Detailed Thermal Inbreathing Analysis for API 12-F Tanks

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Background

Venting of atmospheric and low pressure storage tanks is an important aspect of the tanks' overall design in order to prevent overpressure or vacuum collapse of the tanks. Lower pressure systems are typically considered to be lower risk systems, but their large volume can result in catastrophic consequences if a loss of containment does occur. Vacuum prevention can be especially troublesome for the sole reason that it is often overlooked. API Standard 2000, Venting Atmospheric and Low-Pressure Storage Tanks [1] is one of the most widely recognized industry standards that covers the overpressure and vacuum venting requirements for above ground liquid petroleum or petroleum product storage tanks designed for operation from a full vacuum through 15 psig pressure.

The size (diameter) of the vent is not usually a limiting factor on larger storage tanks such as those designed to API Standard 650, but can become a significant road block on smaller tanks frequently used in wellsite storage tanks designed to API Specification 12-F [2]. The single 4" and 6" nozzles provided by API 12-F as standard connections are adequate for tank vent sizing using older tables originally developed to be used for a stable fluid similar to hexane, but proved problematic for venting of tanks containing lighter condensates using the rigorous sizing methods first proposed in API 2000 6th Edition. Using a standard 300 barrel API 12-F wellsite storage tank as an example, tank vent sizing using a more rigorous approach was investigated. The more rigorous approach proposed in this paper leverages much of the work completed in support of the 6th Edition revision of API Standard 2000, but modifies it to allow for user specified rainfall rates and compositions in the tank vapor space other than air.

Rigorous Calculation Methodology

Beginning with its 6th Edition (November 2009), API Standard 2000 introduced a new rigorous sizing method for quantifying the required inbreathing and outbreathing rates to prevent overpressure or vacuum collapse of low pressure storage tanks. Previous methods relied on simplified tabular data which assigned a standard breathing rate based on the volume of the tank and the fluid's boiling and flash points. The simplified approach requires several conditions be met in order to ensure an adequate tank vent design:

- Tank contents of gasoline or something similar
- Tank volume less than 180,000 BBL
- Maximum operating temperature of 120°F
- Tank is uninsulated

- Temperature of the tank cannot exceed the bubble point of its contents or feed stream (no vaporization within the tank occurs).

The previous simplified sizing method has been in use by a wide range of industries dating back to the 1940's, but the technical basis has not been documented as far as the author is aware. There was some evidence that the simplified basis may have resulted in undersized tank vents when the above criteria were not being met; therefore, a new investigation into tank vent sizing was started. The new rigorous method first proposed in the 6th edition of API Standard 2000 almost universally requires a greater inbreathing rate than that calculated using the previous simplified methods, but is developed based on actual data collected by Protego, a German based tank vent manufacturer [3]. In many instances, the simplified approach provides a sufficiently conservative tank vent design, but some installations, such as the storage of lighter unstabilized hydrocarbons, may justify a more rigorous tank vent design. The rigorous method changes how outbreathing rates are calculated as well, but the less efficient convective heating of the tank by the sun and other outbreathing requirements such as for an external fire dilutes the impact of this change, leaving our focus on thermal inbreathing.

Through the process of designing vent systems for several atmospheric storage tanks at wellsite facilities, it became readily apparent to the author how significantly the thermal inbreathing rates could change by applying the rigorous calculation methodology. It was not uncommon for the thermal inbreathing rate to double for a relatively small (600 BBL) production tank. The increased breathing rates limited the choice of tank vents available in the market that could be specified, without having to install additional or larger ports on these smaller tanks built to established industry tank standards (e.g. API 12-F). The author's research into tank vent sizing determined that the rigorous thermal inbreathing design basis in API Standard 2000 is based on a rain fall rate of 8.9 inches per hour, which is excessively higher than the actual weather data suggested for most geographic locations [Appendix 1]; and fluid properties are based on air in the tank vapor space. The author's investigation also identified that the thermophysical properties of the fluid within the tank play a significant role in the thermal inbreathing rate calculation. By leveraging the calculation basis presented in Annex G of API 2000 7th Ed [1], the Protego Report [3] presented to API as the basis for the rigorous method, the actual 100 year rain fall rate for a geographic location and thermophysical properties of the actual fluid in the tank vapor space (air is assumed by default), significantly lower yet accurate inbreathing rates may be achieved.

