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A Novel Oil-Water Emulsion Burner Concept for Offshore Oil Spill Clean Up

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Abstract

In-situ burning has been considered as a primary spill response option for oil spills since offshore drilling began in the Beaufort Sea (1970s). Since then, many studies and tests have been performed but researchers are still looking for a more efficient, simple and low cost way to burn the oil faster and as completely as possible. In this study, a new burner concept capable of enhanced combustion of oil-water emulsions and requiring no atomizing nozzles, moving parts and compressed gas for operation is discussed. The operating principle is based on use of immersed noncombustible objects of suitable geometry to transfer the heat generated by the combustion back to the fuel to create a feedback loop thereby sustain an increased burning rate. A 0.5 meter diameter prototype burner showing the viability of the design concept is discussed. Tests show that the submersed lower part of the conductive object can get hot enough to sustain nucleate boiling, significantly increasing the burning rate, when compared to the baseline pool fire, where vaporization is achieved solely by evaporation at the pool surface.

Introduction

In situ burning (ISB) of oil spills on water has a great deal of promise to quickly remove large quantities of oil from the water surface and can be an effective countermeasure during a spill cleanup [1]. Most ISB research is focused on open water burns and investigated the varying factors such as oil type, emulsification, degree of weathering (evaporation) and atmospheric conditions on the burning efficiency [2]. A relatively small amount of published research has focused on the usage on-site incinerators for offshore oil spill cleanup. The major drawback of the current ISB methods is the time required to contain and burn the spilled oil. Delayed intervention results in evaporation of the volatile, light hydrocarbons from the crude oil and leaves the heavier fractions that lead to formation of a stable water-in-oil emulsion [3]. This results in the oil slick becoming progressively more difficult to ignite and burn. One of the most promising strategies to dispose of large quantities of water-in-oil emulsions would be the use of on-site incinerators that are readily portable. Most incinerators deployed in the field use atomizing nozzles, moving parts or compressed gases [4-9]. Usage of electronics and moving parts demands frequent maintenance, which limits the operation of incinerators in extreme weather conditions and remote locations. This forms the motivation of the current study to develop a new burner technology capable of enhanced combustion of water-in-oil emulsions. The operating principle of the burner is based on use of immersed noncombustible and thermally conductive objects to transfer the collected radiative and convective heat generated by the combustion back to the fuel (US. Patent 20160123582). Figure 1 shows a schematic of the concept. The mechanisms that control the burning rate in the presence of thermally conductive immersed objects (metal cylinders in this case) are also shown.

