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Transportation of Multiple Grades of Crude Oil on Tankers: Understanding the Risk of Tank Overflow

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ABSTRACT

The possibility of oil spill from a crude oil tanker without any human intervention is analyzed. The spill can occur due to the communication of tanks containing dissimilar grades of crude oil. It will be shown that the difference in the densities of two or more grades of crude oil is possible to cause the over-fill of a tank and can raise the level to a significant height, finally leading to over flow through a purging device fitted on the top of the tank. The case is analyzed also in terms of the time needed for such over-fill to occur by studying the fluid dynamics of the self-initiated flow between tanks. Measures to prevent possible flow between tanks are presented as well as measures to avoid the spill once the flow is initiated.

1. Introduction.

Transportation of crude oil in tankers has reached high levels of pollution-free operations nowadays. In particular, the average number of large oil spills, spills of over 700 tons, during the 2000's was just a seventh of that during to 1970's (ITOPF, 2018). About 80 pct of spills are of amount of less than seven tons. Any oil spill however, despite how small, is given a very high publicity (Anderson, 2002). The effect to the environment is extremely serious and local authorities impose heavy fines to the carrier both for covering the cost for the clean-up and for the compensation of lost income to the local economy.

There have been steady and continuous improvements in the marine technology as well as in building awareness and responsibility to the shipping community. Despite the advances in marine technology, accidents continue to happen, as the recent accident of Sanchi in East China Sea has shown (Carwell, 2018). The effects to the environment range from minor to catastrophic, not mentioning the loss of credibility and loss of market share of the shipping companies involved. It is therefore important to take all possible measures available to minimize such risk (Devanney), and to understand the conditions which may lead to such an event.

The case which will be studied is the overflow of crude oil from the purging pipe fitted on top of a crude oil tank loaded with a light grade of crude oil. A much heavier grade is also loaded in different tanks. A heavy crude oil is considered one with density 900 kg m^{-3} while a light crude oil has a density of 700 kg m^{-3} with all intermediate values possible. The tanks are isolated from each other by isolating valves but there is a possibility the valves to fail and the tanks to communicate. Flow will then occur between the tanks unless they are already in hydrostatic equilibrium. Equilibrium is almost impossible to have been achieved considering that a crude oil tanker must load nowadays more than one parcel in varying quantities determined by the needs of the shippers, receivers and charterers.

The geometrical lengths and the crude oil properties used in the present work are based on actual characteristics of a tanker ship. The scenario is based on a real-life incident.

Mathematica software is used throughout this analysis. Nomenclature is added at the end. An Appendix discusses the case of three communicating tanks.

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2. Description of the Overflow Scenario.

Crude oil is transported by tankers, being ships consisted of holds (tanks) protected from external impact by void spaces (double hulls). The void spaces are used to carry the ballast water, which is necessary to attain the minimum needed immersion in water (draught) when there is no crude oil loaded. The tanks are not all of the same dimensions. Crude oil tankers, as being separated into tanks, carry several grades of crude oil. Ideally, different grades must be loaded by grouping them in specific tanks, the groups being isolated between them with double valves. This is not always possible. Very often, different grades are carried in tanks which are isolated from others by one valve only. The valves are mechanical devices, which are controlled by a remote system in the accommodation part of the ship. The tanks are topped up with inert gas to displace oxygen and thus prevent explosion, but to avoid excessive built of pressure, all tanks are fitted with exhaust devices (P/V valves) on top, which can release the excessive pressure if needed. The devices will be referred to as purging pipes throughout this work, although the exact meaning of a purging pipe is a pipe without a release valve fitted on top. These pipes start from the deck level of the ship, being also the top of the cargo tanks, and extend to about 2.0 m height.

Hydrostatic ballast loading (HBL) has been studied considerably in the past as a means to control the outflow of bottom grounding in single hull, pre-MARPOL tankers (OCIMF, 1999). HBL consists of filling a side tank, being a cargo tank which is in direct contact with the marine environment, up to a level where the hydrostatic pressure due to crude oil inside the tank is less than the hydrostatic pressure due to water outside. HBL was proven to be an efficient method to avoid oil pollution resulting from bottom grounding, although it was not as effective in side damage. HBL has become obsolete as the new generation of double hull tankers have been introduced and have completely displaced the single hull tankers from the trading market. The principles, however, behind HBL remain as valid as ever (Devanney).

3. Analysis.

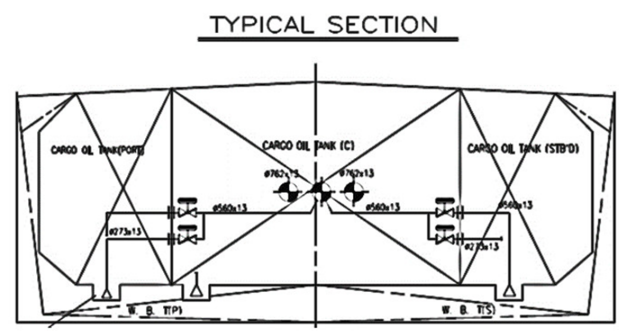
The principles of hydrostatics (Balachandran, 2011) (Som and Biswas, 2010) will be applied to the case of two communicating tanks containing liquids with different densities. This will lead to some conclusions on the conditions needed to prevent the fluid flow or to predict the final stage until equilibrium is reached. In addition, a dynamic analysis of the fluid flow will follow. This will assist to understand the time scale needed for the transfer of liquid from one tank to another until the overflow is observed and until equilibrium is established (overflow is stopped).

