Paraffinic sludge reduction in crude oil storage tanks through the use of shearing and resuspension

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Abstrakt

This paper presents a method of cleaning paraffinic crude oil sludge from storage tanks by shearing and resuspension using an in-line jet mixer. An explanation is presented of why sludge deposition occurs in storage tanks that contain paraffinic crude oil. Conventional methods of tank cleaning are discussed. A theory regarding the behaviour of a submerged fluid jet is presented and the concept of "critical energy minimum' is established.

This paper presents a method used to successfully clean a crude oil storage tank using an in-line jet mixer and the results of a practical case study are presented.

Key words: Paraffinic sludge reduction,

Notation

Vs Minimum critical velocity for suspension (Eqn. 1-1)
Shear stress (Eqn. 1-1)
μ Fluid viscosity (Eqn. 1-1)
du/dy Velocity gradient (Eqn. 1-1)
r_V Radius of transition for Vs

The formation of crude oil sludge

Most crude oils that are transported for refining have a propensity to separate into the heavier and lighter hydrocarbons from which the crude oil is composed. This problem is often exacerbated by cool temperatures, the venting of volatile components from the crude, and by the static condition of fluid during storage. The heavy ends that separate from the crude oil and are deposited on the bottoms of storage vessels are known as "tank bottoms", or "sludge".

Tank bottoms are a combination of hydrocarbons, sediment, paraffin and water. Tank bottoms can accelerate corrosion, reduce storage capacity and disrupt operations.

Paraffin-based crude oil sludge forms when the molecular orbitals of individual straight-chain hydrocarbons are blended by proximity, producing an induced dipole force that resists separation. These dipole forces are called London Dispersion Forces, or Van der Waal bonds, and are responsible for like molecular aggregation.

As the 'heavier' straight-chain hydrocarbons flocculate (heavier meaning predominantly the C_{20+} hydrocarbon molecules), they tend to fall out of suspension within a static fluid, where they accumulate on the tank floor as a viscous gel. Over time, this gel stratifies, as the volatile components within the gel are 'flashed' from the gel with changes in temperature and pressure. This departure of the volatile components results in a concentration increase of the heavier fractions within the sludge, resulting in increased density and viscosity and decreased mobility.

Conventional methods of reducing crude oil sludge

Traditionally the cleaning of crude oil storage tanks can be done using one of four methods:

Manual Cleaning

Manual cleaning is the most common and historically has been the cheapest method of tank cleaning. The cleaning is completed by entering the tank and using manual labour to move the sludge either out the door or to pumps stationed in the tank. Personnel spend long periods of time working in a toxic, flammable environment.

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The sludge may contain such harmful compounds as H_2S, benzene and lead. This method usually takes a long period of time, costing the tank operator money in lost storage capacity. Using this method, it is difficult to recover the usable hydrocarbons from the sludge that is removed. The majority of the sludge that is removed is usually disposed of as hazardous waste or incinerated. During the clean-out period, the tank is vented to atmosphere and releases vapours that can be harmful to the environment.

Robotic Methods

This is really a variation of the manual cleaning method, except that a remotely controlled robot is used to enter the tank and complete the labour. This method is very expensive and does not solve the venting and disposal problems. This is not a popular method with refinery owners and is primarily used in very dangerous environments only.

Chemical Cleaning

Chemical cleaning is gaining popularity and credibility as a method of tank cleaning. Various surfactants, solvents or bacteria are used to break down the complex molecules contained in the sludge and render them to their basic constituents – water, crude oil and particulate. This method relies on a chemical reaction and the speed, efficiency and thoroughness of the reaction are proportional the exposed surface area of the sludge. Therefore chemical cleaning methods require some sort of mixing apparatus or method of agitation.

Reduction through resuspension and shearing by fluid jet

Recently, significant advances have been made in the application of high velocity fluid jets that are introduced into the full crude oil tank for the purpose of resuspending the accumulated sludge and shearing the paraffin to prolong resuspension of the heavy hydrocarbon molecules.

The 'Critical Energy Minimum'

The basis for agitation of static volumes of crude oil lies in the theory that it is possible to introduce sufficient kinetic energy into the system to retard or prevent the formation of the induced dipole (the Van der Waal bond).

Preliminary investigations into sludge deposition by Exxon in the 1980's concluded that light crude oils require a minimum continuous energy input of 190 Watts/100 m^3 of volume in order to prevent sludge deposition. Typically, side-entry propeller mixers used for storage tank mixing and agitation are sized using this criteria.

More recent empirical evidence suggests that the continuous energy input required to prevent sludge formation in medium and heavy crudes is 280 – 375 Watts/100 m^3 of volume. This 'critical energy minimum' can be related to a minimum critical velocity for suspension, or V_S, which must be maintained throughout the entire fluid volume in order to prevent sludge formation.

The majority of crude oil storage tanks in use today are under-serviced in terms of V_S, resulting in uneven sludge deposition. This manifests as a sludge-free area immediately surrounding the propeller mixer, with substantial or severe deposition occurring beyond a specific radius, r_V, at which the fluid velocity drops below V_S.

