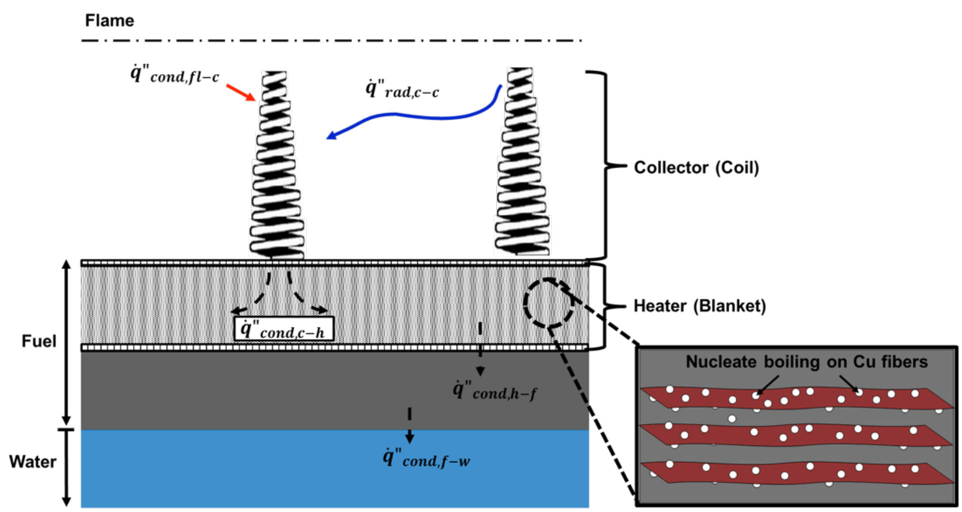

Figure 1 Schematic of the controlling heat transfer mechanisms during burning of a liquid fuel on water with the presence of immersed object. The collector(s) comprises of conical copper coils and are used to transfer the heat from the fire to the heater, comprising of a blanket made up of copper wool immersed in the oil layer. Bubbles formation on the copper blanket forms the main mode of heat transfer within the oil layer. Subscripts: cond = conductive, fl = flame, f= fuel, c = collector, h = heater, w = water, rad = radiative.

It is clear that besides heat from the flame, the liquid fuel is also receiving heat from the collector and heater. This additional heat causes the burning rate to increase significantly, thereby promoting faster and cleaner combustion. The coupling between flame heat transfer and fuel vaporization because of the presence of the coil and blanket are discussed in Sezer et al., 2017b. The main controlling parameters, given knowledge of oil flammability and thickness were determined to be the height, and number of coils for the collector (Fig. 1) and the thickness, porosity, and volumetric specific heat (J/m^3) of the blanket comprising the heater. One of the important properties of the oil in addition to its average pyrolysis temperature and average latent heat of gasification was its nucleate boiling curve (Sezer et al., 2017b). For the current experiments, the boiling curve of dodecane was used as an approximate substitute for crude oil (Sezer et al., 2017b). An experimental and numerical study were performed at the bench scale to optimize the Flame Refluxer^{TM} geometry for the field trials to be ½ cm thick copper porous wool heater, with copper wire (thickness 0.04 m) coils of height 0.2 m serving as the collectors. While, the blanket thickness was kept constant, the number of coils and their location were varied in a series of 5 experimental field trials. Further details about the optimization carried out during the bench scale and large-scale trials are discussed in Arsava et al., 2017a.

3 Experimental setup and procedure

Five field experiments were conducted in Joint Maritime Test Facility (JMTF) at Little Sand Island in Mobile Bay, Alabama (Hansen and Stone, 2016). The facility is owned and operated by the US Coast Guard with support from the US Naval Research Laboratory. It is located on a remote island in the Mobile Bay and accessible by ferry only. The JMTF maintains a 9.2 m x 30.5 m x 1.5 m burning pool, which provides a realistic setting for large-scale oil spill scenarios. An aerial view of the test facility is shown in Fig. 2.

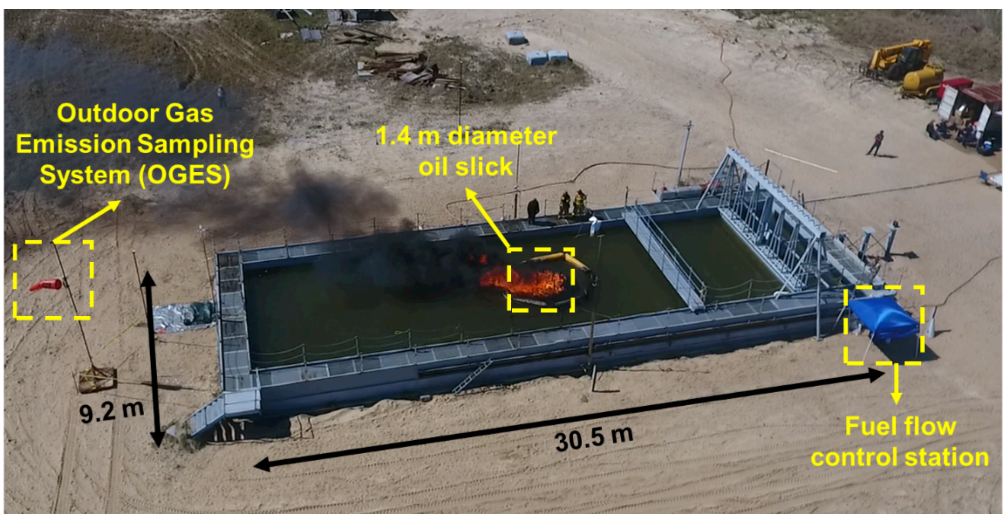

Figure 2 Aerial view of the experiments at the US Coast Guard's Joint Maritime Test Facility in Mobile, AL. The experiments had 4 stations: a) Oil slick burner, b) Outdoor emission sampling, c) Fuel flow control, and d) Instrumentation shed (not shown, but to the right of the tank). The oil slick burner comprised of a metal containment ring 1.4 m in diameter instrumented with thermocouples and heat flux gauges to monitor oil slick temperatures during the combustion. The Outdoor Gas Emission Sampling System(OGES) was used for combustion plume collection and analysis. The fuel flow control station was used to continuously supply the fuel so as to maintain a constant thickness of 1 cm over the span of the experiment (20 – 30 min).

The experiments comprised of one baseline (confined pool fire), one blanket and three blanket with coils with different coil configurations were conducted in a 1.4 m diameter (inner) steel burning ring placed at the center of the pool (Fig. 3). All experiments had a constant fuel layer thickness of 1 cm, which was maintained using a fuel control station for 20 to 30 minutes.