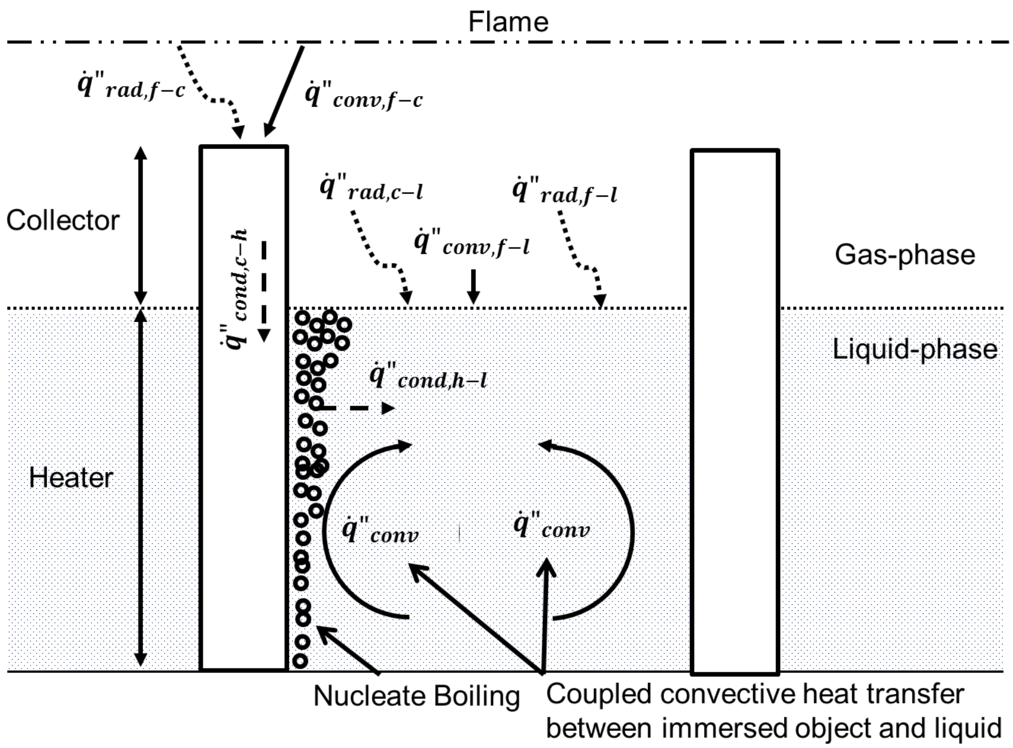

Figure 1. Schematic of the controlling heat transfer mechanisms during burning of a liquid fuel in the presence of immersed objects. Subscripts: conv = convective, cond = conductive, rad = radiative, f = flame, l = liquid, c = collector, h = heater.

As shown in Fig. 1, the flame immersed section, collector, is heated predominantly by the convective and radiative heat flux from the flame shown by $\dot{q}"_{conv,f-c}$ and $\dot{q}"_{rad,f-c}$, and radiative exchange from the neighboring cylinders. The heat is transferred from collector to heater via conduction (Fig.1). Then the heater heats the liquid by conduction, $\dot{q}"_{cond,h-l}$ and convection, $\dot{q}"_{conv}$. It is clear that besides heat from the flame denoted by $\dot{q}"_{conv,f-l}$ (convective) and, $\dot{q}"_{rad,f-l}$ (radiative), the liquid fuel is also exchanging heat from the cylinder. This causes the burning rate to increase by an order of magnitude, thereby promoting faster combustion. The heat and mass transfer are further coupled by 2-phase flow effects (film boiling, nucleate boiling) that can occur on the surface of the heater.

Immersed objects can be in any shape, size, material and number to optimize heat transfer from flame to the fuel. This study uses a simple geometry comprising of a 1 cm diameter cylinder made of stainless steel (ss). The thin cylinder minimizes the transition period to preheat the system and ensures that there is no axial temperature gradient.

A 0.5 m diameter burner is designed and experiments using pure Alaska North Slope (ANS) crude oil (0% water content), and water-in-oil emulsions with a water content of 25%, 40% and 60% are performed to show the viability of the design concept. Temperature profile and mass loss rate data explain the coupling between the heat transfer from the flame to the immersed object. It is shown that the burner is able to burn water-in-oil emulsions achieving an efficiency of 174% above baseline (without immersed objects).

Experimental Apparatus

The burning behavior of water-in-oil emulsion with and without immersed objects was studied by performing pool fire tests in a 0.5 meter diameter, 15 cm deep steel burner as shown in Fig. 2. The burner was equipped with a cooling jacket (Fig. 2a). Tap water with a flow rate of 12 L/min passed through the cooling jacket. This method minimizes the influence of the hot pan on combustion to ensure the immersed object is the only factor that affects the burning behavior. A continuous feeding system comprised of a fuel supply tank, an Omega FPU5MT peristaltic pump, and a fuel level observation pipe was used to keep the fuel level constant at 14 cm during the tests (Fig. 2a). The intent was to maintain the high thermal output from cylinder to fuel by keeping the fuel-heater interaction surface constant during the test. The fuel supply tank (19 lt pail) was placed on a load cell with an accuracy of ± 0.5 g. The fuel level observation pipe, a 2 cm diameter polycarbonate tube, was used to visually monitor the fuel level in the burner. The pumping rate, which is equal to the mass loss rate, was adjusted to keep the fuel level constant in the fuel level observation pipe.