Submerged Fluid Jet Theory

The ability of a submerged fluid jet to resuspend crude oil "sludge" is dictated primarily by two aspects of the sludge and parent fluid. These properties are the chemical composition of the material (i.e.: what molecules make up the sludge) and the viscosity of the material. In relation to the effectiveness of a jet mixer, the temperature-viscosity and composition-viscosity interrelationships and their effects on the efficiency of resuspension and shearing are of primary interest.

The ability of the system to "shear" the paraffin molecules depends in part on the viscosity of the fluid, as viscosity is a measure of the energy dissipated by a fluid in motion as it resists an applied shearing force. Fluids can exhibit two types of viscous behavior – Newtonian or non-Newtonian. When a fluid's resistance to a constantly changing applied shear stress increases as the shear stress increases and retraces the same curve when the shear stress rate change is reversed, that fluid is said to be exhibiting Newtonian behavior. Paraffin-based crude oil sludge (also commonly called "wax") behaves as a thixotropic non-Newtonian fluid. The behavior of the wax is classified as thixotropic because it physically displays thinning properties when shear stress is applied. This thinning is a result of the shear stress breaking the London Dispersion Forces that exist between wax molecules. This behavior is classified as non-Newtonian because when exposed to a critical level of shear stress, the resistance of the fluid to that stress is overcome and a physical change in the fluid results. When dealing with solid materials, this change is commonly referred to as hysteresis.

Therefore in the application of a resuspension jet, efficiency of the system is critical. The system must be designed to deliver as much shear stress as possible to the volume of fluid within the tank. Shear stress of a fluid is a function of the rate of angular deformation of the fluid and this rate is dependent on the velocity of the fluid. For example, in differential form, Newton's Law of Viscosity is stated as:

$$\tau = \mu \, (du/dy)$$

The velocity gradient *du/dy* may be visualized as the rate at which one layer of fluid moves relative to an adjacent layer. The term μ is a proportionality factor and is called the viscosity of the fluid. So the ability of a system to shear the wax molecules contained within the sludge is dependent on the velocity of the fluid jet and viscosity of the fluid.

Furthermore, research completed by Hjulstrom, Sundborg and Shields has quantitatively equated fluid velocity and viscosity with its ability to keep particles entrained. Based on our calculations and observations, the critical velocity of a typical crude oil required to keep sheared wax particles in suspension appears to be 0.6 – 1.2 m/sec. It also appears that the velocity required to initially entrain wax particles is higher, as the effects of friction and cohesion must be initially overcome. Computational Fluid Dynamics simulation research completed both by Heath Services Ltd. and independently by Dr. Siamack Shirazi of the University of Tulsa has accurately simulated the behavior and velocity a fluid jet when introduced to the storage tank environment.

In order to produce a resuspension system that is effective, losses in the pumping system must be reduced, in order that the maximum amount of energy is delivered to the sludge. The system must be further designed so that this energy is transmitted as fluid velocity, in order that the wax may be sheared, entrained and kept in suspension. The system must deliver maximum velocity in laminar flow, so that the energy is concentrated.

A data set has been collected which clearly demonstrates that side-entry propeller-type mixers are inefficient at generating the energy required to maintain wax in suspension in a sizeable crude oil tank. In tanks that have been agitated for long periods of time by propeller mixers, it has been repeatedly observed that only the area near the mixer (e.g. 6 – 10 metre radius) is clean of wax accumulation; beyond this area wax has continued to be deposited. This observation suggests that propeller mixers do not deliver enough kinetic energy to the fluid environment to maintain all the fluid in the tank at a velocity greater than the critical velocity required to keep the paraffin molecules entrained.

Successful application of jetting

Heath Services has designed an in-line jet mixer that uses a jet of crude oil to resuspend crude oil sludge. Permanent installation of an in-line jet mixer allows for the resuspension of sludge and the cleaning of the crude oil tank without removing the tank from service or emptying product from the tank.

The in-line jet mixer is energized by a diesel-driven centrifugal pump. The ball joint design of the jet mixer combines with a hydraulically actuated piston to sweep the nozzle through 120° of motion on the horizontal plane, allowing the mixer to resuspend a high percentage of the sludge accumulated in the tank. The in-line design of the jet mixer creates a focused, high-velocity cutter jet with a cleaning radius in excess of 45 metres (see Figure 1).

