DEVELOPMENT OF THE ELECTROMAGNETIC BOOM **AND MOP SYSTEMS (EMOP)**

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Several large-scale oil spills typically occur in the USA and other places around the world, and the Great Lakes are not immune from such threatening events. The clean-up process is inefficient and can have severe environmental impacts. An innovative, electromagnetic-based approach for oil spill remediation has been developed by Natural Science, LLC that uses micron-sized magnetite (Fe₃O₄) particles which are reusable, recoverable, and environmentally safe.

INTRODUCTION

must maintain attribution In the past four decades, there has been an oil spill somewhere in the world each year, and in some years there are several. While many of these are small, larger spills are not work uncommon. Though oil spills are inevitable, the techniques this we use to combat them are choices based on available technologies, insight, and innovation. of

Clean up of these spills is still largely inefficient, timedistribution consuming, and expensive. One of the most widely used devices during an oil spill is the boom, which is supposed to provide a containment barrier for the spilled oil and to protect our shores. Although some effort has gone into the **V**I design of deployment mechanisms and designs aimed to 8 improve the tow rates and buoyancies of these passive de-20 vices, no innovation has been made toward making these 0 devices active. The ability to deploy a single device (syslicence (tem) that controls and efficiently removes spilled oil is a much-needed innovation to adequately protect and prepare for future oil spills worldwide. 3.0

In addition, standard oil booms and skimmer combina-ВΥ tions generally target surface oil. However, a relatively re-00 cent complication is starting to emerge. The explosion in the tar sands production in western Canada also means increasof ing amounts of heavy crude oil is making its way to the terms American Midwest via the Great Lakes. There is a growing concern regarding our ability to remediate spills for such the i heavy hydrocarbons that have the potential to sink. The magnetite particles used in our process have been demonunder strated to target oil below the water surface. The particles used will descend in pure water until they encounter and bond with oil. The electromagnetic field of our booms can exè tend some distance below the surface and will attract any mav magnetizable oil within its reach.

work The likelihood for spills has increased over time, but environmentally safe methods of remediation, control and from this manipulation of oil have not been fully developed. The electromagnetic boom technology is a potentially gamechanging advance [1]. The process works when micronsized magnetite (Fe₃O₄) particles are dispersed in oil on water. The particles form a unique and preferential bond with the oil due to a combination of forces, dominated by the Van der Waals force. Magnetic fields can then be used to manipulate, trap and remove the oil with high efficiency. In the case of oil spills on water, the water becomes the primary transport medium for manipulating the oil. Both the particles and the oil are recaptured and separated for reuse. This process is being applied to electromagnetic systems that can replace and/or increase the efficiency of the passive boom and skimmer systems used today. In addition, the methods described can be used to remove oil from other surfaces and can target oil on the order of scale of the particles (micron scales).

THE FUNDAMENTAL CONCEPTS

The fundamental concepts involved in the seeding of oil with magnetite, the magnetic manipulation of the combination, the separation of the magnetite particles at the end of the process, and the magnetorheological effects are described in this section.

Seeding Process

This invention [2] provides a seeding process that preferentially targets oil on water by trapping the micron sized magnetite or iron oxide particles (the "particles") in the oil/water combination. The process is dominated by the Van der Waals force in the aqueous phase. The particles preferentially bond with the oil while passing through any water free of oil. As a result, this provides a method to determine where the oil is located at the micron scale (even when it is not visible to the naked eye). Figures 1 and 2 below illustrate the concept. The limiting scale is of the order of the size of the magnetite particles used. This method can therefore be used as a probe for targeting oil on water at the micron scale and above and thus



Figure1: Illustrating the fact that the particles preferentially stay with the oil.

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render it magnetic. The application of the appropriately designed magnetic fields can then be used to manipulate the oil and is described later.



Water with no oil present

Water with oil presen

Figure 2: Magnetite particles preferentially bond with the oil when it's present in the water.

Magnetic Manipulation

Oil on water will typically diffuse outward as shown in Fig. 3 under its own viscous forces until it reaches an equilibrium. We demonstrate in Fig. 4 that this diffusion rate is reduced (or inhibited) as a consequence of the seeding process depending on the concentration of particles dispersed. In the absence of external forces, the parcel of oil is confined and can be controlled by magnetic forces.



Figure 3: Illustration showing a parcel of oil diffusing outward without magnetite particles. The same parcel of oil does not diffuse outward if the particles are added.