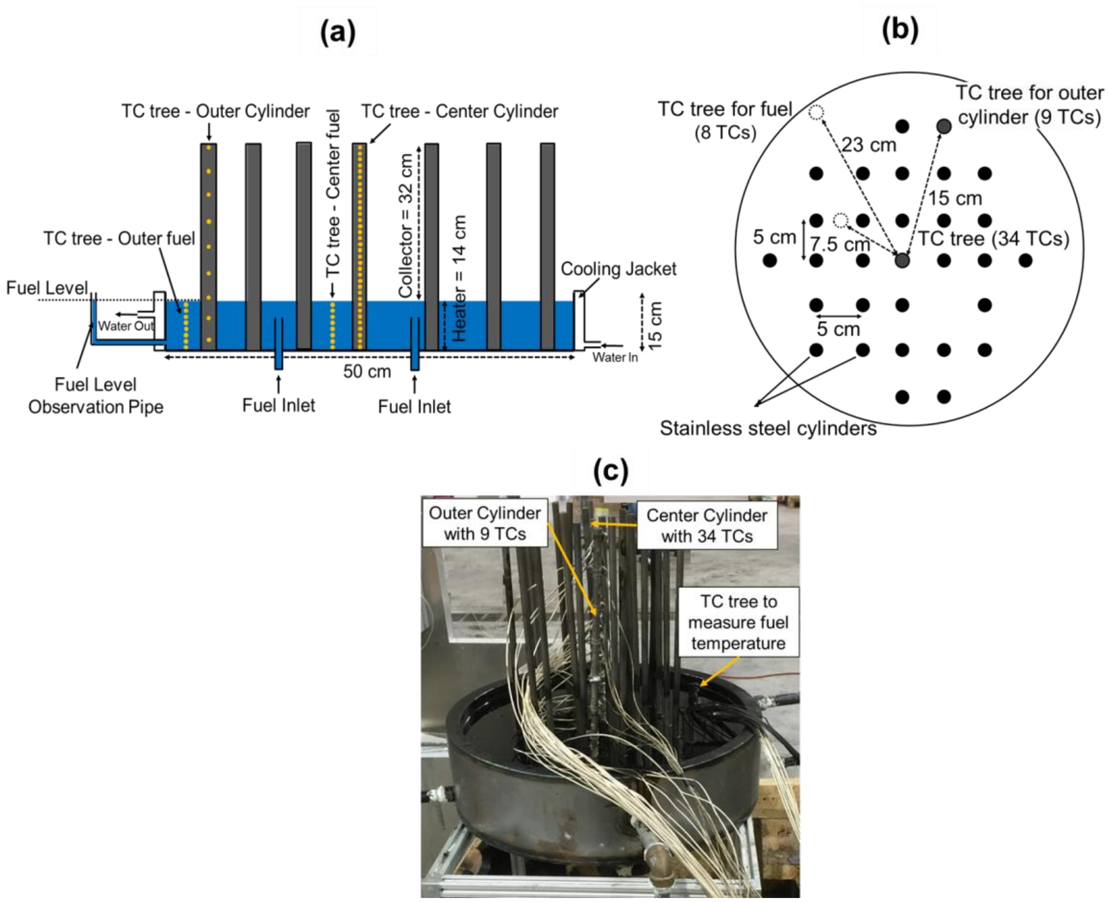

Figure 2. Prototype burner (a) Side view (b) Top view (c) Photograph of burner with instrumentation

As shown in Fig. 2a, two 1.3 cm diameter perforated inlet pipes were used to uniformly supply the ANS crude oil-water emulsion into the burner. A similar pipe (not shown) was used to drain the fuel out, enabling quick extinction of the flame by simply draining the burner. Further, crude oil-and-water emulsion samples were also collected during a burn, to ensure quality of the emulsion during the tests. The main advantages of the prototype burner are: high efficiency, no moving parts, minimum maintenance, low cost, ease of modification (by changing the height and number of immersed objects) and safe operation and extinguishment.

Experiments were performed with and without immersed objects to analyze the effectiveness of the proposed concept. The immersed objects in the current experiments comprised of 30 stainless steel cylinders, 1cm in diameter and 46 cm high (Fig. 2b). The cylinders were fixed using a portable non-conductive base (3 cm thick). The portable base allowed easy changes to the layout of cylinders, instrumentation, and transition between baseline tests and tests with immersed objects.

As shown in Fig. 2, four thermocouple (TC) arrays (0.05 cm diameter, K-type) were used to measure the temperature distribution of the emulsion and the cylinders. The cylinder at the center was instrumented with 34 TCs embedded on the surface a spacing of 1.3 cm to measure the axial temperature gradient. Nine TCs were also embedded on the surface of an outer cylinder (close to the rim) with 5 cm spacing. As shown in Fig. 2b, two TC arrays with 8 TCs each were used to measure the temperature distribution inside the fuel at two locations. The first fuel TC array was placed 7.5 cm away from the center, while the second was 23 cm away from the center.

