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ASPHALT OIL SPILL MODELED BY VISCOUS FLOW

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INTRODUCTION

Civil engineering designs often apply the risk-cost approach to assess the relationship between design capacity and total cost (Guo 1998a). Design constraints are a set of parameters to warrant safety and to avoid conflicts during and after the construction. By the same token, the design of an asphalt oil refinery has a safety concern about the storage tank used in the cooling process. In general, a single tank can hold 25,000 barrels or a volume of one million gallons. The impact assessment of a storage tank failure leads to the question as to how far the hot asphalt oil can run on a sloping ground surface. The hot asphalt oil behaves like a non-Newtonian laminar fluid that has the nature to increases its viscosity as the temperature cools down. Based on the field report (Ruzzo 2003) in Figure 1, the hot asphalt oil in the refinery yard can have an initial temperature as high as 300^{o}F, and takes approximately two hours to reduce the temperature to the operating condition at 140^{o}F. At operating temperatures, the asphalt mass is considered solid-like. Therefore, it takes two hours for hot oil asphalt to cool down and reaches the operating temperature. Therefore, it is reasonable to assume that during a spill, the asphalt oil remains fluid-like for the first two hours and then becomes solid-like after two hours. Figure 1 also indicates that the hot asphalt oil cools down much faster in the first hour than that in the second hour. During the second hour, the range of temperature is from 180 to 140^{o}F. Within such a temperature range, the viscosity of fluid-like asphalt oil remains almost constant. Or, the final cooling stage of the asphalt mass is under a quasi-steady state flow condition.

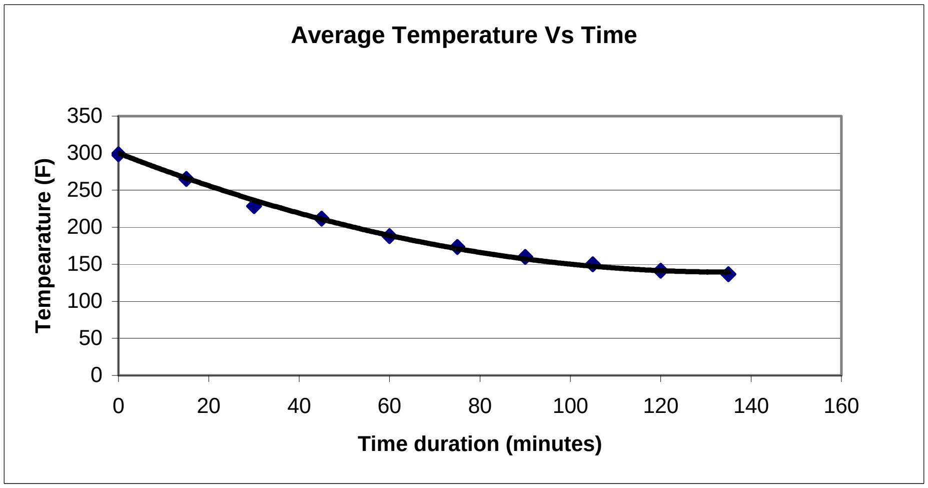

Figure 1. Temperature Variation of Hot Asphalt Oil during a Cooling Process

This paper presents a hydraulic analysis of an asphalt oil spill in a refinery yard. The purpose of the analysis is to estimate how far an asphalt oil spill can travel on a sloping ground surface.

OVERLAND FLOW MODEL FOR ASHPALT SPILL

As soon as the storage tank is ruptured, the hot asphalt oil spills to the ground through an angle of spread as illustrated in Figure 2.

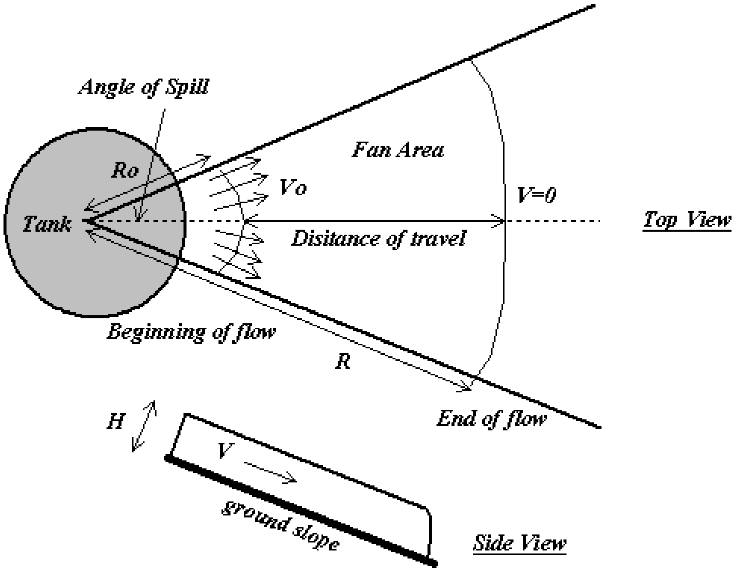

Figure 2. Illustration of Overland Flow For Asphalt Oil Spill

After the initial splash, the asphalt mass will undertake a deceleration process until the entire mass comes to a stop. The volume of the asphalt mass in Figure 2 is