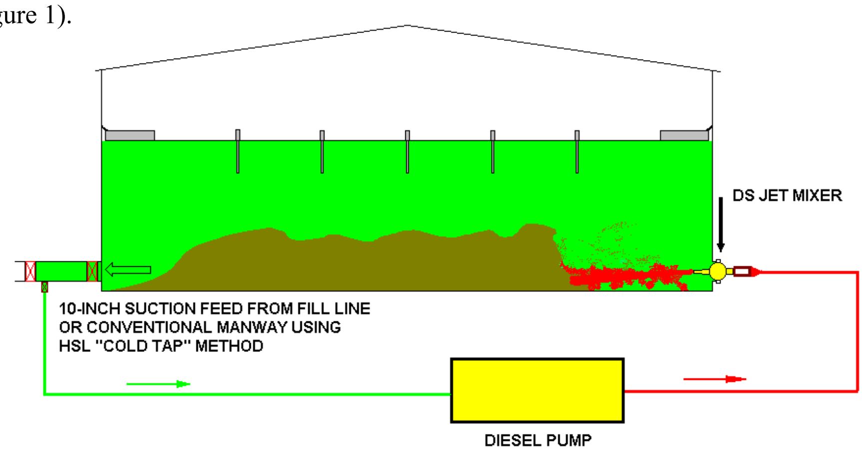


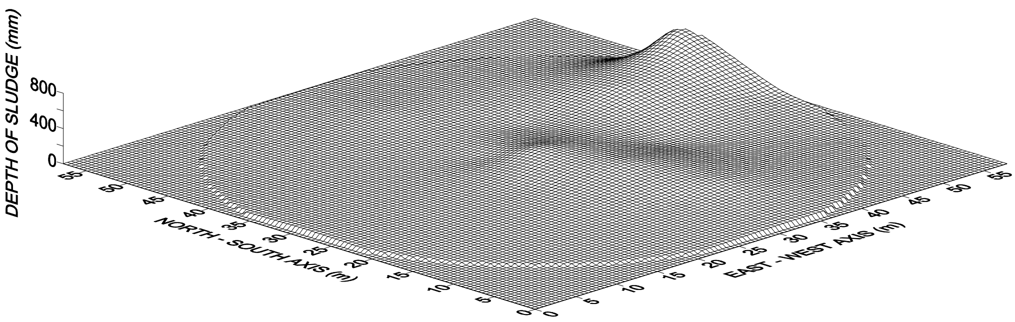
Fig. 1. *A schematic of the in-line jet mixer during resuspension of accumulated sludge within a crude oil storage tank (not to scale). Crude oil is circulated in an external system by a diesel-driven centrifugal pump and reintroduced into the storage tank as a high velocity, laminar jet.*

The in-line jet mixer system was also modified for use with the double shell storage tank design to used at the MERO storage facility in Nelahozeves in the Czech Republic. The in-line jet mixer system can be effectively operated on both standard tanks and non-standard, double shell tanks.

Case study –results from mero, Nelahozeves, Czech republic

In 2002, two 50 000 m^3 capacity crude oil storage tanks located in Nelahozeves, CR were cleaned of their sludge accumulations using an in-line jetting system to resuspend and shear the accumulated sludge. The jetting resulted in the recovery of 1 200 m^3 of oil from the tank bottoms and elimination of the need for incineration of the sludge. Shown below in Figure 2 are two three-dimensional sludge profiles illustrating the deposition of sludge in tank H03 before and after mixing. After successful trial project in the tank H03 were jet mixed other five tanks resulted in the recovery over 3847 m^3 of oil from the tank bottom during tank cleaning.

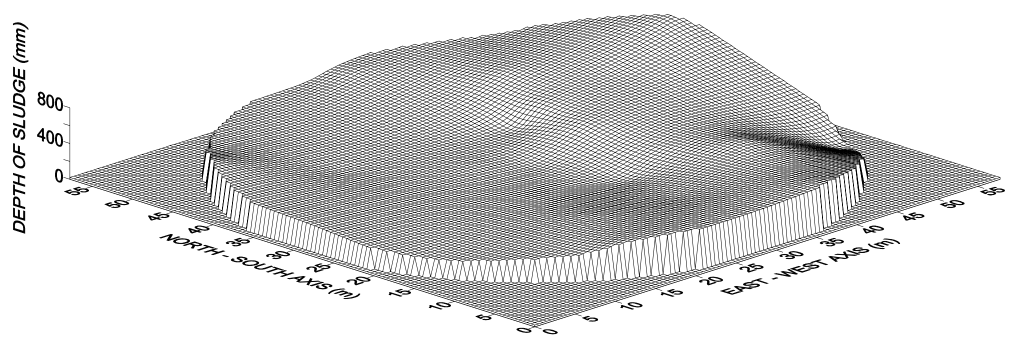
MERO Tank H03 Sludge Profile
After Resuspension with DS Jet Mixer
April 2002



Volume of sludge in Tank H03 after jetting
is calculated to be 210 m3 based on 23 sampling points.

Vertical exaggeration factor is 10.

MERO Tank H03 Sludge Profile
Prior to Resuspension with DS Jet Mixer
April 2002



Volume of sludge in Tank H03 prior to jetting
is calculated to be 871 m3 based on 22 sampling points.

Vertical exaggeration factor is 10.

Fig. 2

Conclusion

The use of an in-line jet mixer system is an effective method to clean the sludge from crude oil storage tanks through shearing and resuspension. The use of an in-line jet mixer greatly reduces the personnel exposure risks and hazards associated with tank cleaning. It provides a cost-effective, permanent method of managing tank bottom accumulation without the need to vent the tank or remove it from service. Periodic resuspension of accumulated bottoms reduces inventory requirements and liberates additional storage capacity. With the permanent installation of an in-line jet mixer system, the need to continuously run propeller mixers is eliminated, allowing the realization of significant power savings.

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