Results and discussion

Figure 3 shows the temperature distribution at steady state for three types of fuels tested (pure ANS crude oil, ANS crude oil with 25 % water content, and ANS crude oil with 40 % water content). The addition of immersed objects causes a ~ 60 ^{o}C increase in the fuel temperature compared to the baseline. The increase in the fuel temperature is because of a heat feedback loop enabling increased heat transfer from the flame to the fuel. As water content increases, the overall burning rate decreases. This is also evident from the average collector temperature reducing from ~700 ^{o}C to 667 ^{o}C as the water content increases to 40 %. However, the presence of the cylinders significantly increase the burning rate compared to the baseline as shown in Fig. 4. The collectors effectively heat up and transfer the heat to the heater. As shown in Fig. 3, as the water content increases, the effective height of the collector decreases and the cylinder is subjected to higher heat loss. The height where the collector reaches to the highest temperature value was considered as the effective height. As an example, the effective collector height is 21 cm for pure ANS, while it decreases to 11 cm for the 40% emulsion. The results clearly show that finding a universal effective collector height, which covers all cases, is not possible. The collector height, shape and material can be computationally optimized to further enhance the burning rate, which was not attempted in the current study.

Figure 4 shows the mass loss rate in g/min with the prototype burner tested with increasing water content. The mass-burning rate significantly increases (~ average of 174 %) with the addition of the immersed cylinders when compared to the baseline cases as shown in Fig. 4. Further, the prototype burner is able to burn ANS crude oil with 60% water content which is impossible to burn in the baseline case as shown in the photographs in Fig. 5. In this context, a 0.1 cm (0.04") heptane layer was added as a starter fuel to the surface of the emulsion. The objective was to ignite the emulsion and achieve a self-sustaining steady state burn. However, the flame extinguished by itself in 3 min. When tested with the cylinders using the same approach, steady burning was achieved with an average mass loss rate of 20 g/min for the entire duration of the test. Figure 5 shows photographs of the baseline, baseline with starter and cylinders with starter for an ANS crude oil mixture with 60% water content.