Methodology

Heat Transfer Mechanism

The atmospheric storage tank thermal contraction (inbreathing) calculation follows the generalized form of many heat transfer problems present in chemical engineering. The storage tank material (metal), fluid within it (some gas or vapor) and atmosphere are operating in a steady state under most conditions. Under these steady state conditions, there is no heat entering or leaving the tank vapor space and there is also no fluid movement in or out of the tank (it is important to note the effects of liquid movement are accounted for separately in the total breathing requirement determination). If the gas within the tank were to cool, it would contract due to a reduction in density and begin to pull a vacuum on the storage tank. The required thermal inbreathing rate is the rate of contraction and adequate available vacuum capacity is needed to prevent a vacuum collapse of the storage tank There are two somewhat related events that may result in cooling of the tank fluid. Both result in cooling of the outside of the tank due to a change in ambient conditions, which is then propagated to the inside vapor space through natural convection between the vapor space and the inner tank wall.

1. A change in ambient temperature cools the storage tank through natural convection with the ambient surroundings. Air acts as the heat transfer medium, but is a poor conductor of heat so the overall heat transfer and required inbreathing rate are generally minimal.
2. A sudden rain storm cools the storage tank through forced convection with the falling (cooler) rain. Higher rain fall rates may result in significant cooling of the storage tank and thus higher inbreathing rates due to a higher rate of gas contraction.

Calculation of the rate of gas contraction (inbreathing requirement) is then completed by determining the rate of heat transfer (cooling) from the falling rain to the metal tank wall and roof, across the tank metal surfaces and then from the tank inner surface to the vapor space with the tank. A stepwise approach is then taken to evaluate how the gas within the vessel contracts over time. The thermal inbreathing rate is based on the maximum rate of contraction, which is then converted to a standard volumetric flowrate of air, a unit commonly used to simplify tank vent specification.

Detailed Calculations

Physical properties for the storage tank, gas volume, and ambient conditions are required to complete the detailed thermal inbreathing analysis. [1,3]

Table 1 - Detailed Calculation Variables

Description	**Variable**	**Unit**
Surface area	A	ft^2
Volume	V	ft^3
Mass	m	lb
Density	ρ	lb/ft^3
Temperature	T	°F
Specific heat	Cp	Btu/lb-°F
Thermal conductivity	k	BTU/hr·ft·°F
Viscosity	μ	cP
Rain fall rate	R	in/hr
Inner wall heat transfer coefficient	$\alpha_{G,w}$	$Btu/hr\text{-}ft^2\text{-}°F$
Outer wall heat transfer coefficient	$\alpha_{w,u}$	$Btu/hr\text{-}ft^2\text{-}°F$
Change in gas temperature vs. time	dT/dt	°F/sec
Volumetric inbreathing rate	$\dot{V}$	SCFH Air
Tank Wall	$_w$	Subscript

Description	Variable	Unit
Gas	$_G$	Subscript
Ambient (rain)	$_U$	Subscript
Air at 120°F	$_A$	Subscript

Physical properties of the storage tank and vapor space are easily determined based on the dimensions and densities of the storage tank and gas within the tank. The gas volume should be based on the total available volume of the tank (assuming it is empty) as this represents the worst case scenario with respect to thermal inbreathing rates. The inner wall heat transfer coefficient is based on the heat transfer coefficient between air and a vertical cylinder wall undergoing natural turbulent convection, corrected for the actual tank vapor using a ratio of the fluid's Nusselt number (Eq. 1). The inner wall heat transfer coefficient for air at 120 °F is determined to be ≈ 0.88 Btu/hr-°F-ft^2 [3] and is confirmed by other references [4].

$$\frac{h_{Vapor}}{h_{Air}} = \left(\frac{cp_G(\rho_G)^2 k_G \mu_G}{cp_A(\rho_A)^2 k_A \mu_A}\right)^{1/4} \cdot \frac{k_A}{k_G} \qquad \text{Equation 1}$$