4. Hydrostatic Analysis.

A typical valve arrangement is shown in Fig.1. It is worth mentioning that in order two tanks to be communicated, at least two valves must be in open position. During cargo operation while a tank is either in a loading or discharging stage, one only valve is needed to fail in order such communication to occur. Efflux times have been studied before for single tanks (Subbarao et al., 2012). The present work gives emphasis on the liquid transfer between two (or more) communicating tanks with different liquid densities as well as different geometries (liquid height and tank surface area).

We model the case by assuming to a very good approximation that the two intercommunicated tanks are represented by rectangular parallelepipeds connected by a pipe, as shown in Fig.2. The parallelepipeds have different sizes and volumes and are filled with liquids of different densities.

Figure 1: Typical section of tank arrangement of a double hull VLCC. The wing ballast tanks and the suctions in the cargo tanks with the interconnecting valves are shown.



Source: Author.

The tanks, represented by the parallelepipeds, are initially filled with liquids at different heights. When the isolating valve is closed, there is no flow. When the valve is opened, there is efflux from one tank and influx to the other. To prevent this flow, the two heights must fulfill the following condition:

$$h_{1o} = h_{2o}\frac{\rho_2}{\rho_1}$$

If this condition is not met, and the height in tank 1 containing the heavier grade is higher than $h_{2o}\frac{\rho_2}{\rho_1}$, influx into tank 2 will be initiated.

We assume firstly that the tank 2 has sufficient volume to contain all influx from tank 1.

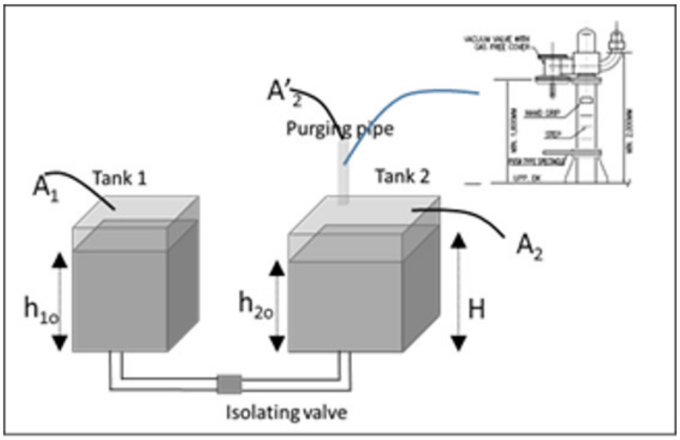
Then, the final liquid height in tank 2 will be:

$$H_2 = \frac{h_{1o} - h_{2o}\frac{\rho_2}{\rho_1}}{1 + \frac{A_2}{A_1}} + h_{2o} \tag{1}$$

The final condition is shown in Fig.3. It is readily evidenced that the final height in the tank with the light grade depends on the ratio of the densities of the two liquids as well as on the ratio of the areas of the two tanks. The size of the two tanks plays an important role. Communicating the tank with the light grade to a large tank loaded with the heavy grade will have a more pronounced effect to the final height in the tank receiving the influx.

A simple physical explanation of this dependence is that a small tank 1 with heavy oil connected to the tank with the light

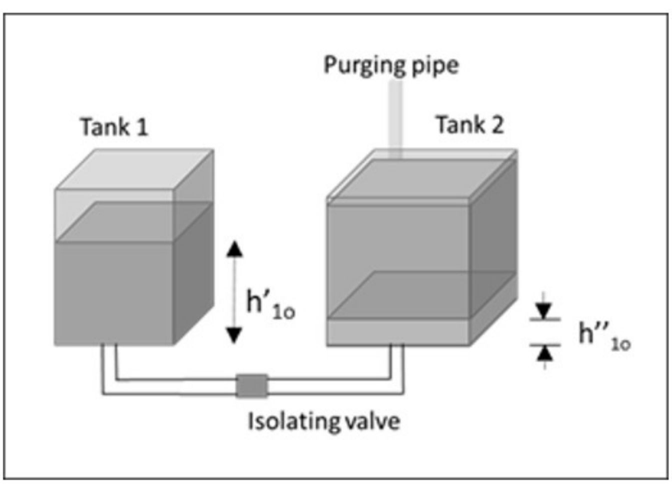
Figure 2: Schematic diagram of two cargo tanks filled with liquids at different levels and different densities. Each tank is fitted with a purging pipe (shown here only for tank 2 for simplicity purposes), on top of which a release valve is fitted.



Source: Author.

oil will be lowered fast and will reach the equilibrium point (when the efflux will be stopped) faster than a larger tank 1. A more detailed explanation will be given in the following section.