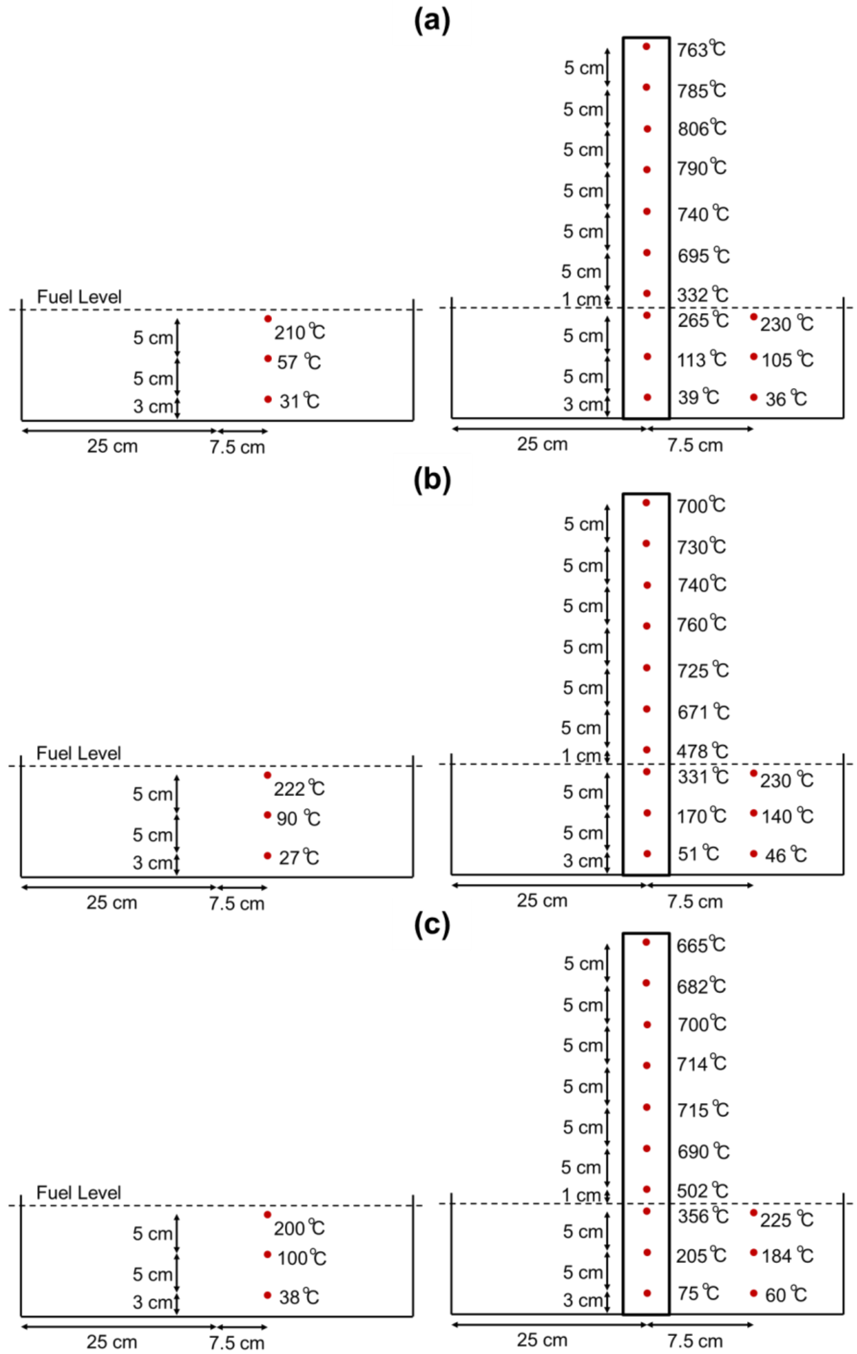

Figure 3. Temperature distribution within the fuel and cylinder at the center at steady state (ºC) – (a) Pure ANS (b) 25% water-in-oil emulsion (c) 40% water-in-oil emulsion

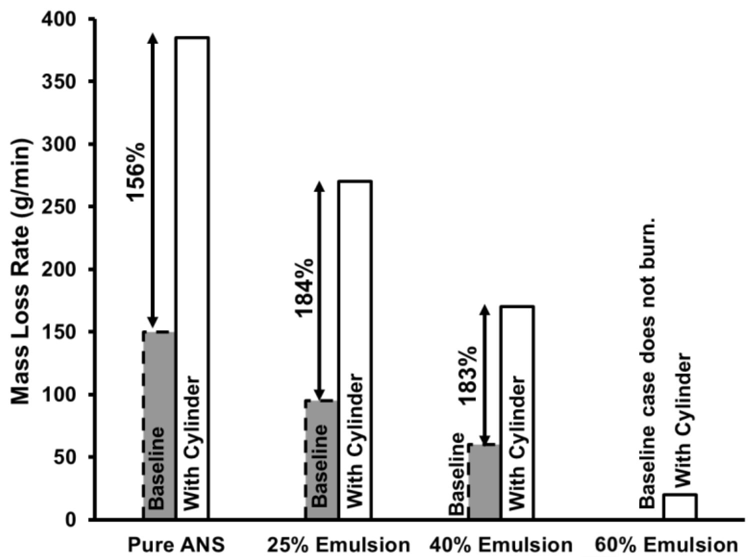

Figure 4. Burning enhancement (Efficiency)

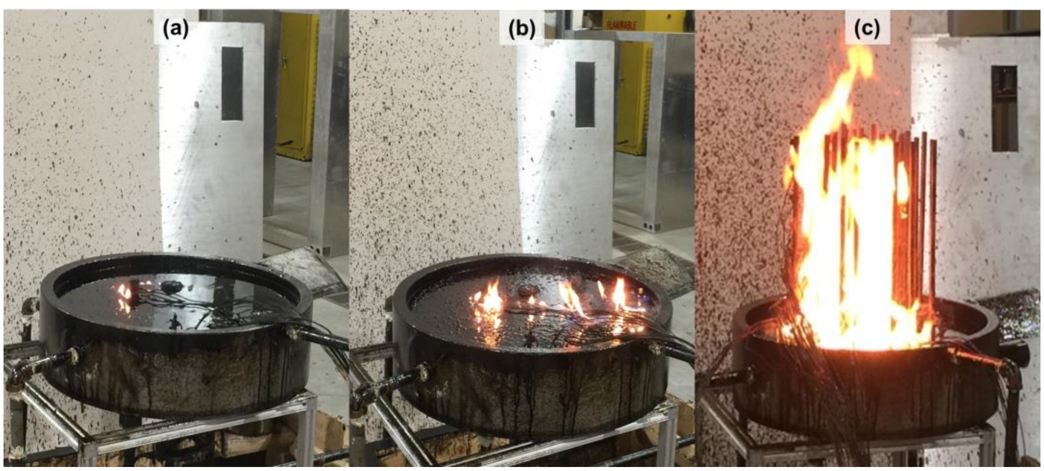

Figure 5. 60% water-in-oil emulsion tests (a) Baseline without starter (b) Baseline with starter (c) With cylinder with starter at steady state

Figure 6 shows the temperature distribution along the vertical axis of the cylinder at different time intervals both for the collector and heater. Fig. 6b shows the temperature of the cylinder immersed in the liquid (heater) and also the temperature of the fuel layer. As shown in Fig. 6a, initially at t =100 s, the temperature of the cylinder both in the liquid and the gas is low. The maximum temperature is around 200 ^{o}C around 30 cm in the gas phase. After 200s, the maximum temperature doubles to around 400 ^{o}C and occurs at a lower portion of the cylinder at around 22 cm. At around 700s, which is when steady state was reached based on the pumping rate of the fuel the temperature profile is almost constant from around 22 cm upwards in the gas phase (avg. temperature of ~ 700C). The temperature below 22 cm decreases and reaches a value of ~ 350 ^{o}C at the fuel-gas interface.