The calculation of the tank wall temperature (T_w) and gas temperature (T_G) at each time step from the start of the cooling process is based on a set of equations presented in the Protego report and listed here (Eq. 2 - 11) for reference. Note that the outer wall heat transfer coefficient is back calculated from published data as is described later in this paper, but may also be specified directly. The calculations assume that the tank wall and gas temperature are in equilibrium at the start of the cooling event. The example at the end of the Protego Report [3] outlines this stepwise calculation process. Using the difference in gas temperature (T_G) between each time step, the instantaneous change in temperature over time (dT/dt) is obtained. Once a maximum dT/dt is reached, this maximum value is used to calculate the tank inbreathing rate accordingly (Eq. 11). Finally, the actual volumetric inbreathing rate is corrected to represent flow at standard conditions.

$$B_{G,W} = \frac{\alpha_{G,W} \cdot A}{cp_G \cdot m_G} \qquad \text{Equation 2}$$

$$B^*{}_{G,W} = \frac{\alpha_{G,W} \cdot A}{cp_W \cdot m_W} \qquad \text{Equation 3}$$

$$B_{W,U} = \frac{\alpha_{W,U} \cdot A}{cp_W \cdot m_W} \qquad \text{Equation 4}$$

$$\lambda_W = -\frac{B_{G,W} + B^*{}_{G,W} + B_{W,U}}{2} - \sqrt{\left(\frac{B_{W,G} + B^*{}_{G,W} + B_{W,U}}{2}\right)^2 - B_{G,W} \cdot B_{W,U}} \qquad \text{Equation 5}$$

$$\lambda_G = -\frac{B_{G,W} + B^*{}_{G,W} + B_{W,U}}{2} + \sqrt{\left(\frac{B_{G,W} + B^*{}_{G,W} + B_{W,U}}{2}\right)^2 - B_{G,W} \cdot B_{W,U}} \qquad \text{Equation 6}$$

$$C_G = -\frac{(T_{G,t=0} - T_U) \cdot \lambda_W + (T_{G,t=0} - T_{W,t=0}) \cdot B_{G,W}}{\lambda_G - \lambda_W} \qquad \text{Equation 7}$$

$$C_W = -\frac{(T_{G,t=0}-T_M)\cdot\lambda_G+(T_{G,t=0}-T_{W,t=0})\cdot B_{G,W}}{\lambda_G-\lambda_W}$$ Equation 8

$$T_G = T_U + C_G\cdot e^{(\lambda_G\cdot t)} + C_W\cdot e^{(\lambda_W\cdot t)}$$ Equation 9

$$T_W = T_U + C_G\cdot\left(\frac{\lambda_G}{B_{G,W}}+1\right)\cdot e^{(\lambda_G\cdot t)} + C_W\cdot\left(\frac{\lambda_W}{B_{G,W}}+1\right)\cdot e^{(\lambda_W\cdot t)}$$ Equation 10

$$\dot{V} = \frac{V_G}{T_{G,t=0}}\cdot\frac{dT}{dt}\cdot\frac{T_{STD}}{T_U}$$ Equation 11

Outer Wall Heat Transfer Coefficient

The outer wall heat transfer coefficient ($\alpha_{W,u}$) is based on the rate of rain fall on the exterior of the tank wall. The greater the rain fall rate, the greater the heat transfer possible. API 2000 Figure G4 presents a set of data comparing the rate of temperature change in the tank gas space as a function of tank volume for four different rain fall rates. Given the rate of temperature change and the defined vessel dimensions, the outer wall heat transfer coefficient could be back calculated using the full set of developed detailed inbreathing equations and an iterative (goal seek) process. Note that the rain fall vs. outer wall heat transfer coefficient plot was only completed for one tank having a height to diameter ratio of 1.3, but API Standard 2000 Figure G2 shows that the resulting dT/dt is stable for a wide range of tank height to diameter ratios (H/D = 0.2-2.0). Plotting the rate of rain fall vs. the back calculated outer wall heat transfer coefficient resulted in a linear regression comparing rain fall rate to heat transfer coefficient that could be used in the detailed heat transfer calculations for the tank thermal inbreathing problem being evaluated. Data extracted from API Standard 2000 Figure G2 and the calculated outer wall heat transfer coefficients are shown in Table 2, while the resulting equation of best fit is in Equation 12.