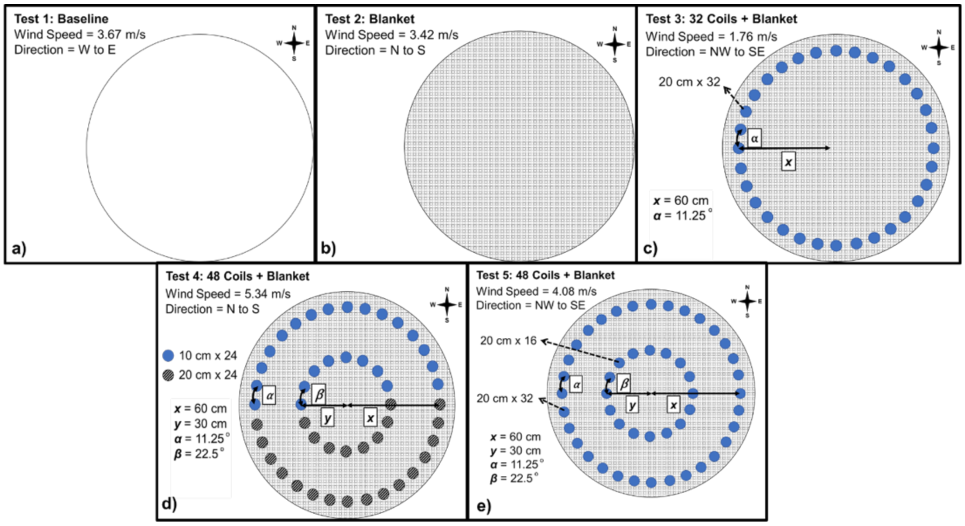

Figure 3 Blanket-coil configurations, a) Test 1: Baseline, b) Test 2: Blanket, c) Test 3: Blanket with 32 coils of 20 cm height, d) Test 4: Blanket with 48 coils (Various coil heights) e) Test 5: Blanket with 48 coils of height = 20 cm. For all experiments, the blanket was made of copper wool of porosity 94% and thickness equal to ½ cm.

The baseline experiment is shown in Fig. 3a (Test 1). The wind speed and direction were measured for each experiment and shown in Fig. 3. The remaining four experiments shown in Fig. 3b-e were performed with different coil configurations with Test 2 comprising of only a copper blanket of ½ cm thickness. In this case, it was assumed that radiative heat transfer from the flame would heat the blanket, as there were no coils to collect the heat. The blanket used in all field experiments was a 0.4 cm thick layer of porous copper wool of 0.0127 cm (0.005") diameter copper (Cu) fibers (Fig 4).

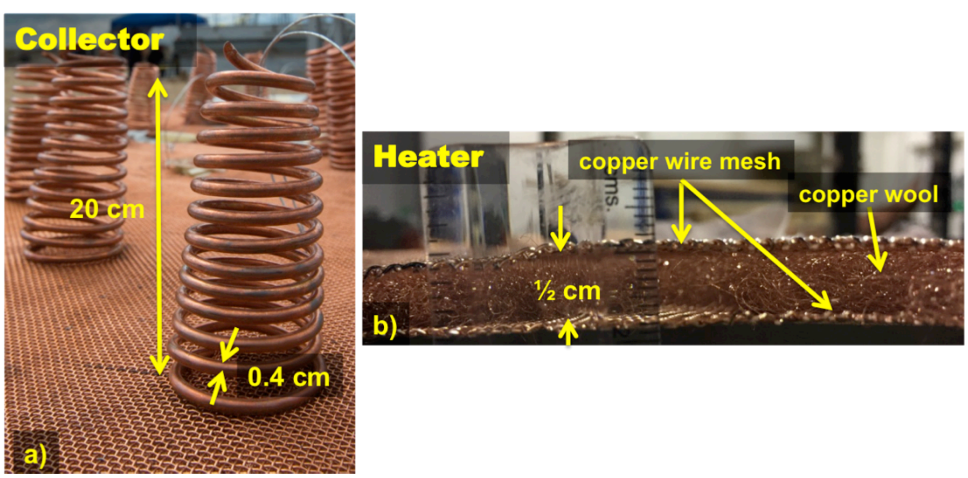

Figure 4 Photograph of a) Coils (collector) and b) Blanket (heater). Both coils and blanket are made of copper. The blanket had a thickness of ½ cm and porosity equal to 94%.

To increase the structural stability, the copper fiber was sandwiched between two copper meshes (wire diameter of 0.05 cm (0.023") with an opening of 0.15 cm between wires). The porosity of the resulting ½ cm blanket was equal to 94% (Arsava et al., 2017a). Test 3, 4, and 5 were performed by placing coils (0.4 cm wire diameter, 0.5 cm pitch, 6 cm base and 2 cm top diameter) on top of the blanket. Previous studies showed that for pool fires greater than 1 m in diameter, the radiative heat transfer from the flame to the fuel surface decreases because of radiative blockage caused by soot accumulation at the center (Brosmer and Tien, 1987, Gritzo and Nicolette, 1997). Addition of copper coils in the flaming region will influence this radiative blockage. To investigate this further, intermediate scale experiments using a 0.7 m diameter oil slick of 1 cm thickness were performed before the field trials (Arsava et al., 2017a). It was shown that the maximum efficiency was obtained by placing the heaters on the periphery where the heaters have high contact area with the hot flame. The coils located at the center of the pool did not significantly increase the burning efficiency. This experimental observation was tested during the scaled up field trial by performing experiments (Tests 3 and 4, Fig. 3) where the coils were placed along the outer and inner periphery as shown in Fig. 3c and 3d.

The optimum coil height in the field trial experiments was calculated using experiments performed at the bench scale and intermediate scale in the laboratory (Arsava et al., 2017a) in conjunction with a mathematical model developed by Rangwala et al., 2015a. The influence of flame tilt because of wind speeds up to 5.14 m/s (10 knots) was analyzed using Fire Dynamic Simulator (FDS) code (Mc Grattan et al., 2013) where baseline outdoor crude oil pool fires with 1.4 m diameter were simulated. Both cases with and without unidirectional wind were simulated. The mean flame height at the periphery (10 cm away from the burner rim) was found to be approximately 0.7 m and 0.28 m for the stagnant and with wind cases respectively (Arsava et al., 2017a). In addition to flame heights, plume trajectories were also determined which allowed an approximate range of elevation for the placement of the outdoor gas emission sampling system (OGES, Fig. 2). These calculations are further discussed in Tukaew et al., 2019. Based on these simulations, 0.2 m (20) cm high coils were used for the field trials as shown in Fig. 4. All coils were placed 60 cm away from the blanket center with 11.25^{o} angle (x and α in Fig. 3). Test 4 was conducted by adding 16 extra coils 30 cm away from the ring center (y in Fig. 3). They were placed with 22.5^{o} angle (β in Fig. 3). One experiment (Test 4) was also planned with shorter coils on one side as shown in Fig. 3d, where the coils on the North side, upwind direction, were half in height compared to south side. The last experiment (Test 5, Fig. 3e and Fig. 5) was conducted with the maximum coil density of 48 coils with a constant height of 20 cm throughout.