Figure 3: Diagram of the final condition where tank 2 has sufficient volume to withhold all the influx from tank 1.



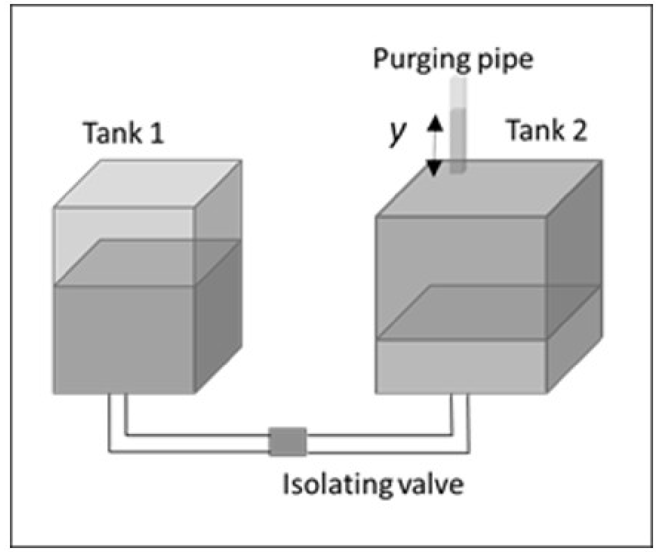
Source: Author.

We assume now that the tank 2 does not have sufficient volume to contain all the influx from tank 1. The final condition is shown in Fig.4.

The liquid in tank 2 will be raised above the top height and will reach a height y in the purging pipe. This height will be:

$$y = \frac{(H - h_{20})\left(1 + \frac{A_2}{A_1}\right) + h_{20}\frac{\rho_2}{\rho_1} - h_{10}}{\frac{A_2'}{A_2} - \frac{\rho_2}{\rho_1} + \frac{A_2'}{A_2}(1 + \frac{\rho_2}{\rho_1})} \tag{2}$$

Figure 4: Diagram of the final condition where tank 2 does not have sufficient volume to withhold all the efflux from tank 1 and the incoming liquid pushes the volume in tank 2 up into the purging pipe.



Source: Author.

For the extreme case where the tank 2 is already full, thus $H = h_{20}$, and $A_2' \ll A_2$, the above relation is reduced to:

$$y = \frac{h_{10}\rho_1 - h_{20}\rho_2}{\rho_2} \tag{3}$$

The condition for overflow is $y > h_p$, when the rise in the pipe exceeds the pipe height.

5. Hydrodynamic analysis.

The rate of change of height in each tank can be calculated by finding firstly the speed of the liquid leaving tank 1. The valve opening can be considered as an orifice. Using Bernoulli's equation (Spurk, 2008) (Kundu, Cohen and Dowling, 2012) (Smits, 2018) for any intermediate level the following will apply:

$$P_2 + \frac{1}{2}\rho_1 V^2 = P_1 - P_f.$$

Reference Point 1 is regarded to be the bottom of tank 1, and reference point 2 is regarded to be the bottom of tank 2. P_f are the friction losses. Friction losses are given by the Darcy-Weisbach formula $P_f = f\frac{L}{D}\frac{\rho V^2}{2}$, where f is the Darcy friction factor (about 0.02), L is the length of the pipeline and D is the diameter of the pipeline (Crane, 1999). It is assumed that the flow is in the turbulent flow regime where Darcy-Weisbach formula applies. For the characteristics of the fluid and the pipeline, the Reynold's number $R_e = \frac{\rho V D}{\mu}$, μ being the dynamic viscosity, is well above 4000 even for very moderate velocities.

Since

$$P_1 - P_2 = \rho_1 g h_1(t) - \rho_1 g h_1'(t) - \rho_2 g h_{20},$$

we have

$$\frac{1}{2}\rho_1 V^2 + f\frac{L}{D}\frac{\rho_1 V^2}{2} = \rho_1 g h_1(t) - \rho_1 g h_1'(t) - \rho_2 g h_{20}.$$

Using the conservation of mass,

$$h_1(t) A_1 + h_1'(t) A_2 = h_{10} A_1$$

we get:

$$V(t)^2 = k^2\, 2g\left(1 + \frac{A_1}{A_2}\right) h_1(t) - k^2\, 2g(h_{1o}\frac{A_1}{A_2} + \frac{\rho_2}{\rho_1} h_{2o}) \quad (4)$$

where $k^2 = 1/(1 + f\frac{L}{D})$. The physical meaning of k can be extended to include also the effect of the orifice geometry.

At the same time, from continuity equation we have:

$$\frac{dh_1(t)}{dt} = -V(t)\, S/A_1$$

where S is the cross sectional area of the pipeline. Finally:

$$\frac{dh_1(t)}{dt} = -kS\sqrt{2g\left(1 + \frac{A_1}{A_2}\right) h_1(t) - 2g(h_{1o}\frac{A_1}{A_2} + \frac{\rho_2}{\rho_1} h_{2o})}/A_1$$

The above differential equation can be solved to express the level of liquid in tank 1 as a function of time.