Figure 4: Oil seeded with magnetite is held from diffusing outward to cover the entire surface area as normally would

when the particles are not present. It is not necessary to uniformly distribute the particles to achieve confinement. The entire parcel of oil sits on water and moves when magnetic forces are applied as shown in Fig. 5. The water serves as the transport medium [3].



Figure 5: Snapshot of oil with a small amount of magnetite on water moving in the presence of a magnetic field. The arrows show the direction of the field gradient and the force direction.

Magnetic Separation

Due to the size of the particles and the nature of the bond with the oil, magnetic forces work well at moving the combination (oil + magnetite) on water. At the interface of the water with another surface (the container in this case) the friction and surface tension forces differ enough to extract the particles as they pileup at the boundary interface between the magnet and the water. The magnet can easily lift the particles from the water against this interface. See snapshot images below in Fig. 6.



Figure 6: Sequence of images illustrating the magnetic separation of the magnetite particles from the oil using a permanent magnet.

Magnetorheological Effect

When the particles are dispersed in oil on water or on any non-porous surface they are for the most part randomly distributed. In the presence of an applied magnetic field the particles will align themselves with the direction of the magnetic field.



Figure 7: Oil and particles without the magnetic field and with a magnetic field present.

Each particle is essentially a very small dipole magnet in the presence of the external magnetic field. In addition to

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aligning with the field, they also attract each other. This directional alignment adds rigidity to the fluid combination (oil + magnetite) which enhances its viscosity effects orthogonal to the direction of the induced field. This induced viscosity effectively ("effective viscosity") produces the rigidity that allows the combination to be lifted either from water or from other surfaces. Figure 7 shows snapshot images of the combination before and after the magnetic field is applied.

DESIGN CONCEPT

author(s), title of t We have demonstrated how oil moves on water when we add magnetite particles and apply a magnetic field. We are to the engineering a system that will automate the process by shaping the magnetic fields so that we can guide spill oil attribution efficiently to a separation system where it is then collected, and the particles that were injected are removed for reuse. The system consists of modular boom structures made of solenoid magnets that are driven by a time dependent maintain pulsed current. This current, which gradually grows stronger axially, is distributed along the boom creating a must magnetic field gradient that attracts the magnetizable oil. The last solenoid in a module is coupled to a magnetic belt work (conveyer ramp) system illustrated in Fig. 8. The boom, which has a Teflon-like exterior, traps and moves the oil this along its axis. The rate at which this magnetized oil moves of along the axis is directly proportional to the magnetic field gradient and viscosity of the spilled oil. The water acts as the medium for transporting the oil.

distribution Once this magnetized oil moves along this electromagnetic boom it will eventually reach the belt that is magneti-Any cally coupled to the boom. Due to the angle of inclination 8. of the belt system, the belt speed, and the magnetic force, any excess water drips off the belt system while it keeps 201 the magnetized oil, delivering it to a separation container. 0 This container (not shown) is designed with a yet stronger licence magnetic field at its base. The magnetite naturally goes to the strongest magnetic force and will stick to the bottom of 3.0 the container while the oil and any remaining water sepa-BY rate. This allows for the magnetite to be reused and the oil to be removed. An animated demonstration is available 00 here: http://www.naturalscienceusa.com/products.html.



Figure 8: Simplified schematic of gradient solenoid and magnetic ramp system.

Pulsed Magnetic Field Concept

A traveling magnetic "pulsed-wave" gradient field system has been designed that produces the magnetic potential which attracts and moves oil on water. The system parameters are based on a stepped multiphase concept. The number of phases is chosen based on power consumption, flow efficiency, magnetic field strength, timing and the spacing of the magnets. This also includes the geometric factors associated with the magnets.

For the case of the solenoid magnets, chosen to produce a time varying magnetic gradient pulse that travels along its axis, the magnets are separated spatially by ~0.79 times the radius "R" of the coils. This spatial configuration provides gradient coupling between the coils because this spacing is less than the so called "Helmholtz spacing" for the coils. The dynamics of the system can be described in terms of the magnetic gradient of the configuration or analogously in terms of the magnetic potential of the configuration. The magnetic potential is proportional to the magnetic field squared. All of the parameters mentioned above are optimized to accommodate the magneto-fluid dynamics associate with oil flow on water in the presence of a magnetic force. This depends on the gradient of the magnetic force, the viscosity of the oil, drag force due to water and coupling among the particles in the oil.