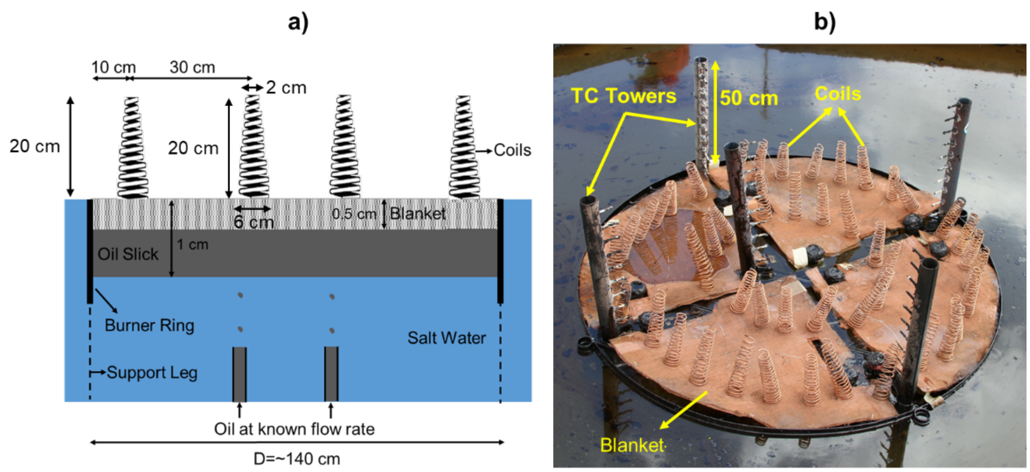

Figure 5 **The coil configuration used in Test 5 a) Sketch b) Photograph**

The instrumentation deployed around the oil slick burn area is shown in Fig. 6. The ring comprised of thin bars (0.002 m diameter) running across the center to provide support to the blanket and keep it level (Fig. 6a). Five identical thermocouple (TC) towers (30 TC each) placed on four sides and at the center of the ring (Fig. 6b) were used to measure the temperature profiles in the flame, oil-layer and water-sublayer. Four TC arrays, which had 32 TCs (with 0.1 cm vertical spacing) each, were placed 0.35 m away from the center to measure detailed liquid fuel and water temperature profiles (Fig. 6b). As shown in Fig. 6, five total and five radiative heat flux gauges /radiometers (Medtherm 64 series) were used to measure the total and radiative heat flux from the flame to the oil surface. One total and one radiative heat flux gauge were placed at the center of the ring, while the others were placed 35 cm away from the ring center with their measuring surfaces pointing upward and elevated 5 cm above the oil surface. Each heat flux gauge was calibrated before the field experiments using a cone calorimeter (ASTM E1354, 2017). Further details on measurement devices, their construction and calibration are in Arsava et al., 2017a.

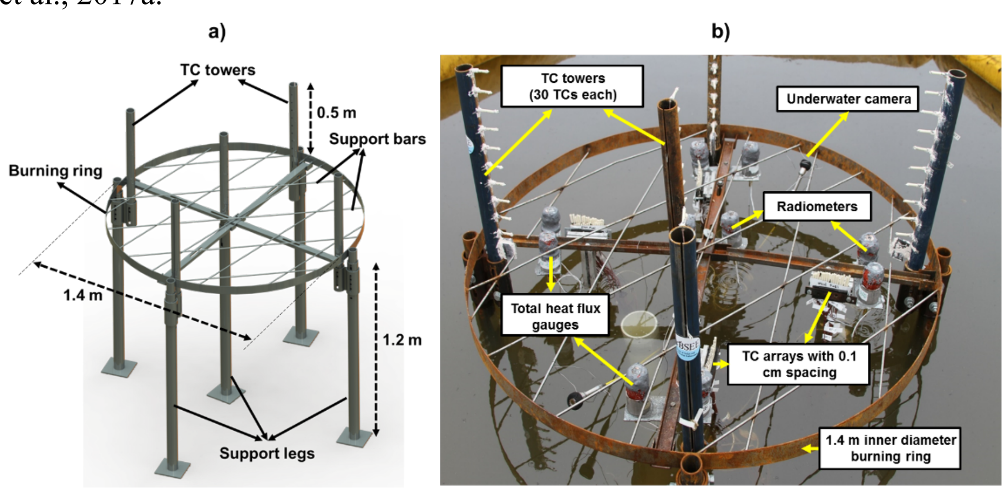

Figure 6 **Burning ring and instrumentation a) Sketch, b) Photograph.**

The tank was filled to a 1.2 m level with the water drawn directly from Mobile Bay. The ambient air and water temperatures were equal to 15 ^{o}C (standard deviation of 2.8 ^{o}C) and ~13

^{o}C (standard deviation of 0.8 ^{o}C) respectively. In all experiments, the oil slick thickness was maintained at 1 cm with a continuous fuel feeding system that was placed immediately under the burn area (details in Arsava et al., 2017a). The 1 cm slick thickness was based on Garo et al., 1999 where it was shown that the fuel burning rate is independent of the initial fuel layer thickness for fuel layers thicker than 1 cm. An electrical pump with a maximum capacity of 22 gal/min was used to supply the fuel inside of the burning ring. After the ignition, the flow rate was adjusted to keep the fuel thickness constant at 1 cm. To monitor the fuel thickness, two underwater cameras (Forbest FB-PIC3188D-130) were placed under the North and South side of the burner ring (Fig. 6b). The wall of the ring was marked by 0.2 cm intervals as shown in Fig. 7. A researcher stationed at the fuel flow control station shown in Fig. 2 continuously monitored the 1 cm mark and adjusted the fuel flow rate to maintain constant layer thickness at 1 cm. Adjustments were made during the initial phase of the experiments but after around 6 – 10 minutes, steady state burning was observed and further adjustments were not necessary. The mass loss rate, which is equal to the pumping rate, was monitored by an Omega FLR6115D flow meter connected inline with the fuel delivery pipeline to the burner. All instruments were sampled at 1Hz.

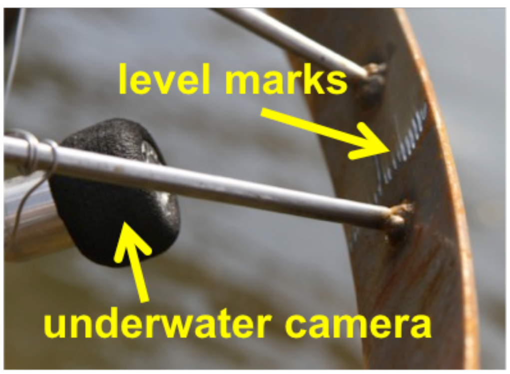

Figure 7 Underwater camera pointing on the inside of the burner ring to observe fuel level thickness. The pump speed was increased or decreased manually by a researcher stationed at the fuel control station to maintain a constant 1 cm thickness of the oil layer during the duration of the experiments.

An Outdoor Gas Emission Sampling System (OGES) was designed and used to sample and analyze the gas concentrations of O_2, CO_2, and CO (Tukaew, 2017). In addition, a US Coast Guard Strike Team was deployed on site to measure particulate concentrations (PM10 and PM2.5) during the experiments. Further details of the emission measurements are discussed in a second paper in the current AMOP proceedings (Tukaew et al., 2019) and in Tukaew 2017.

The Mobile expedition required a significant amount of forethought and logistics planning. The test apparatus, data collection system, fuel delivery system, and various assemblies of customized instrumentation were all required to be both robust and easily relocatable. In order to economically transport the test equipment safely, a crate was constructed atop a 3 m by 1.2 m standard long pallet. The final crate dimensions were 3.35 m (l) x 1.37 m (w) x 1.52 m (h), constructed in place for transport pickup. A single long pallet was determined to be more cost effective than multiple smaller pallets, and allowed for the transport of longer material. The system contained several single-point-of-failure components that required extra effort and caution to transport. The transport of the NI-PXI data collection system (thermocouple and heat flux data were collected through this system) was accomplished within a pelican case, along with the control computer and interface electronics. Desiccant was added as appropriate to prevent moisture buildup in the humid Alabama environment. The fiber optic cable was contained in a second pelican case, along with the Servomex 4200 gas sampling system and associated sample conditioning components. The burner ring was considered robust and simple enough that any shipping damage could be repaired at the Coast Guard facility. The thermocouple towers built for the Mobile expedition by WPI required special packaging, due to both their odd shape, and the delicate nature of the thermocouple arrays. To compensate for potential vibrational damage, the thermocouples were transported thermocouple-down, in a protective housing, bespoke for the expedition. Thermocouple wiring and PXI integration cards were transported within the same container, with the wiring isolated from the thermocouples via internal baffling. The protective housing was mounted within the container with rubber shock mounting. Similar care in packaging was also used after the experiments when the equipment was shipped back to WPI.