Table 2 - Rainfall Rate vs. Outer Wall Heat Transfer Coefficient

Rain Fall Rate (R)		**dT/dt**	**Outer Wall HTC ($\alpha_{w,u}$)**
Kg/m^2-hr	**in/hr**	**K/hr**	**W/m^2-K**
225.0	8.9	395	2,128
112.5	4.4	275	1,481
56.3	2.2	170	916
21.1	1.1	130	700

$$\alpha_{W,U} = 31.778\cdot R$$ Equation 12

Note that the highest value of these rain fall rates (225 kg/m^2-hr) corresponds to a relative rain fall rate of 8.9 in/hr and is the basis for the thermal inbreathing calculation presented in the body of API Standard 2000. The maximum rate of 8.9 in/hr is conservatively used in API 2000 as this is the highest 100 year rain fall rate expected worldwide where atmospheric tanks are expected to be found. According to the NOAA 100 year rain fall chart included in Appendix 1 [5], the maximum rate expected in the United States is 4.5-5.0 in/hr along the gulf coast and parts of southern Florida. While published in 1964, the rainfall atlas [5] is still an accepted and published source for rainfall data. It is worth noting that these rainfall rates are based on a one-hour average, but rainfall rates based on a shorter duration, such as a few minutes, may be significantly higher and will result in a greater degree of cooling than the lower hourly rates would as the cooling is an instantaneous process. The 30-minute rate map (the shorter duration published in the 100 year chart) shows rainfall rates in the same areas of 8 in/hr. It is ultimately the operator’s responsibility to determine what is appropriate for their geographic location and risk profile.

Case Study

Many wellsite facilities in the United States utilize relatively small storage tanks designed in accordance with API Specification 12-F for temporary storage of produced water and light condensate. As previously discussed, current API Standard 2000 tank vent sizing techniques for tanks containing lighter fluids such as these assume that the tank is located in an area where a 100 year rainfall rate in excess of 8 in/hr may be present and that the tanks contains air. Using the detailed analysis approach outlined in this paper with data of the 100 year rain fall rates based on the actual geographic locations and the actual gas space fluid compositions for the tanks, a case study was compiled to illustrate how lower venting rates may be calculated when applying the more rigorous sizing method.

The case study evaluated a typical 300 barrel API 12-F wellsite storage tank having an inside diameter of 12 ft and a height of 15 ft, a cylindrical wall and a flat roof. The initial operating temperature of the tank was 130°F and the rain temperature during the rain storm was 60°F. The focus of the case study was on determining the thermal inbreathing rate that might occur in the event of a sudden rain storm on a hot day. The scenario is that the rain storm rapidly cools the gas space within the storage tank, resulting in contraction of the gas inside the tank and formation of a vacuum. Typically, the normal inbreathing rate due to liquid movement out of the tank would be independently determined and added to this thermal requirement. The liquid movement rate is fixed based on the rate of liquid leaving the tank and is added to the thermal inbreathing rate, defining the total inbreathing requirement for the required vacuum vent.

In the case study, it is assumed that the gas space within the tank is a saturated vapor based on the composition of liquid feeding the tank, unless noted otherwise as air in the baseline case. Four fluid compositions were evaluated at three different rain fall rates varying from 2.1-8.9 in/hr, the rainfall rates noted in the original API 2000 Protego work. Details on the fluids evaluated are presented in Table 3.

Table 3 - Fluids Evaluated

Fluid	MW (lb/lb-mol)	Gas SG (Air = 1)	Cp (Btu/lb-°F)
Lt. Condensate	42	1.45	0.445
Hexane Vapor	86	2.03	0.454
Natural Gas	20	0.69	0.504
Air	29	1.00	0.241

The thermal inbreathing rate was calculated for each scenario using the described approach and the results tabulated for further analysis.

Table 4 - Thermal Inbreathing Case Study Results

Fluid	Rain Fall (in/hr)	Inbreathing (SCFH)	vs. Air[1]
Lt. Condensate	8.9	1,580	0.78
Hexane	8.9	1,748	0.86
Natural Gas	8.9	1,504	0.74
Air	8.9	2,031	1.00
Lt. Condensate	4.4	1,176	0.81
Hexane	4.4	1,257	0.87
Natural Gas	4.4	1,134	0.78
Air	4.4	1,444	1.00
Lt. Condensate	2.2	803	0.85
Hexane	2.2	833	0.88
Natural Gas	2.2	784	0.83
Air	2.2	950	1.00

1. Ratio of thermal inbreathing rate compared to that of air at the same rainfall rate, using the described approach

The effect of the reduced rain fall rate on the thermal inbreathing requirement was expected and has been previously documented [6], although not necessarily using smaller wellsite storage tanks. What was not expected, but in retrospect not surprising, is the effect that the tank's fluid composition and its thermodynamic properties had on the thermal inbreathing requirement. The higher specific heat (Cp) of many hydrocarbon components compared to that of Air resulted in a slower contraction of the gas and thus a smaller inbreathing rate when all other inputs were the same.