Finally:

$$h_1(t) = 2g\frac{(\frac{S}{A_1})^2}{4}\left(1 + \frac{A_1}{A_2}\right)\left(\frac{A_1}{S\left(1 + \frac{A_1}{A_2}\right)}\sqrt{2\frac{h_{10} - \frac{\rho_2}{\rho_1} h_{20}}{g}} - kt\right)^2 ...$$

$$... + \frac{h_{10}\frac{A_1}{A_2} + \frac{\rho_2}{\rho_1} h_{20}}{1 + \frac{A_1}{A_2}} \quad (5)$$

The height of liquid in tank 2 will be:

$$h_2(t) = h_{20} + \frac{A_1}{A_2}(h_{10} - h_1(t)) \quad (6)$$

Overflow from tank 2 (for $h_p \cong 0$) will occur when the height of liquid reaches the height of the tank, or when:

$$h_{20} + \frac{A_1}{A_2}(h_{10} - h_1(t)) = H.$$

Solving for $T_{o.f}$, the time when overflow will occur, we get:

$$T_{o.f} = \frac{A_1}{kS\left(1 + \frac{A_1}{A_2}\right)}\sqrt{2\frac{h_{10} - \frac{\rho_2}{\rho_1} h_{20}}{g}} - \frac{\sqrt{\frac{h_{20}\frac{A_2}{A_1} + h_{10} - H\frac{A_2}{A_1} - \frac{h_{10}\frac{A_1}{A_2} + \frac{\rho_2}{\rho_1} h_{20}}{1 + \frac{A_1}{A_2}}}{2g\frac{(\frac{S}{A_1})^2}{4}\left(1 + \frac{A_1}{A_2}\right)}}}{k} \quad (7)$$

The speed of the efflux, is given by

$$V(t) = -\frac{A_1}{S}\frac{dh_1(t)}{dt}$$

which is reduced to:

$$V(t) = \left(1 + \frac{A_1}{A_2}\right) gk\frac{S}{A_1}\left(\frac{A_1\sqrt{2\frac{h_{10} - h_{20}\frac{\rho_2}{\rho_1}}{g}}}{\left(1 + \frac{A_1}{A_2}\right)S} - kt\right) \quad (8)$$

The speed is highest at the beginning and thereafter is gradually decreased reaching the zero point when the equilibrium is established.

The efflux from tank 1 will be stopped at the point where the liquid in tank 1 will generate a pressure at reference point 1equal to the pressure at reference point 2 generated by the original level of liquid 2 and the in-fluxed liquid 1. The time T needed to reach equilibrium is derived by solving the equation $V(t) = 0$.

We get:

$$T_{eq} = \frac{A_1\sqrt{2\frac{h_{10} - h_{20}\frac{\rho_2}{\rho_1}}{g}}}{(1 + \frac{A_1}{A_2})kS} \quad (9)$$

Similar expression has been derived elsewhere for two tanks of same liquid density (Som and Biswas, 2010).

It can be shown that if the tank is already filled up to the top, an external pressure of about 0.5 kg/cm^2 can raise the liquid level inside the tank further into the purging pipe, thus causing an overspill. The time for the overflow to occur as derived in this section was taken to be the time needed for the liquid to reach the top of tank 2, rather than the top of the purging pipe. It can be proved that this is a very good approximation: since the volume of the purging pipe is only 1 m^3, once the liquid reaches the top of the tank, its height will continue to be raised quickly and will reach to top of the purging pipe in a few seconds.

6. Results and discussion.

Several conclusions can be derived from the analysis above. The two time quantities to be investigated are the time needed for overflow to occur and the time needed for equilibrium to take place.

For overflow to occur, two conditions must be fulfilled. These conditions link the geometrical dimensions of the two tanks and the densities of the two liquids:

a) $\rho_1 h_{10} > \rho_2 h_{20}$, meaning that the pressure exerted by the liquid in tank 1 must overcome the pressure exerted by the liquid in tank 2.

b) $\frac{A_2}{A_1} < \frac{H - h_{10} + h_{20}\frac{\rho_2}{\rho_1} - h_{20}}{h_{20} - H}$, meaning that the capacity of tank 2 cannot withhold all the influx liquid.

The present discussion is concentrated to the flow from Tank 1 to tank 2, but the opposite flow can also be considered under analogous conditions.

In the event both the above conditions are met, overflow will occur. The time taken for the liquid to reach the top of tank 1 is given by the relation of $T_{o.f}$ derived in the previous section. We will examine how $T_{o.f}$ depends on the various parameters.

Firstly, $T_{o.f}$ is increased as k is decreased: the stricter the flow through the orifice, the longer it will take for the overflow.