4 Experimental results and observations

The experimental results are analyzed from the perspective of quantifying the improvement in heat transfer by the flame to the oil slick because of the Flame Refluxer™ and the influence of the Flame Refluxer™ on the burning efficiency in terms of mass loss rate and post burn residue removal. The first step in processing the data was to establish a steady state burning behavior so that the five field trials could be analyzed using a common reference.

4.1 Determination of steady state

Figure 8 shows the temperature distribution along the vertical axis of the gas-liquid interface of the baseline experiments at different time intervals. The t = 30s time frame (Fig. 8) shows the ignition phase where the fuel was in the process of being ignited by a propane torch. The propane torch was held at the edge of the oil slick for around 30 – 50 s until a steady flame was observed after which the torch was removed. At t = 130 s, a flame is established on the entire surface of the oil slick. The surface temperature or the temperature at the interface between the oil slick and the air reaches 190 ^{o}C. The temperature within the oil slick linearly decays to a depth of about 0.6 cm followed by a sharper decline to 1 cm, where the oil and water sub layer temperatures are equal. Figure 8 shows that at t = 300 s and beyond, the temperature profiles do not change. The temperature profiles for the other experiments (Tests 2 – 5) show similar behavior where steady is achieved around 300 s. All experimental results in this study are therefore time averaged around this steady state time frame. The time averaging was done using data collected during the time interval of 360 s to 480 s for all experiments.

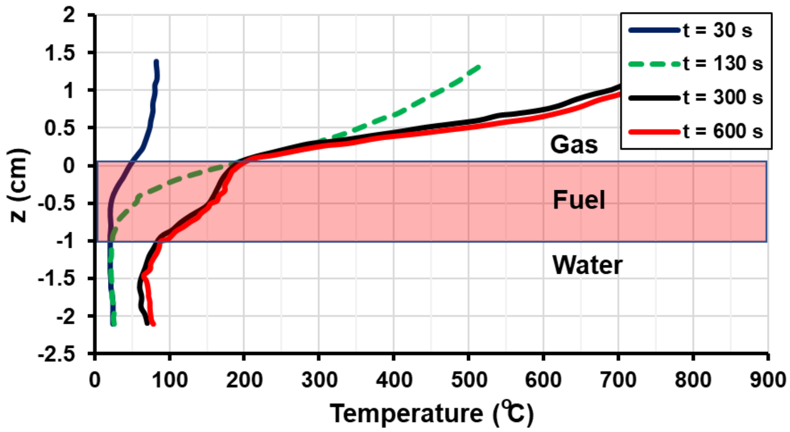

Figure 8 Temperature profile measured at the centerline of the oil slick pool fire for Test 1 (baseline case). Steady state in depth temperature distribution is achieved within 6 minutes (300 s).

It is interesting to note that the temperature decays slowly up to a distance of around 0.4 cm showing the presence of a hot layer of fuel approximately 0.4 cm thickness where the temperature is around 180 – 190 ^{o}C. A similar behavior is observed in our earlier experiments and also reported in literature (Rangwala et al., 2015a, Wang, 1989). The temperature below this hot layer decays linearly and a second discontinuity is observed at the oil water interface because of the difference in thermal properties (Wu et al., 2000)

4.2 Burning rate

Figure 9 shows the average burning rate (mm/min) measured when the steady state profiles are reached during the 360s to 480s time frame as discussed in section 4.1. Each experimental value denotes the time averaged pumping flow rate of the crude oil (kg/s) divided by the density of HOOPS oil (825 kg/m^3) and the surface area of the burner ring. The maximum standard deviation equals 0.78 mm/min .

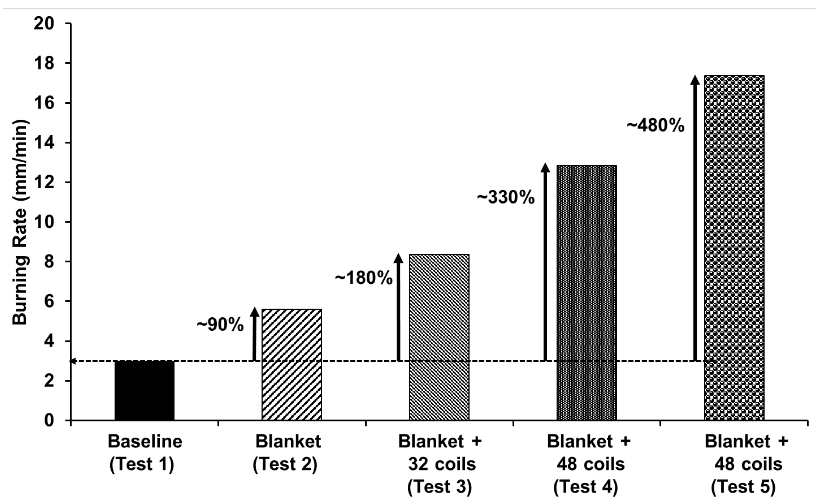

Figure 9 Steady state average burning rate (mm/min) of field experiments 1 – 5. The burning rate enhancement for Test 5 is around 6 times that of baseline.

As shown in Fig. 9, the average burning rate for the baseline field experiment equals 3 mm/min which is characteristic of ISB of crude oil (Fingas, 2006). With the addition of the 5 mm copper blanket, the steady state burning rate doubles as shown in Fig. 9 (Test 2). This is because the immersed blanket is able to absorb the radiative heat flux from the flame. Inamura et al., 1992, have shown that for crude oil in-depth absorption is around 2 kW/m^2 close to the surface and decreases exponentially to zero at 1 cm thickness. The immersed blanket receives an average radiative heat flux of around 1.5 kW/m^2, which heats the blanket thereby lowering the sensible enthalpy of gasification. This reduction causes more fuel to be vaporized thereby increasing the burning rate, which further increases the radiative heat flux. However, because there are no collectors in Test 2, the blanket is heated only by radiative absorption, which limits the burning rate to 6 mm/min as shown in Fig. 9. Note, that this is double the baseline value of 3 mm/min, showing that efficient collection of radiative absorption alone can increase the burning rate.

When coils are added to the blanket, the burning rate increases even more as shown in Fig. 9, Test 3 – 5. The coils collect heat from the flame and serve as additional pathway providing heat to the immersed blanket by conduction. Figure 9 shows that the steady burning rate reaches a value of 17.3 mm/min at 48 coils (Test 5) which is ~6 times the baseline case (3 mm/min).