The diagram in Fig. 9 shows a group of thin solenoid magnets that are pulsed in a 4-phase sequence. The resultant direction of flow is in the direction of the magnetic gradient which results from the pulse which moves to the right in the diagram. Figure 10 shows the magnetic potential, the flow direction, and the motion of the magnetic particle represented here by plus (+) signs.



Figure 9: Illustration of a pulsed magnetic system of magnetics for moving oil along the axis from left to right.



Figure 10: Magnetic potential and particle motion.

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Figure 11: Sequence of images showing oil and magnetite moving.

Engineering Demonstration

An engineering test of the "pulsed wave" system was conducted with oil and magnetite at various concentrations in a test pool of water to optimize the dynamics and efficiency for fluid flow. Figure 11 shows a module consisting of 9 solenoids optimally spaced and powered to provide a traveling magnetic gradient. Three (3) snapshots of the flow are shown. The light emitting diodes (l.e.d.) on the magnets indicate the amplitude of the voltage across each solenoid and the timing of the pulse sequence for each magnet. In snapshot 1, the oil and magnetite particles which have already been mixed are poured into the water as the magnetic pulse is initiated at the first solenoid. Snapshot 2 shows the fluid flowing into the first coil, and snapshot 3 shows the time at which the first solenoid is turned off and the second one is turned on. The arrow points to the combination entering this second solenoid. This pattern of flow repeats as the combination travels along the axis of the system from magnet-to-magnet as the magnetic field gradient moves through the 9-magnet arrangement in a pulsed sequence.

Description of the Pulsed Wave Sequence

Each magnet in a module goes through an identical on/off cycle governed by four variables illustrated in Fig. 12.

- The ramp time, T_{ramp}, mentioned above is the time it takes for the magnet to turn on or off and is fixed at 0.1319 s in our example.
- The peak time, T_{peak}, is the time in which the solenoid is at its peak current of 25 amps for this case.
- The off time, T_{off} is the time between pulses
- The delay time, T_{delay}, is the time between the start of a magnet's power cycle and the start of the next magnet's power cycle.

We also define a magnet's on time, $T_{on} = T_{ramp} + T_{peak} + T_{ramp}$, as the total time in which the magnet receives power, and the power cycle period $T_{period} = T_{on} + T_{off}$. In order to produce a chain of magnetic dipole fields that move from one end of a string of magnets to the other, T_{delay} must divide evenly into T_{period} . The optimum separation between

the dipole fields occurs when $T_{on} = T_{off}$. This was verified to be the cases where $T_{delay} = T_{on/2}$, $T_{on/3}$, and $T_{on/4}$.



Figure 12: A schematic plot of current versus time indicating the different time variables.

THE EMOP SYSTEM

The system will be modular and scalable. The final size and scale of the boom modules will be determined by the power and gradient optimization calculations. However, preliminary calculations suggest a starting size of 18 inch (0.45 m) O.D. x 60 inch (1.52 m) long would be adequate to demonstrate the principle. The maximum magnetic field on axis and the maximum achievable gradient should be optimized with all the functional requirements considered.



Figure 13: Modules combined to form electromagnetic boom.

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A visualization of the design concept for a configuration with several modules is shown in Fig. 13, and a cut-away of a standard module is shown in Fig.14.



Figure 14: Cut-away view of a standard module.

The electromagnetic boom system with separator will involve a unique set of capabilities compared to passive boom technology. The main aspects are: (1) the fundamental effects of the gradient of the boom solenoid fields on magnetized oil flow rate, (2) the pulsing of the field strength through the boom for "pumping action", (3) dispersal of the magnetite, (4) the efficacy of the magnetized conveyor belt coupled to the boom (see Fig. 15), and (5) the separation efficiency in the collection area for oil and magnetite. However, the bottom line will still be quantifying oil removal efficiency by comparing the collected separated oil volume to the initial spill oil volume. Another critical aspect will be the rate of recovery where the dynamics may be affected by temperature, oil viscosity, field gradient, conveyor belt speed, and other factors. These results can be compared to passive skimmer technology results previously obtained.



Figure 15: Schematic of collector and separator component of the system.

SUMMARY

In summary, we have described the fundamental concepts including the process that renders the oil magnetizable and susceptible to manipulation and control by gradient magnetic fields. We have also shown the model and the engineering test for a system based on gradient solenoidal coils. These provide the bases for the scalability of an electromagnetic boom system capable of remediating an oil spill on water. The technique uses micron-sized magnetite or other iron oxide particles which are recoverable, reusable, and environmentally benign compared to chemical dispersants.

PATENTS

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