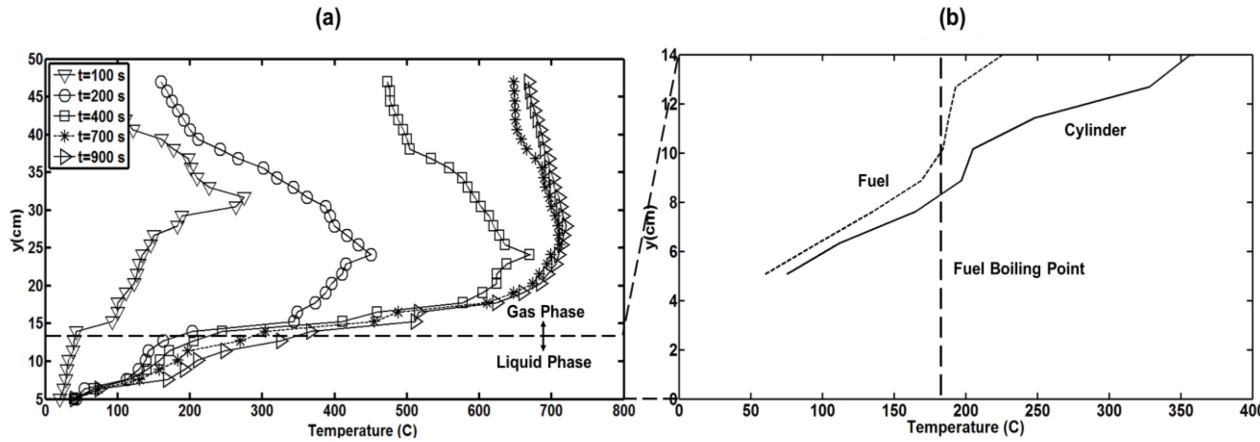

Figure 5: Temperature profile for the 40% emulsion test - (a) Vertical axis of the cylinder at the center (b) Liquid immersed section at steady state (700 s).

Distillation measurements of the ANS crude oil show that 32% of the components in the oil have boiling points in the range of 180 °C [10]. Figure 5b shows that temperatures in the upper section of the heater (~ 7 - 8 cm below the fuel surface) are well above the boiling point of the fuel, which indicates that the section of the cylinder immersed in the liquid is hot enough to result in significant nucleate boiling. In nucleate boiling, vapor forms on heater surface and separates as isolated bubbles, jets and columns, resulting in high heat transfer. Further, the additional vapor formed on the surface of the cylinders also acts as a source term for additional mass transfer.

Conclusions

This study investigated the use of conductive nonflammable objects immersed into a liquid pool to enhance its burning rate. A prototype burner was designed and built to show proof of concept of the proposed concept. Experimental results showed that the prototype burner successfully directs radiative and convective heat generated by the combustion back to the fuel; creating a feedback loop and thereby sustaining a significantly increased burning rate. The burner is able to burn water-in-oil emulsions achieving an efficiency of 174% above baseline. Further, the burner can achieve sustained combustion of a water-in-oil emulsion with 60% water that is not combustible otherwise. It should be noted that the burning rate can be further enhanced by optimization of the geometry/material/shape of the immersed object, which form future research directions of the study.

Acknowledgements and Disclosure

This study is funded by the Bureau of Safety and Environmental Enforcement, US Department of the Interior, Washington, D.C., under Contract Number E14PC00043. The contents do not necessarily reflect the views and policies of the BSEE, nor does mention of the trade names or commercial products constitute endorsement or recommendation for use. The burner described in this study is patented (US. Patent 20160123582) and licensed to Global Fire Products Inc. Rangwala has an equity interest in Global Fire Products Inc. and also serves on the Scientific Advisory Board. The terms of this arrangement have been reviewed and approved by Worcester Polytechnic Institute in accordance with its conflict of interest policies.

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