Table 1 Heat Transfer Analysis of the Field Experiments

Test #	**Description**	**MLR (mm/min)**	$\ddot{Q}_{VAP}$ **(kW/m^2)**	χ_r **(%)**
1	Baseline	3.04	27.29	1.39
2	Blanket	5.60	50.91	2.59
3	Blanket with 32 coils	8.33	75.76	3.86
4	Blanket with 48 coils	12.81	116.49	5.94
5	Blanket with 48 coils	17.33	157.63	8.04

Table 1 shows the fraction of the heat received by the oil to the total heat released χ_r, the fraction of total energy transmitted back to the fuel, is calculated by

$$\chi_r = \frac{Q_{VAP}}{HRR_{Baseline}} \times 1, \quad (1)$$

where, $HRR_{Baseline}$ is the heat release rate of the baseline test assuming complete combustion. Heat of combustion of crude oil, 38 MJ/kg (Iwata et al., 2001), was multiplied with the measured baseline MLR to calculate the $HRR_{Baseline}$. $\ddot{Q}_{VAP}$, the total heat feedback from the flame needed to vaporize the liquid fuel, is calculated by multiplying the heat of vaporization, ΔH_{VAP}, with the measured MLR. In the calculation of ΔH_{VAP} (sensible and latent), it is assumed that HOOPs crude oil has the heat capacity similar to a long chain alkane molecule such as nonadecane (19 carbon atoms) and has a boiling regime of ~200-300 °C. Crude oil does not "boil off" in a pool fire. Light fractions may boil off but the more predominant heavy components break down into lighter molecules and vaporize at temperatures in the range of 250 – 350 °C. This breakdown is endothermic and is assumed equivalent to a latent heat of vaporization of ~ 250 kJ/kg (Torero et al., 2003). Table 1 shows that for the baseline field experiments, the χ_r is 1.4 %. Adding the Flame Refluxer™ increases the heat transfer efficiency levels to 3, 4, 6, and 8% with increasing additions of coils to improve the collection of heat.

It is clear that with an increase in the number of coils the collection of heat improves significantly, which results in a greater component of the heat generated by the fire to be drawn back to the liquid fuel which enhances vaporization and promotes burning. For the optimum case (Test 5), χ_r equals 8.04%. This value can be increased even further by proper choice of collector material and further optimization of the collector geometry. Arsava et al., 2018b and Sezer et al., 2017b show the controlling parameters for the collector-heater sections of the Flame Refluxer and can be used to scale the technology based on oil slick thickness.

4.3 Temperature distribution (in-depth and lateral)

A total of 238 TCs were used to measure lateral and in-depth temperature profiles in the gas phase just above the fuel layer (y = 0.5 cm), gas-fuel-blanket interface (y = 0 cm), blanket-fuel interface (y = -0.5 cm) and fuel-water interface (y = -1 cm) (Fig. 10 - 12). Figure 10 shows the steady temperature profiles in the gas phase at different horizontal planes along the vertical axis. The temperature at 5 cm above the burning liquid is around 800 °C for all experiments. The flame tilt in the direction of the wind speed is also observable from the temperature profiles as shown in Fig. 10. For example, in the blanket only case (Fig. 10 c), the average wind speed is 3.42 m/s in the North to South direction. Correspondingly the flame tilts at an angle of 39° (Fig. 10a) in this direction. The temperature profiles also align in the North to South direction in this case as shown in Fig. 10c. The alteration of the temperature profile because of wind tilt becomes more pronounced with elevation as shown in Fig. 10. The flame tilt influences the heat transfer to the coils. However, the high conductive blanket immersed in the liquid layer is able to distribute the heat laterally. Heat transfer is coupled by 2-phase flow effects (film boiling, nucleate boiling) that occur on the blanket. Visual observations during the experiments revealed significant nucleate boiling on the heater surface, i.e. a rush of vapor bubbles rising up along the heater perimeter and flowing radially outward to form a thin froth on the pool surface.

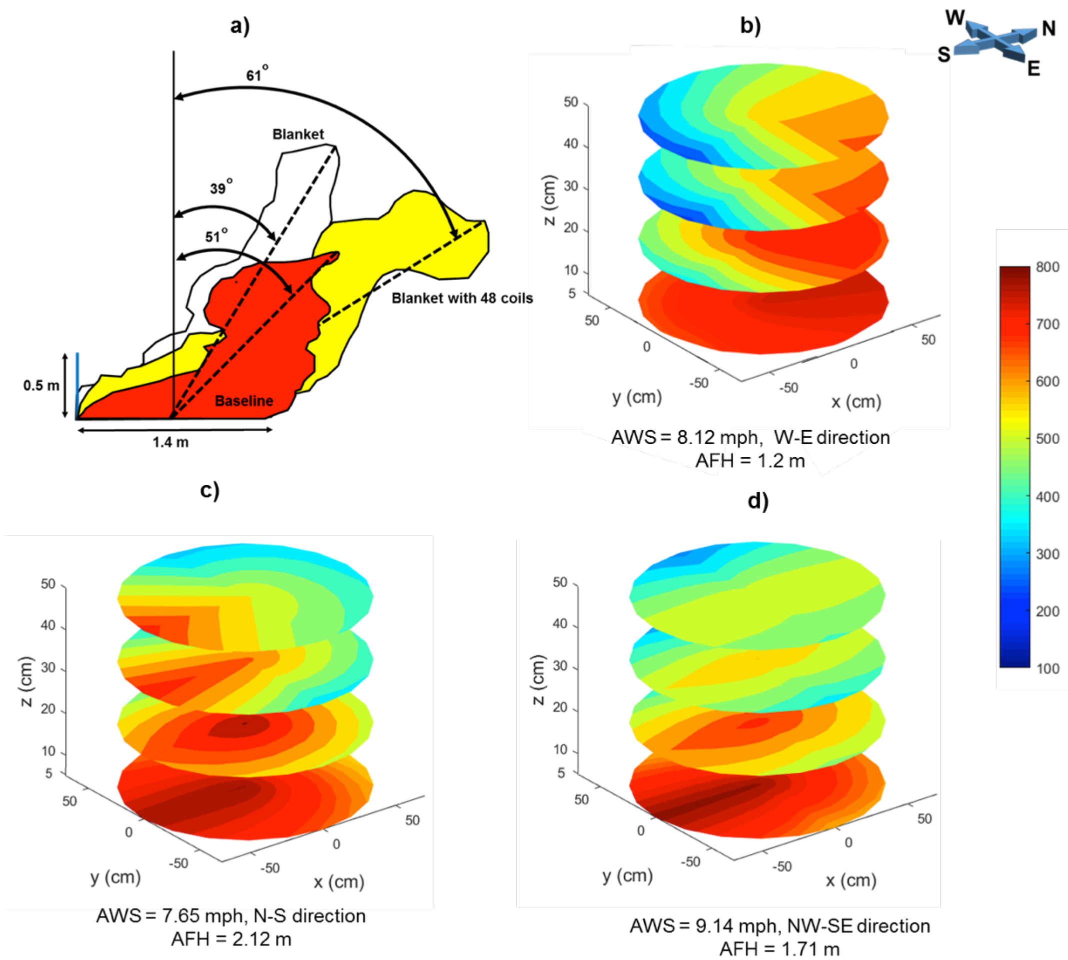

Figure 10 Flame geometry and plume temperature contours at steady state a) flame tilt angle on downwind direction b) baseline, c) blanket, d) blanket with 48 coils (Test 5). Contour units are in °C, AWS = Average wind speed, AFH = Average flame height.