$$V = AH \tag{1}$$

in which V = asphalt mass volume, H = thickness of asphalt layer, and A= surface area of asphalt spread and is equal to:

$$A = \frac{\theta}{2}(R^2 - R_o{}^2) \tag{2}$$

in which A = surface area of asphalt spread, θ = angle of spread, R_o= initial splash radius, and R = final radius of spread area. Since asphalt cools mainly by convection, it is likely that the surface of the mass would solidify before the center of the mass, which is evidenced by the "skin" formed on the surface of cooling asphalt mass. The friction between the upper skin and the ground surface reduces the velocity of the asphalt mass to a quasi-steady state shortly before the mass dries up to a solid like. Considering the laminar flow theory (Pao in 1973, Li in 1983), the flow velocity distribution shown in Figure 3 was derived as a parabolic curve across the thickness of the asphalt mass:

$$\frac{u}{U_m} = \frac{y^2}{H^2} - \frac{y}{H} \tag{3}$$

in which u = flow velocity at depth y, U_m= central velocity, and H= thickness of oil asphalt layer, Eq 1 satisfies the boundary conditions, including (1) u=0 at y=0, (2) u=0 at y=H, and (3) the first derivative vanishes when y=H/2 because of the maximum velocity.

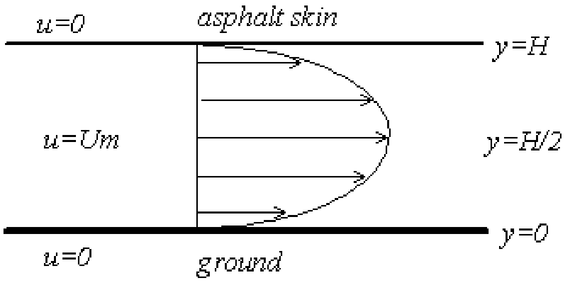

Figure 3 Laminar flow velocity profile

Like an overland sheet flow, the external forces exerting on the asphalt mass includes the shear force and the body force (Guo 1998b). The shear force in a laminar flow can be related to its velocity gradient. Using Eq 3, the shear stress is determined as:

$$\tau = \mu \frac{du}{dy} = \mu \frac{U_m}{H}(2\frac{y}{H} - 1) \tag{4}$$

in which τ = shear stress and μ= asphalt viscosity near the normal operating condition. Eq 4 indicates that the shear stress, τ_o, on the two solid surfaces is

$$\tau_o = \mu \frac{U_m}{H} \quad \text{at } y/H=0 \text{ and } y/H=1 \tag{5}$$

As a result, the shear force, F_o, applied to the asphalt mass is

$$F_o = 2\mu \frac{U_m}{H} A \tag{6}$$

By the nature of laminar flow, the central velocity is twice the average flow velocity (Pao 1973). As a result, Eq 6 becomes

$$F_o = 4\mu \frac{U}{H} A \tag{7}$$

in which U = average flow velocity. According to the Newton's 2nd law, the net force is responsible for the deceleration of the mass. Therefore, we have

$$\rho Va = 4\mu \frac{U}{H} A - \gamma VS \tag{8}$$

in which ρ = density of asphalt, a = deceleration of asphalt mass, γ = specific weigh of asphalt, and S = ground slope. Shortly before the mass comes to a stop, the deceleration of the mass is close to zero, or the two forces in Eq 8 are nearly balanced as:

$$U = \frac{\gamma SH^2}{4\mu} = \frac{gSH^2}{4\nu} \tag{9}$$

in which g = gravitation acceleration, and ν = asphalt oil's kinematic viscosity at operating condition. Eq 9 is similar to the exact solution for laminar open channel flow (Chow 1949). Having known the average velocity, the travel distance can be estimated as:

$$D = UT \tag{10}$$

in which *D* = travel distance, and *T* = travel time or spill time. As aforementioned, the fluid-like hot asphalt will reach its solid-like stage in two hours. Therefore, the travel time in Eq 10 is conservatively assumed to be equal to the spill time of two hours. It is also noted that Eq 10 must agree with

$$D = R - R_o \tag{11}$$

In practice, the volume of hot oil asphalt in a tank is given. Scenario studies begin with a specified angle of spill and a guessed distance of spread, i.e. the value of R_o in Eq 2. The guessed spread is accepted as the solution for the scenario case when the numerical difference between Eq 10 and Eq 11 becomes negligible.