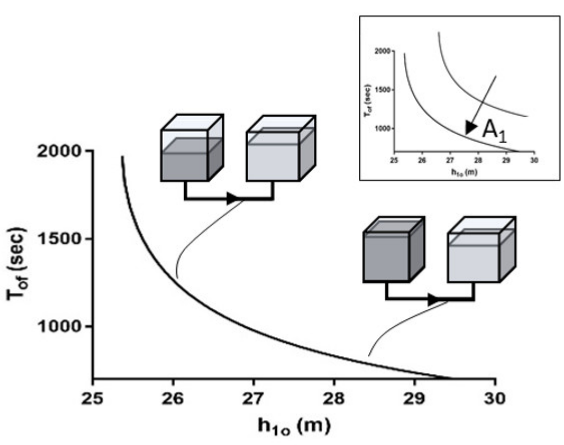
Secondly, $T_{o.f}$ is increased as the quantity $\rho_1 h_{10} - \rho_2 h_{20}$ is increased. This is a direct result of the pressure differential.

Also, $T_{o.f}$ is reduced as the volume of liquid in tank 1 is increased for a given liquid volume in tank 2: a large tank 1 will overfill tank 2 quicker than a smaller tank 1. This has direct effect to potential overspill accidents as it will be discussed later. The effect of a large tank can be quantitatively explained by noting that a volume change in tank 2, being smaller than tank 1, will correspond to a big height increase. The 3D graph in Fig.5 below shows the variation of $T_{o.f}$ with both the height of liquid and the surface area in tank 1. $T_{o.f}$ drops as the height in tank 1 is increased for a given surface area in tank1, and as the surface area in tank 1 is increased for a given height in tank 1.

This is explored further in Figs 6 and 7. Fig.6 shows the variation of $T_{o.f}$ with the height of liquid in tank 1 while the surface area of tank 1 is assumed constant.

Fig. 6 is shown for k=0.4, S=0.28 m^2, A_1=2000 m^2 A_2=400 m^2, h_{2o}=27.4 m, ρ_1=863 kg m^{-3}, ρ_2=722 kg m^{-3}, H =29.5 m. The figure illustrates the evident result that as the height of liquid in the tank containing the heavy substance is increased, the time needed for the overflow is decreased.

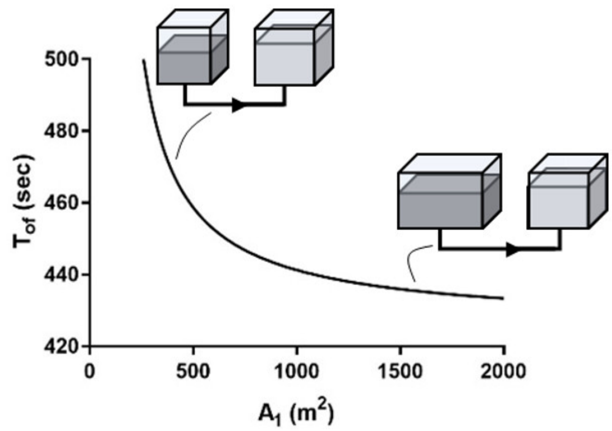
Figure 6: Variation of $T_{o.f}$ with the height of liquid in tank 1. Below a certain threshold there is no flow from one tank to another (reverse flow from the lighter to the heavier liquid is excluded in this version).



Source: Author.

While Fig.6 shows the variation of the time needed for the overflow to occur with respect to the liquid height of tank 1 for a fixed surface area, Fig.7 shows the variation of the time needed for overflow this time versus the surface area of tank 1 for a fixed height. The figure is shown for k=0.4, S=0.28 m^2, A_2=400 m^2, h_{10}=26.8 m, h_{20}=27.4 m, ρ_1=863 kg m^{-3}, ρ_2=722 kg m^{-3}. At low values of A_1, not fulfilling criterion b, there is no flow. Tank 1 with big volume and same liquid height can cause the overspill to occur faster than a smaller tank.

Figure 7: Time needed for overflow in tank 2 to occur as a function of surface area of tank I for a given height.



Source: Author.

These observations have the prevailing meaning that it is the interplay between height and surface area of Tank 1 which determines the behavior of the time of overflow of Tank 2.

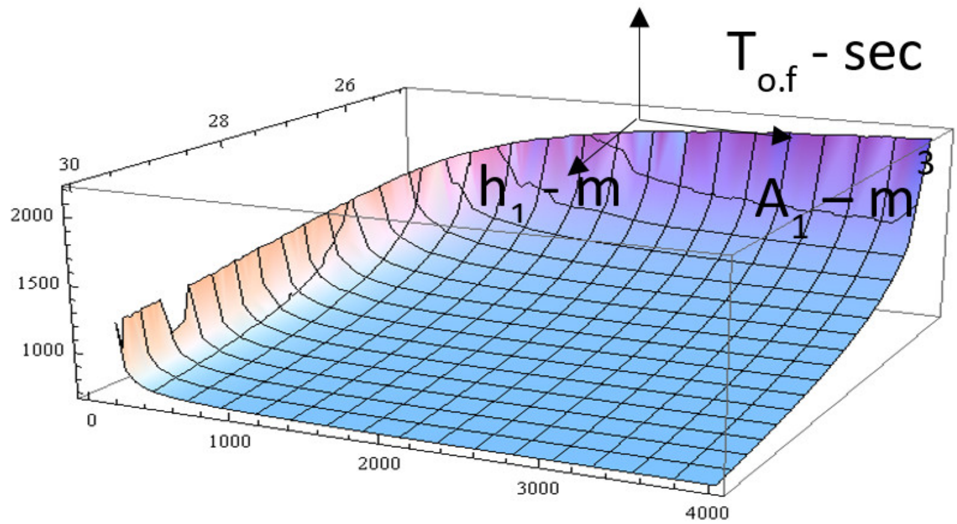
Another parameter which can be derived from the analysis is the rate of change of height in the tank receiving the influx, especially at the last stages before overfill occurs. The flow from tank 1 to tank 2 may become unnoticed at the early stages of the flow, but it will almost unavoidably become noticeable at some point during the flow either through the sounding of an alarm or by the officers and crew in the control room where the repeaters of the tank meters exist. It is important to know therefore at what rate the height increases and how much time is available for the crew to take remedial actions.