Figure 11 shows the in-depth temperature profiles for the baseline (Test 1), blanket (Test 2), and blanket + 48 coils (Test 5) along the centerline. It is clear that the blanket + 48 coils (Test 5) field experiment shown by the red curve in Fig. 11 has significantly increased in depth heat penetration. The baseline (dotted curve) shows a high temperature at the oil surface and slowly decreases up to a depth of 0.4 cm followed by a sharp decrease to the oil-water interface where there is a sharp decrease at the oil water interface. With the addition of a blanket (dashed curve) the surface temperature increases by 20 °C. This is mainly because of indepth radiation absorption as explained earlier. This causes a decrease in the specific enthalpy of the oil layer in contact with the blanket facilitating evaporation. The resulting nucleate boiling may also lead to the increase in the mass transfer. With the addition of coils (solid red curve), there is an overall increase in the temperatures throughout the oil layer, especially in the layer of oil below the blanket-oil interface. Somewhere around the middle of the blanket, a high temperature zone exists where the temperature gradient is extremely high as shown in Fig. 11. This region has very high heat transfer rates probably because of nucleate boiling.

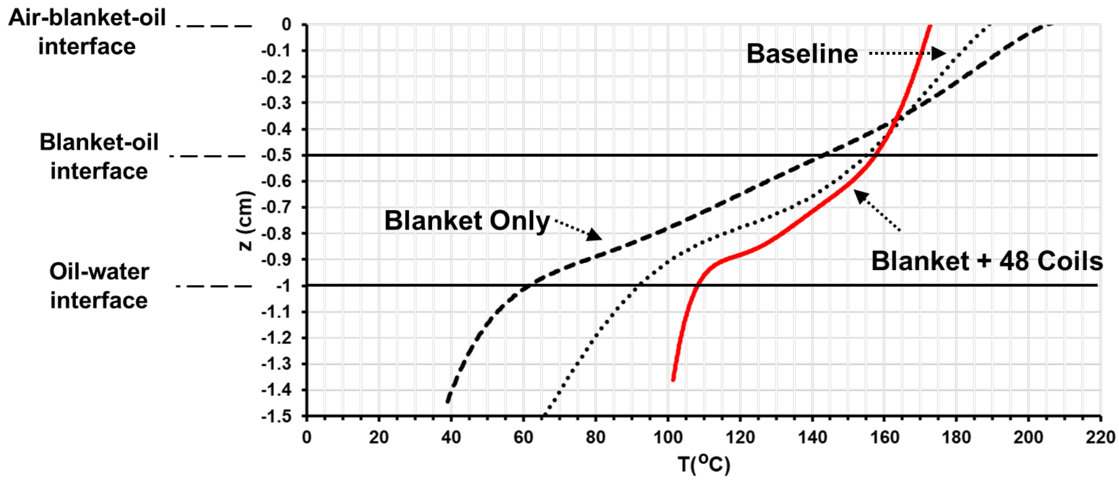

Figure 11 Steady state gas-liquid interface temperature of the baseline, blanket, and blanket with 48 coils (Test 5) collected from the center TC tree (Fig. 5).

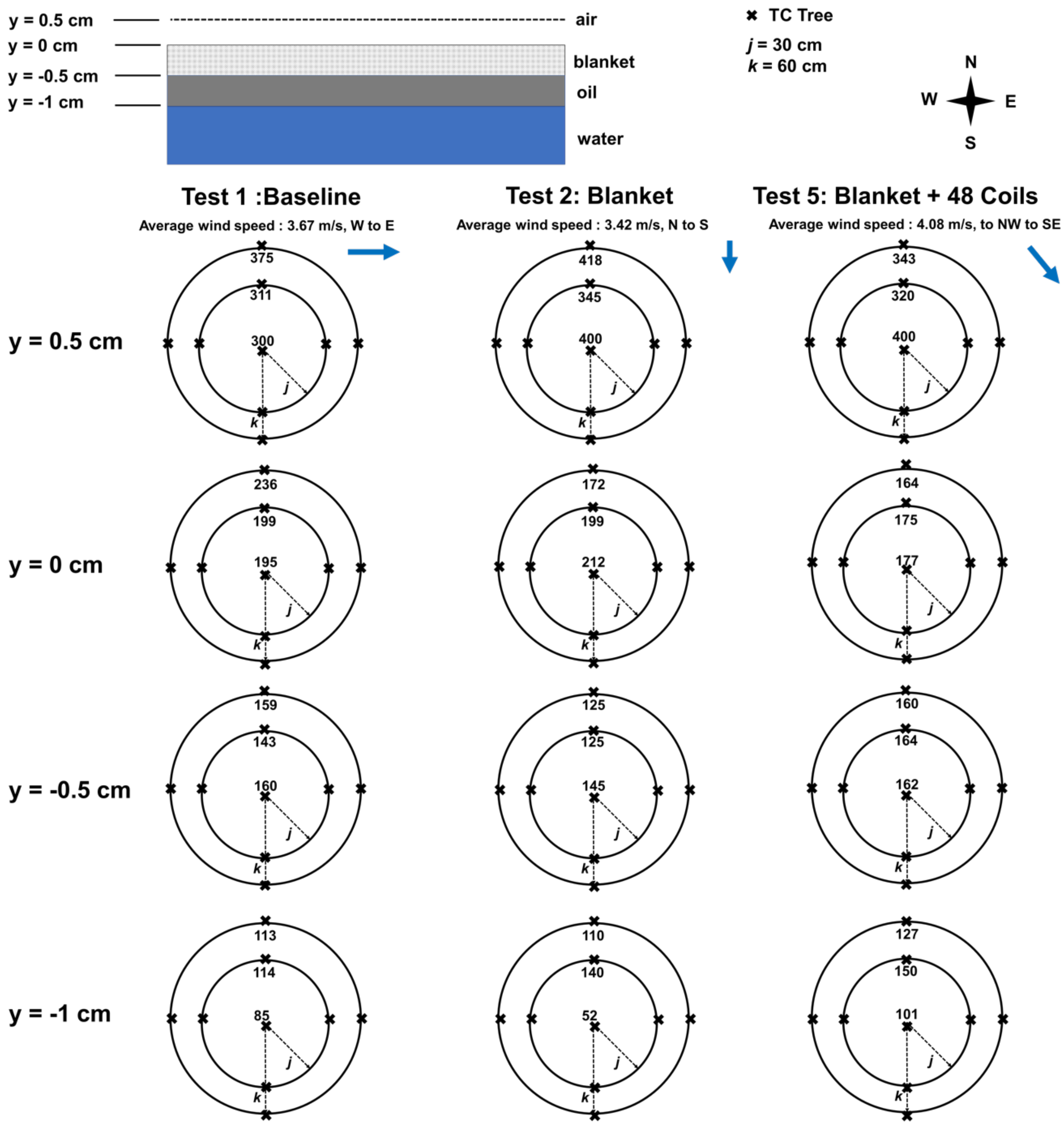

Figure 12 Temperature at steady state for baseline (Test 1), blanket (Test 2) and blanket with 48 coils (Test 5). All numbers are in °C. Crosses denote the location of thermocouples. Numbers denote average temperature spatially averaged (4 locations) and temporally averaged (120 data points). The arrow indicates average wind direction during the experiment.

Figure 12 also shows that the addition of a blanket improves the lateral heat transfer. At y = 0 cm the temperatures are more uniform compared to the baseline case. Just above the surface, in the gas phase, the temperatures are higher compared to the baseline showing re-radiation from the blanket surface to the gas layer above. However, further in depth at y = -0.5 cm and y = -1 cm, the temperatures measured in the blanket are lower than the baseline case. The doubling of the mass-burning rate with the blanket only experiment (Test 2) is mainly because of heat retention in the blanket and the corresponding decrease in the specific enthalpy.