While air will enter the tank through an open vacuum vent during an inbreathing event, most tanks would not contain air initially as this would create a potentially explosive atmosphere and is thus undesirable. The effects of the mixing air entering the tank through the tank vent were discussed during the early development of API Standard 2000, but no consensus on considerations for those effects made its way into the final document. If a heavier hydrocarbon component were stored that was not capable of creating its own vapor space within the tank (vapor pressure < tank operating pressure), it is likely that some other gas (e.g. natural gas) would be used as a blanket gas on the tank to prevent an explosive atmosphere from forming. Alternately, the tank may in fact contain an air vapor space if explosion is not a hazard, in which case using air as the fluid medium would be appropriate.

In general, basing the fluid properties on the actual fluid in the tank's vapor space may result in approximately a 20% reduction in the required thermal inbreathing rate, when volatile hydrocarbons are present. If this is coupled with of a more realistic year rain fall rate, such as 4.4 in/hr (typical 100 yr, 1 hour rain fall rate - also mid point used in API 2000 Protego work), the required inbreathing rate would be further reduced. Using light condensate and the 300 barrel tank in our case study, the end result is a reduction of 68% in the thermal inbreathing rate from 3,630 SCFH calculated using API Standard 2000 Equation 6 to 1,176 SCFH using the detailed approach described in this paper. It is worth noting that every case is unique; and although this case study has focused on smaller tanks typical to wellsite installations, the generalized impact of using a more detailed analysis is applicable anywhere.

Using the detailed analysis described in this paper to calculate the total inbreathing requirement based on the sum of the reduced thermal inbreathing rate and the breathing rate required for pump-out, more tank venting options become available for use on API 12-F storage tanks with standard nozzle sizes.

Proposed Approach

Based on the results of the detailed analysis presented in this paper using more appropriate inputs for the fluid composition and rain fall rate in the rigorous sizing method for tank vent sizing, Inglenook recommends the following approach for low pressure tank thermal inbreathing calculations. As with all things in engineering, the proposed approach starts with the easiest, but often most limiting or conservative analysis (API Standard 2000 7th Ed Annex A or §3.3.2) and progresses from there to a more rigorous and detailed approach.