The first thing that one can notice is that the overflow does not take place in a time span of seconds. It takes several minutes, the exact duration being determined by the geometrical characteristics of the two tanks.

Also, one factor that varies unknowingly is k, the parameter which determines the geometry of the orifice and the losses in general. The reason is that the exact percentage the isolating valve is opened, either accidentally due to mechanical failure or due to mishandling by the crew, cannot be known. It is essential therefore to examine the rate of increase of liquid height in tank 2 for different values of k (the time of overflow for example is inversely proportional to k). In any case, the crew will have several minutes to react and to determine the valves that must be handled to avoid the overflow. Acting in panic should be avoided as redirecting the flow to the wrong tanks may accelerate the flow.

The rate of change of liquid level in tank 2 is linear with time, as Eqs 5 and 6 show. For typical values of the parameters, it can be evaluated that initially the liquid in tank 2 increases at a rate which is close to 2 mm/sec and then the rate drops linearly. The initial rate does depend on the liquid level in tank 1 but not on the volume of the tank, and is given by:

Figure 5: 3D graph of the time needed (vertical axis) for the liquid to reach the top of tank 2 as a function of the height of liquid and the surface area in tank 1.



Source: Author.

$$\left.\frac{dh_2(t)}{dt}\right|_{t=0} = \frac{S\,k\sqrt{2\frac{h_{10}-h_{20}\frac{\rho_2}{\rho_1}}{g}}}{A_2} \qquad (10)$$

We present below the results of two cases using actual dimensions and ship characteristics. Case 1 refers to the condition where the tank 2 loaded with the light grades is communicated with a small tank 1 loaded with the heavy grade, and case 2 refers to the condition where the tank 2 is communicated with a large tank 1. The densities are chosen to be 870 kg m^{-3} for the heavy grade and 720 kg m^{-3} for the light grade, corresponding to API 31 and 65 respectively.

From the above analysis it is evident that communicating tank 2 with a small tank 1 in this example does not cause overflow, but a large tank 1 loaded with heavy grade can push the liquid into tank 2 over the top. In this example, the liquid in the purging pipe for Case 2 will reach a height of 2.8 m. Considering that the purging pipe extends to a height of 2.0 m from the top of the tank, it is clear that the difference in densities between two communicated cargo tanks will cause the spill to occur.

Table 1: Values of parameters, taken from real ship characteristics.

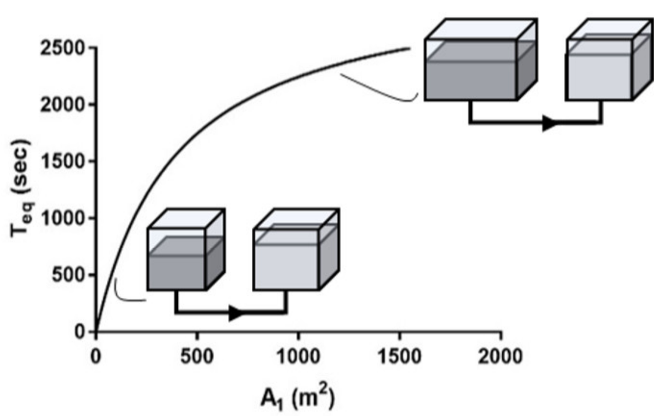
CASE 1		CASE 2	
A_1	143 m^2	A_1	1280 m^2
A_2	400 m^2	A_2	400 m^2
A'_2	0.2 m^2	A'_2	0.2 m^2
D	0.6 m	D	0.6 m
S	0.28 m^2	S	0.28 m^2
H	28.5 m	H	28.5 m
ρ_1	870 kg m^{-3}	ρ_1	870 kg m^{-3}
ρ_2	720 kg m^{-3}	ρ_2	720 kg m^{-3}
h_{1o}	26.8 m	h_{1o}	26.7 m
h_{2o}	27.4 m	h_{2o}	27.4 m
h'_{1o}	23.9 m	h'_{1o}	25.9 m
h'_{2o}	27.4 m	h'_{2o}	25.6
h''_{1o}	1.016 m	h''_{1o}	2.95 m
H_2	28.4 m	H_2	28.5 m
y	0 m	y	2.8 m

Source: Author.