With the addition of coils (Test 5) it is observed that the temperature is mostly uniform all across the oil slick at all depths. This shows the excellent in-depth dissipation capability of the system. In addition, the coils serve as good heat collectors thereby adding more heat to the blanket, which causes significantly higher temperatures in-depth. For example, at y = -1 cm which is at the bottom of the oil slick, the highest temperatures are recorded in Test 5. This in-depth and lateral dissipation of heat increases the number of nucleate boiling sites as well. The mass burning rate is significantly improved (6 times of baseline).

4.4 Residue Removal

Table 2 shows the post burn oil-residue measurements for the 5 field trials. Analysis of the amount of post burn residue left on the water is important because it shows how efficiently the flame burns the tar (heavy components of oil) and reduces the post burn cleaning cost.

Table 2 Post burn residue

	Baseline	Blanket	Blanket + 32 coils	Blanket + 48 coils (Test 4)	Blanket + 48 coils (Test 5)
Fuel pumped into the burner ring (kg)	62.15	150.78	156.81	349.16	279.00
Residue left on water (kg)	20.03	2.87	1.83	2.30	1.04
Residue accumulated in blanket (kg)	-	2.95	2.82	3.06	4.00
Residue (%)	**32.2**	**3.8**	**2.9**	**1.5**	**1.8**

The residue removal was calculated as:

$$Residue = \frac{Residue\ collected\ on\ water\ (kg)}{Total\ fuel\ pumped\ (kg)} \times 100. \quad (2)$$

Table 1 shows that only 68 % (62 kg fresh oil pumped, 20 kg residue collected) of the oil pumped during the baseline experiment actually burned. The residue was significantly reduced by around 15 times with the introduction of blanket and coils into the pool. As an example, only 1.8% of the oil pumped into the system was left on water for the blanket with 48 coils (Test 5) case (Table 1).

Figure 13 shows the post burn residue remaining on the water after the baseline and blanket with 48 coils tests (Test 5).

a) b)

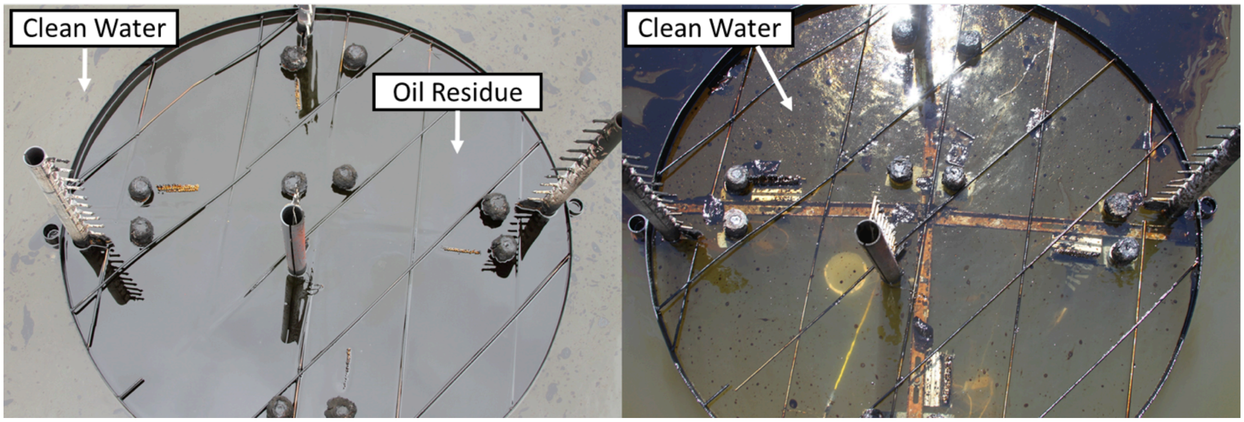

Figure 13 Post burn residue left on water a) Baseline, b) Blanket with 48 coils (Test 5).

Figure 13a shows the unburned residue remained as a thick layer (~3 mm) of tar on water. Figure 13b shows the burner ring after removing the blanket with 48 coils (Test 5). 279 kg (~240 l) of fresh HOOPs crude oil was pumped into the burning ring to maintain the 1 cm thick fuel layer during the test. Note that this is ~5 times higher than the baseline case. Even with the high amount of fuel put in to the burner ring there was almost no post burn residue. Except for small oil pockets, the water was clean.

The blanket increases the residue removal by extending the extinction time, adding nucleate boiling regions, and acting as a wick. With addition of blanket, the volumetric specific heat increases thereby increasing heat retention in the oil slick, which facilitates sustained combustion even in very thin oil slicks (2-3 mm). High thermal capacity of the blanket prevents the blanket to cool down even when it is in contact with water.

5 Conclusions

Five field scale experiments were performed at the United States Coast Guard (USCG) test facility at Little Sand Island in Mobile Bay, to demonstrate the effectiveness of the Flame Refluxer technology in increasing the burning rate, reducing post burn residue and reducing emissions. The experiments comprised of a 1.4m diameter oil slick of thickness equal to 1cm. The experiments showed that the Flame Refluxer can increase the burning rate of oil slicks on water by a factor of 6 mainly because of an increase in fraction of heat transmitted to the oil slick by the flame. In depth and lateral heat penetration and an increase in temperature of the blanket causes nucleate boiling promoting the heat and mass transfer processes. A significant reduction in post burn residue on water was also observed. The heat stored in the blanket facilitated an efficient burn of tar.

The field trials demonstrate that immersed thermally conductive porous media can provide a second heat feedback path between the flame and the pool, thereby increasing the burning rate when compared to the baseline case. The concept can be applied as a new in-situ burning concept capable of enhanced combustion of oil slicks in containment booms. Additional work will also be needed to develop this concept into an operational system.

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References

Arava, S., K.S. Arsava, A.S. Rangwala, H. Sezer, A. Walawalkar, V. Raghavan, "Method and Apparatus for Waste Combustion", Patent, US20180149356A1, 2018.

Arsava, K. S., A.S. Rangwala, G. Mahnken, "Systems and Methods for In-situ Clean-up of Burnable Aaterials", Patent, US10167602B2, 2016.

Arsava, K.S., H. Sezer, P. Tukaew, T. J. Borth, D. J. Petrow, S.P. Kozhumal, G. Mahnken, R.G. Zalosh, J. L. Torero, A. S. Rangwala, "Enhanced Burning of Oil Slicks," Report, BSEE Contract No. E15PC00004, 2017a.

Arsava, K.S. A.S. Rangwala, K. Hansen, "An Offshore In-situ Burn Enhanced by Immersed Objects" in *Proceedings of the Fortieth AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Calgary, Alberta, 833-843, 2017b.

Arsava, K.S., G. Mahnken, A.S. Rangwala, "Use of Immersed Conductive Objects to Enhance the Burning Rate of Hydrocarbon Pool Fires" *Cold Regions Science and Technology*, 146:133-141, 2018a.

Arsava, K.S., V. Raghavan, A.S. Rangwala, "Enhanced Oil Spill Clean-Up Using Immersed Thermally Conductive Objects" *Fire Technology*, 54:1745–1758, 2018b.

ASTM E1354, "Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter", 2017.