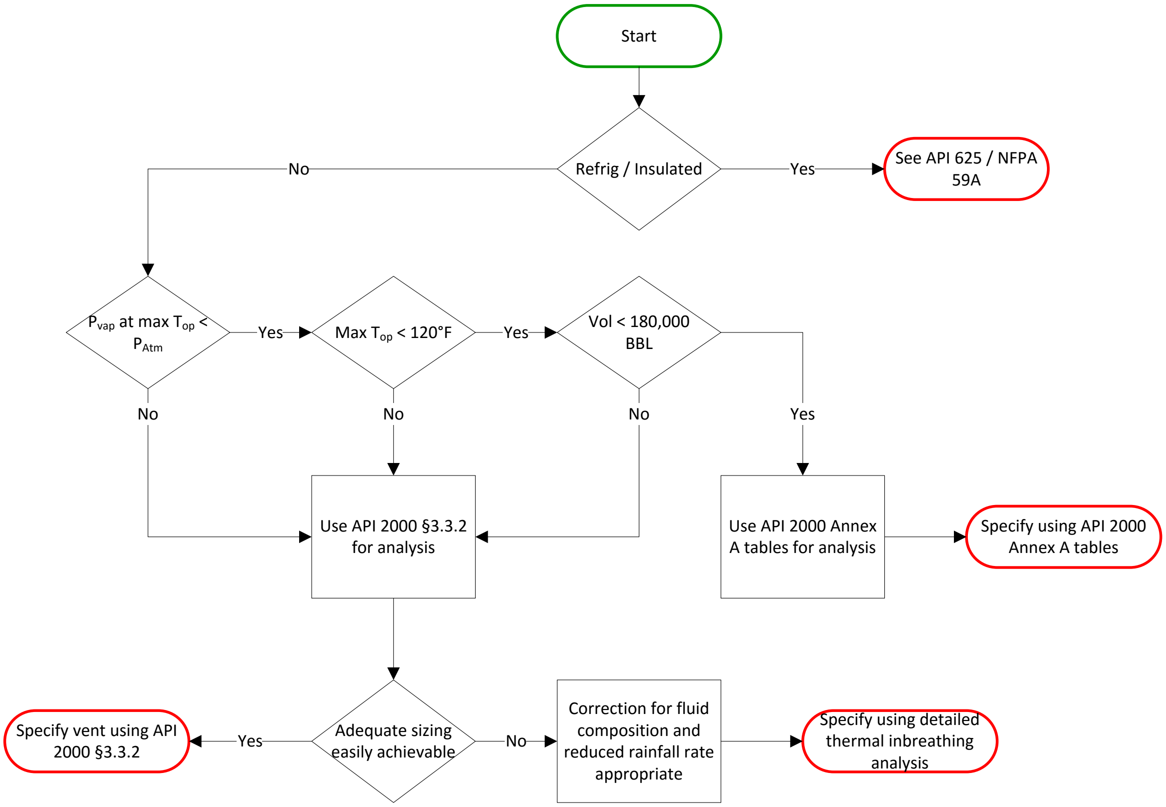

Figure 1 - Low Pressure Tank Thermal Inbreathing Calculation Basis Flow Diagram

Conclusion

As seen in the results of the case study presented, the rigorous sizing method in API Standard 2000 provides a conservative estimation of the venting rate for thermal inbreathing but may over-predict the size of the tank vent required. With generation of additional data, this conclusion can be further validated. It may be possible to develop a correction factor based on the specific fluid in the tank and the area rain fall rate to be used in the API Standard 2000 thermal inbreathing equation. Such an analysis is the next step Inglenook will be taking to further develop this calculation procedure. Anticipated future steps, using the same work process, include:

- Determine the outer wall heat transfer coefficients versus rain fall rates for different tank height to diameter ratios. This is important as the outer wall heat transfer coefficient directly effects the thermal inbreathing rate.
- Repeat the case study presented using different tank height to diameter ratios for different sizes of tanks, including larger storage tanks (e.g. API 650).

It is believed that the use of the detailed analysis approach presented in this paper may result in more realistic thermal inbreathing requirements for atmospheric and low pressure storage tanks in locations receiving less rain fall than the basis of 8.9 in/hr used in the API Standard 2000 and/or containing a gas space composition other than air. In many cases such as large refinery storage tanks, meeting the thermal inbreathing rate is less of a concern due to the larger vent sizes typically installed and higher total inbreathing rates due to pump-out at higher flowrates. In smaller tanks with standard nozzles installed, however, such as those commonly found in upstream wellsites, the advantages of the detailed analysis of thermal inbreathing requirements could be significant.

References

[1] API Std. 2000 - Venting Atmospheric and Low-Pressure Storage Tanks, 7th Ed., Appendix G, March 2013, American Petroleum Institute.

[2] API Spec. 12-F - Specification for Shop Welded Tanks for Storage of Production Liquids, 12th Ed., April 2009, American Petroleum Institute.

[3] Harnaut, Thorsten and Schwoppe, Patrick, "Short Report: A Contribution to Simplified Energetic Modeling of the Respirations of Tanks Above Ground", Protego Corporation, October 16, 2007. Original version in German.

[4] Lindeburg, Michael, Chemical Engineers Reference Manual for the PE Exam, 6th Ed., pg 32-3, Professional Publications, Belmont, CA.

[5] US Dept. of Commerce, Technical Paper No. 40 - Rainfall Frequency Atlas of the United States, 100 Year 1Hr Rain Fall Chart, pg 21, May 1961.

[6] Brooks, Donald, “Thermal Inbreathing Requirements of Low Pressure Storage Tanks at Elevated Temperatures”, Presentation, Spring 2012 DIERS Users Group Meeting, May 2012.

Appendix 1 - NOAA 100 Year Rain Fall Chart [5]