The time needed for the overspill to occur and its dependence on the geometry of the two tanks is different than the time needed to reach equilibrium. In fact, the dependence is opposite: the time needed to reach equilibrium increases as the surface are of tank 1 increases, as depicted in Fig.8. The figure is shown for k=0.4, S=0.28 m^2, A_2=400 m^2, h_{1o}=26.8 m, h_{2o}=27.4 m, ρ_1=863 kg m^{-3}, ρ_2=722 kg m^{-3}. The conclusion is that a large tank 1 loaded with heavy crude oil can cause overspill to tank 2 loaded with a light grade faster than a small tank, but the equilibrium will take longer to be established. This highlights the fact that although the factor $h_i\rho_i$ is the decisive one for initiating the flow, the surface area is the second most important factor for the time scale of the phenomenon.

The above discussion gives an insight on what steps can be taken on board in case a change in the liquid level in the cargo tanks is noticed and an overflow is initiated. It is important to confirm firstly from which tank the liquid is escaping and to which tank the liquid is increasing. If a valve is noticed to be opened, this valve must be closed immediately. In case the suspected valve is defective and cannot be closed, other remedial action should take place.

Figure 8: Time needed to reach equilibrium of the liquid levels in the two communicated tanks as a function of the volume in tank 1 for a given liquid height.



Source: Author.

The efflux from the leaking tank must be redirected to other tanks to establish equilibrium and the flow to be ceased. The leaking tank containing the heavy liquid should then be communicated with another tank, which should not be a tank containing a heavy liquid too of same of higher liquid height. This will increase the influx to the tank with the light cargo grade. On the other hand, the new tank which will be communicated should have sufficient volume to contain influx coming from the leaking tank. The background needed to study the alternative solution of opening the valve of a third tank is presented in Appendix.

7. Process Safety.

As most of accidents in the transportation industry, as well as in any kind of industry, the accident (in this case being the tank overflow) may take place due to technical, human or procedural reasons, or a combination of all (Sam Mannan et al., 2016). A technical factor might be the failure of isolating valves while a human factor might be the mishandling of valves by the cargo officer. The barriers to be introduced therefore should address all factors (Underwood and Waterson, 2013) and can be categorized as follows: 1. Technical barriers: good maintenance of isolating valves, use of double valve segregation between the light and the heavy cargoes, 2. Human barriers: awareness of the risk of overflow, engagement of all cargo officers under the supervision of the chief officer, 3. Procedural barriers: avoidance of filling cargo tanks above 96% or 2% points below the setting of overfill alarm in the tanks loaded with light cargo, use of low level alarm in the tanks loaded with heavy cargo, having one tank at reduced filling level to absorb the efflux once it happens (see Appendix), 4. Mitigation barriers: communicating a third tank once efflux is observed (however, this must be done with care, see Appendix).

Conclusions.

The potential communication of two tanks in a conventional crude oil carrier has been analyzed with the aim to examine the possibility of liquid overflow when the two tanks carry very dissimilar grades. It has been shown that overflow can indeed take place. In order to analyze the effect in detail, the final stage of equilibrium and the intermediate cases have been considered. The overflow can take place in a span of a few minutes to an hour. When a tank is filled up to the top with incoming liquid, the excessive liquid will soon escape from the top of the purging pipe. The effect of the geometrical characteristics of the two tanks has been also studied. It was shown that a large tank 1 loaded with heavy crude oil communicated with another tank 2 loaded with a light grade can lead to overflow faster than a smaller tank 1, and the final equilibrium will take longer to be established. It is now more than evident that specific barriers must be introduced on board a tanker when very different grades are loaded with respect to their densities. One isolating valve only is not sufficient to prevent accidental communication of the tanks. A second valve isolation must be ensured to be in place by adjusting the stowage plan and make use of the vessel's segregated groups. It is also important that the officers are extremely vigilant when they are handling such cargoes, and they monitor any slight change in the liquid height of the tanks.

Nomenclature.

A_1	surface area of tank 1
A_2	surface area of tank 2
A'_2	surface area of purging pipe
D	diameter of connecting pipe
S	sectional area of connecting pipe
H	height of tank 2
ρ_1	density of liquid 1
ρ_2 ($\rho_2 < \rho_1$)	density of liquid 2
h_{10}	initial height of liquid 1 in tank 1
h_{20}	initial height of liquid 2 in tank 2
h'_{10}	final height of liquid 1 in tank 1
h'_{20}	final height of liquid 2 in tank 2

Table 2: Appendix A.1. - Final condition of three communicating tanks with different initial conditions.