CASE STUDY

The spill occurs when a single tank ruptures and completely discharges its contents to a sloping ground. The tank, which holds about 1,050,000 gallons, could rupture and spill the contents in 2-hours, which is a rate of 8,750 gallons per minute. The two-hour time frame was selected based on the cooling process observed in Figure 1. Of course, the engineer may choose otherwise time of spill if the information is available.
As an example, let the volume of 1000 ft^3 be spilled through an angle of 90^o into a fan area starting from R_o=30 feet on a ground slope of 0.01 ft/ft. The kinematic viscosity for asphalt oil between 180 and 140^{o}F is 0.003 ft^2/sec. In order to determine how far the asphalt oil can run, we may begin the fan area as described by Eq 2 as:

$$A = \frac{1.57}{2}(R^2 - 30^2) \tag{12}$$

By Eq. 1, the thickness of the asphalt mass is

$$H = \frac{V}{A} = \frac{1000}{A} \tag{13}$$

By Eq. 9, the average flow velocity is

$$U = \frac{32.2 * 0.01 * H^2}{4 * 0.003} \tag{14}$$

It takes an iterative process to lead to the solution that simultaneously satisfies Eq's 12,13, and 14. For instance, try R=208 feet. The rest of variables are found to be: A=33256 square feet by Eq 11, H=0.03 foot by Eq 12, and U=0.024 feet/sec by Eq 13. For this case, the travel distance is calculated by Eq 11 as:

$$D = R - R_o = 208\text{-}30 = 178 \text{ feet} \tag{15}$$

And also calculated by Eq 10 as

$$D = UT = 0.024*2.0*60*60 = 173 \text{ feet} \tag{16}$$

The engineer may set up the numerical tolerance level to dictate how may iterations required to achieve the accuracy. For this case, both Eq's 10 and 11 produce a good agreement when R =201 feet or D=171 feet.

The above iterative solution procedure was then coded into Excel Spread sheet for sensitivity studies. For a ground slope of 1.0%, Figure 4 was produced for the travel distance under a spread angle of 180° and spill time of two hours. As expected, the more the flow rate spills, the farther the asphalt oil travels.

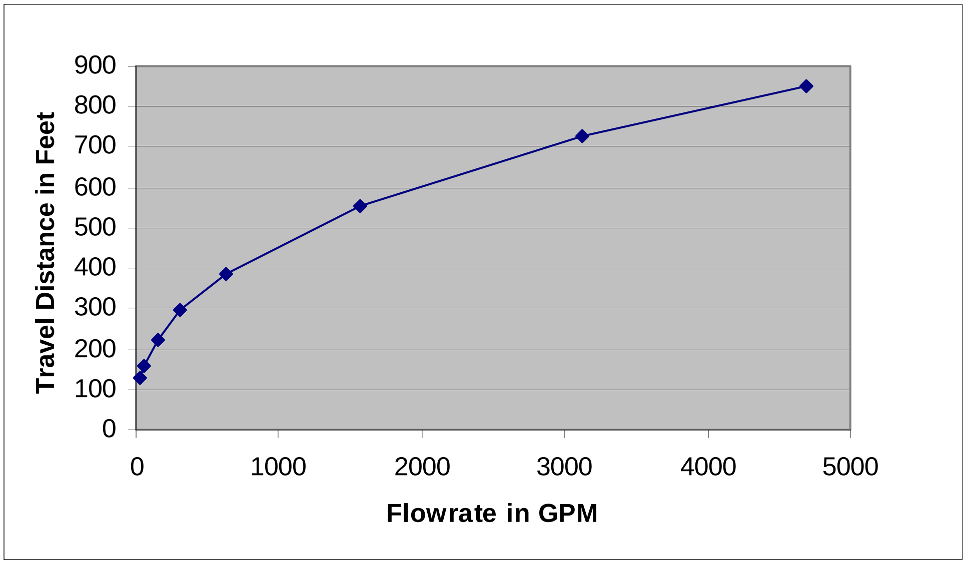

Figure 4 Travel Distance versus Spill Rate for Spill Angle of 180° Over Two Hours

CONCLUSION

This paper presents a simplified model to determine the asphalt oil movement on a sloping ground. Often, the overland flow was referred to the runoff flow that is a transitional or fully turbulent flow (Yen in 1991). In this case, the laminar flow theory was employed to derive the movement of asphalt oil fluid. The major parameters used in the model include flow volume, spill time, angle of spread, viscosity of asphalt oil, and ground slope. The travel distance is found to be proportional to flow rate and ground slope, but reversely proportional to the angle of spread. By nature, the cooling process of hot asphalt oil takes two hours to cool down. With the consideration of the diminishing effects, this paper assumes that the 2nd hour of the cooling process mainly determines the final shapes and deceleration of the solid-like asphalt mass. As a result, the viscosity of the asphalt oil is assumed to be constant.

This study was contracted to investigate the potential risk of a cooling tank and possible travel distances for hot asphalt oil under various scenarios. So far, there isn't any field data or forensic cases to verify the predictions. As a planning tool, this model provides a preliminary assessment and further refinements are needed when conducting the final design.

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