Brosmer, M.A., C.L. Tien, "Radiative Energy Blockage In Large Pool Fires" *Combustion Science and Rechnology*, *51*(1-3):21-37, 1987.

Buist, I., J. McCourt, S. Potter, S. L. Ross, K. Trudel, "In Situ burning." *Pure and Applied Chemistry*, 71(1):43-65, 1999.

Fingas, M., *Oil Spill Science and Technology*, Gulf Professional Publishing, 2016.

Fingas, M., "A Guide to In-situ Burning of Oil Spills on Water, Shore, and Land", ARPEL Emergency Response Planning Workshop, 2006.

Garo, J.P., J.P. Vantelon, S. Gandhi, J.L. Torero, "Some Observations on the Pre-boilover Burning of a Slick of Oil on Water", *Spill Science & Technology Bulletin,* 5(2):141-151, 1999.

Gritzo, L.A., W. Gill, V.F. Nicolette, "Estimates of The Extent and Character of The Oxygen-Starved Interior in Large Pool Fires", *Very Large-Scale Fires*, ASTM International, 1998.

Gritzo, L.A.,V.F. Nicolette, "Coupling of Large Fire Phenomenon with Object Geometry and Object Thermal Response", *Journal of Fire Sciences*, 15:427-442, 1997.

Ghoneim, A.F., X. Zhanga, O. Knioa, H.R. Baum, R.G. Rehm, "Dispersion and Deposition of Smoke Plumes Generated in Massive Fires", *Journal of Hazardous Materials*, 33(2), 275-293 1993.

Hansen, K. A., K. Stone, "Refurbishment of In-Situ Burn Pan at Joint Maritime Test Facility (JMTF)," in *Proceedings of the Thirty-ninth AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Ottawa, ON, 820-830, 2016.

Inamura, T., K. Saito, K.A. Tagavi, "A Study of Boilover In Liquid Pool Fires Supported on Water. Part II: Effects of In-Depth Radiation Absorption", *Combustion Science and Technology*, 86:105-119, 1992.

Iwata

, Y., H. Koseki, M.L. Janssens, T. Takahashi, "Comparison of Combustion Characteristics of Various Crude Oils" *Int. Assoc. Fire Safety Science*, 7: 453–463, 2001.

Mullin, J.V., M.A. Champ, "Introduction/Overview to In Situ Burning of Oil Spills" *Spill Science and Technology Bulletin*, 8: 323-330, 2003.

National Public Radio (NPR), All Things Considered, D. Elliott, "Researchers Test Hotter, Faster, and Cleaner Way to Fight Oil Spills," Mar. 21, 2017.

Panetta P.D., S. Potter, "TRL Definitions for Oil Spill Response Technologies and Equipment", Report, BSEE Contract Number E14PC00020, Bureau of Safety and Environmental Enforcement (BSEE), U.S. Department of the Interior, Washington, D.C, 2016.

Ranellone, R.T., P. Tukaew, X. Shi, A.S. Rangwala, "Ignitability of Crude Oil and Its Oil-In-Water Products at Arctic Temperature", *Marine pollution bulletin*, 115(1-2), 261-265, 2017

Rangwala, A.S., K.S. Arsava, G. Mahnken, and S. Xiaochuan, "A Novel Experimental Approach to Enhance Burning Of Oil-Water Emulsions by Immersed Objects", Report, Bureu of Safety and Environmental Enforcement, U.S. Department of Interior, Washington, DC, USA, 2015a.

Rangwala, A.S., X. Shi, K.S. Arsava, G. Mahnken, "Methods and Systems for Clean-up of Hazardous Spills, Patent, WO US US9772108B2, 2015b.

Russell, L.H., J.A. Canfield, "Experimental Measurement of Heat Transfer to a Cylinder Immersed in a Large Aviation-fuel Fire", *Journal of Heat Transfer,* 95:3:397-404, 1973.

Sezer, H., K.S. Arsava, S.P. Kozhumal, A.S Rangwala, "The Effect of Embedded Objects on Pool Fire Burning Behavior" *International Journal of Heat and Mass Transfer*, 108:537–548, 2017a.

Sezer, H., K.S. Arsava, A.S. Rangwala, "Oil Spill Clean-Up Using Immersed Metal Wool," *Journal of Environmental Chemical Engineering*, 5:(5):5196-5206, 2017b.

Shi, X., P.W. Bellino, A.S. Rangwala, "Flame Heat Feedback from Crude Oil Fires in Ice Cavities", in *Proceedings of the Thirty-eight AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Halifax, Nova Scotia, 767-776, 2015.

Shi, X., N.S. Ghion, Y. Fu, K. T. Sundberg, J. P. Ramos, S. Stephansky, K. Ross, F. Kang, V. Raghavan, A.S. Rangwala, "Influence of Wicking Agent on In-situ Burning of Water-in-oil Products from Alaska North Slope Crude", in *Proceedings of the Thirty-ninth AMOP Technical*

Seminar on Environmental Contamination and Response, Environment Canada, Ottawa, ON, 751-759, 2016.

Torero, J.L., S.M. Olenick, J.P. Garo, J.P. Vantelon, "Determination of the Burning Characteristics of a Slick of Oil on Water", *Spill Science & Technology*, 8(4):379-390, 2003.

Tukaew P., "Outdoor Gas Emission Sampling System: A Novel Method for Quantification of Fires in Outdoor Conditions", MS Thesis, Worcester Polytechnic Institute, etd-050217-121733, 2017.

Tukaew, P., K.S. Arsava, S.L. Fields, A.S. Rangwala, "Outdoor Gas Emission Sampling System – Performance during Large Scale Fire Tests in Mobile Alabama", in *Proceedings of the Thirty-ninth AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Halifax, Nova Scotia, In-Press, 2019.

van Gelderen, L., M.V. Malmquist, G. Jomaas, "Crude oil burning mechanisms: A conceptual model review", in *Proceedings of the Thirty-eight AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Halifax, Nova Scotia, 2015a.

van Gelderen, L., N.L. Brogaard, M.X. Sørensen, J. Fritt-Rasmussen, A.S. Rangwala, G. Jomaas, "Importance of the slick thickness for effective in-situ burning of crude oil", *Fire Safety Journal*, 78:1-9, 2015b.

van Gelderen, L., G. Jomaas, "The Parameters Controlling the Burning Efficiency of In Situ Burning of Crude Oil on Water." in *Proceedings of the Thirty-eight AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Halifax, Nova Scotia 2017.

Wang, Z.X. "A three layer model for oil tank fires." *Fire Safety Science*, 2:209-220, 1989.

Walton, W.D., D.D Evans, K.B. McGrattan, H.R. Baum, W.H. Twilley, D. Madrzykowski, A.D. Putorti, R.G. Rehm, "In Situ Burning of Oil Spills: Mesoscale Experiments and Analysis", in *Proceedings of the Sixteenth AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Calgary, Alberta, 1993.

Wu, N., T. Mosman, S.M. Olenick, J.L. Torero, "The Effect of Weathering on Piloted Ignition and Flash Point of a Slick of Oil", in *Proceedings of the Twenty-first AMOP Technical Seminar on Environmental Contamination and Response*, Environment Canada, Ottawa, ON, 633-649, 1998.

Wu, N., G. Kolb, J.L. Torero, "The effect of weathering on the flammability of a slick of crude oil on a water bed", *Combustion Science and Technology,* 161:1:269-308, 2000.