Case 1.i	Initial Height (m)	Density (kg m^{-3})	Final Height (m)	Case 2.i	Initial Height (m)	Density (kg m^{-3})	Final Height (m)
Tank 1	28	860	24.8	**Tank 1**	28	860	26
Tank 2	28	740	28.6	**Tank 2**	28	740	29.9
Tank 3	26	740	30.5	**Tank 3**	26	860	26
Case 1.ii	Initial Height (m)	Density (kg m^{-3})	Final Height (m)	**Case 2.ii**	Initial Height (m)	Density (kg m^{-3})	Final Height (m)
Tank 1	28	860	25.6	**Tank 1**	28	860	26.7
Tank 2	28	740	27.3	**Tank 2**	28	740	30.6
Tank 3	22	740	27.0	**Tank 3**	28	860	26.7

contained	overflown

Source: Author.

h''_{10} final height of liquid 1 in tank 2
H_2 final total height in tank 2
y height of liquid in the purging pipe
h_p height of purging pipe above deck level

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Appendix: Three Communicating Tanks.

When a tank is found leaking, and another found to be overloaded, the first attempt by the operator will be to close any valve in the pipeline between the two tanks. If the flow continues, the next attempt could be to open the valve of a third tank to divert the flow. This may not always provide the desirable effect. Communicating three tanks is much more complicated than two tanks, although the physical principles are the same.

We assume that three tanks with surface areas A_i, initial liquid heights h_i and densities ρ_i, $(i = 1$ to $3)$, are communicated. We will investigate the case of two tanks 1 and 2 being initially communicated when tank 3 is connected, for two conditions: 1. $h_1\rho_1 > h_2\rho_2 > h_3\rho_3$, and 2. $h_1\rho_1 > h_3\rho_3 > h_2\rho_2$

<u>**Case 1:**</u> $h_1\rho_1 > h_2\rho_2 > h_3\rho_3$

The above hydrostatic pressure condition implies that there is efflux from tank 1 to both tanks 2 and 3, and efflux from tank 2 to 3. There is no efflux from tank 3 but only influx from tanks 1 and 2. Let h'_i be the final height of liquid i in tank i, and h_{ij} the height of liquid i escaped into tank j . The mass conservation of liquids 1 and 3 will give:

$h_1A_1 = h'_1A_1 + h_{12}A_2 + h_{13}A_3$ (Eq. A.1a)

$h_2A_2 = h'_2A_2 + h_{23}A_3$ (Eq. A.2a)

$h_3A_3 = h'_3A_3$ (Eq. A.3a)

The hydrostatic equilibrium of the final stage will give:

$h'_1\rho_1 = h'_2\rho_2 + h_{12}\rho_1$ (Eq. A.4a)

$h'_1\rho_1 = h'_3\rho_3 + h_{23}\rho_2 + h_{12}\rho_1$ (Eq. A.5a)

We need one more equation to evaluate all unknown parameters. We make the logical assumption that the amount of efflux from tank 1 to tanks 2 and 3 is proportional to the hydrostatic pressure differential between tank 1 and tanks 2 and 3 respectively, or:

$\frac{h_{13}A_3}{h_{12}A_2} = \frac{h_1\rho_1 - h_3\rho_3}{h_1\rho_1 - h_2\rho_2}$ (Eq. A.6a)

The above set of equations will give the solution of the unknown variables h_i' (i=1 to 3), h_{12}, h_{13}, h_{23}. The set of equations can be easily solved in any mathematical software.

Case 2: $h_1\rho_1 > h_3\rho_3 > h_2\rho_2$

This hydrostatic pressure condition implies that there is efflux from tank 1 to both tanks 2 and 3, and efflux from tank 3 to 2. There is no efflux from tank 2 but only influx from tanks 1 and 3. The set of corresponding equations will be:

$h_1A_1 = h_1'A_1 + h_{12}A_2 + h_{13}A_3$ (Eq. A.1b)

$h_3A_3 = h_3'A_3 + h_{32}A_2$ (Eq. A.2b)

$h_2A_2 = h_2'A_2$ (Eq. A.3b)

$h_1'\rho_1 = h_3'\rho_3 + h_{13}\rho_1$ (Eq. A.4b)

$h_1'\rho_1 = h_2'\rho_2 + h_{23}\rho_3 + h_{12}\rho_1$ (Eq. A.5b)

$\frac{h_{13}A_3}{h_{12}A_2} = \frac{h_1\rho_1 - h_3\rho_3}{h_1\rho_1 - h_2\rho_2}$ (Eq. A.6b)

We will not present the final relations of each one of the sought parameters, which can be straightforwardly performed in any mathematical software, but rather we will present directly the results of final heights for the two cases. Tank 3 could be a tank of heavier or lighter cargo, however the critical parameters are the $h_i\rho_i$'s.

We firstly assume that tank 3 has lower $h_i\rho_i$ than tank 2, and will then assume that has a higher $h_i\rho_i$. For simplicity we assume that all tanks have the same geometrical dimension A_i. Table A.1 shows the results of four cases with different initial and final conditions. For total tank height 29 m, the final condition of tank levels depends on the which tanks are communicated. If a flow is observed between Tanks 1 and 2, the third tank can contain the flow provided it falls in the category $h_1\rho_1 > h_2\rho_2 > h_3\rho_3$ and has sufficient empty space to withhold the influx (Case 1.ii).