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Breathing losses from low-pressure storage tanks due to atmospheric weather change

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ABSTRACT

Vapors inside atmospheric and low-pressure storage tanks may condense either slowly during rainfalls or abruptly for instance by injection of cold liquid during steaming. Vapor condensation inside tanks may result in deformation and collapse. The latest editions of API 2000 and ISO 28300 standards lack an explicit formulation for the required in-breathing to compensate for vapor condensation, caused by a prolonged rainfall, which is the main topic of this paper. The analytical model here, which includes vapor condensation on the tank walls, predicted total in-breathing requirements for mixtures of air saturated with vapors, which are substantially larger than those calculated using the procedures in the standards. This paper is aimed to provide some realistic guidance for the reader addressing the issue of vapor condensation when determining the worst realistic case scenario for the tank breathing requirements.

1. Introduction and state of the art

Low-pressure storage tanks are large tanks, which contain huge amounts of stored products within thin metal sheet walls. Protection of low-pressure tanks against weather precipitations, which may lead to corrosion of the bare metal surface, is done by applying an organic coating or by painting with a corrosion proof paint. Painting, though usually cheaper, does not protect the stored product from heat transfer with the environment resulting in either more liquid evaporation or vapor condensation. Either condensation or evaporation inside the tank is responsible for an adjustment of the storage pressure, either a rise when the tank products are heated up or a fall when vapors condense. Either way, if no properly sized pressure or vacuum relief valves are mounted, tank deformation or even collapse may occur. As specified in ISO 28300 (ISO 28300, 2008) the in-breathing capacity is the required flow rate of ambient air through the vacuum valve and the out-breathing flow rate is the required capacity of the pressure relief valve to compensate for pressure changes within the tank.

The principal standards governing breathing of low-pressure near-atmospheric storage tanks are ISO 28300 (ISO 28300, 2008), API 2000 (API 2000, 2014), and EN 14015 (EN 14015, 2005). These standards, as far as in-breathing requirements are concerned, vaguely refer to an early work of Förster et al. (Förster et al., 1984), considering the impact of the rain intensity on the tank surface. Vapor condensation was not accounted for in their model. A later work by Salatino et al. (Salatino et al., 1999). discussed the effect of condensation on the in-breathing rate but it could not quantify it, since it missed an explicit modeling for the dampening effect of condensation on the wall temperature cooling. The impact of vapor condensation on in-breathing was modeled and observed by Fullarton (Fullarton, 1986) in a six liter vessel filled with dry air saturated with either steam (humid air) or methanol vapors: in comparison with the case, when the laboratory scaled vessel was filled with only hot dry air, the in-breathing requirements for air saturated with steam were twice and with methanol four times as large.

In this paper the authors are developing an analytical model for an uninsulated tank filled with a mixture of non-condensable gases, namely dry air, saturated with condensable vapors exposed to a severe but realistic rain shower after a prolonged uninterrupted solar exposure. Scope of the model is to achieve a better modeling of the heat and mass transfer mechanisms in order to provide the design and plant engineers with a tool to estimate the impact of condensation in the in-breathing requirements for real tanks, which cannot be found in the established standards.

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2. Theory

A sketch of this tank exposed to a rain shower of given intensity and impingement angle is shown in Fig. 1. For a first analysis the rain film is assumed of constant thickness along the lateral walls and the roof.

In this model the condensed phase is assumed at the same temperature as the gaseous phase, though it spreads over the colder metal surface. Additionally, the eventuality of a non - uniform wall temperature distribution is neglected. Under these assumptions, it is possible to write the energy equation for the tank product and the thin tank walls. The energy balance for the tank product in Eq. (1) is derived by the authors. According to this equation, the rate of cooling of the tank product is accelerated by both the internal heat transfer to the colder walls and the warming-up of the in-breathed ambient air.

$$\left(M_{vap}c_{vap} + M_{liq}c_{liq} + M_{air}c_{air}\right)\frac{dT_B}{dt} = -h_{int}A(T_B - T_E) - \dot{M}_{air}c_{air}(T_B - T_{amb}) \tag{1}$$

In the energy equation for the tank walls in Eq. (2a) the rate of cooling due to heat transfer to the rain film is dampened by vapor condensation. This equation is similar to the one derived by Fullarton (Fullarton, 1986), except for introducing an explicit formulation for the volumetric rate of condensation in the tank in Eq. (2b), which is proportional to the difference between the vapor concentration on the walls and the one inside the tank. Any occurrence, which may delay the start or dampen the rate of condensation, is neglected.

$$M_E c_E \frac{dT_E}{dt} = h_{int}A(T_B - T_E) - h_{rain}A(T_E - T_{rain}) + \rho_B \dot{V}_{cond}\Delta h_{cond} \tag{2a}$$

$$\dot{V}_{cond} = \beta\left[y_{vap}(T_B) - y_{vap}(T_E)\right]A \tag{2b}$$

The integrity of the tank in Eq. (3) imposes that the volume shrinkage caused by gaseous phase compression and vapor condensation inside the tank must be compensated by ambient air in-breathing, see Fullarton (Fullarton, 1986).

$$-(V_{vap} + V_{air})/T_B\, dT_B/dt + \dot{V}_{cond} = \dot{V}_{air} \tag{3}$$

Finally, a formulation for the rain film temperature in function of time is needed. Förster et al (Förster et al., 1984). proposed a general balance considering that the heat subtracted from the tank is either dissipated into the rain film or released to the environment. For the common case of thin rain films, where the film thickness is one order of magnitude smaller than that of the metal walls, the heat from the walls is prevalently used to warm up the colder rain droplet to the film temperature, as shown Eq. (4a). In Eq. (4b) the relationship between the rain mass flux impinging the tank $\dot{m}_{film}$ and the rain intensity on ground $\dot{m}_{rain}$ is evinced.

$$h_{rain}A(T_E - T_{rain}) - \dot{m}_{film}c_{rain}(T_{rain} - T_{amb}) = 0 \tag{4a}$$

$$\dot{m}_{film} = \dot{m}_{rain}\frac{\left[\frac{\pi D^2}{4} + DH\cot\omega\right]}{\left[\frac{\pi D^2}{4} + \pi DH\right]} \tag{4b}$$

For reference, in Continental Europe a rain of intensity around 75 kg/(m^2 h) is occurring once a year; a rain of 150 kg/(m^2 h) intensity occurs once every twenty years, while a pouring rain with an intensity of 225 kg/(m^2 h) happens once in a century (Förster et al., 1984). For comparison, the world record rain intensity of 419.3 kg/(m^2 h) was recorded in Cherrapunji, India in June 1995 (Khaladkar et al., 2009), while the American record rain intensity of 304.5 kg/(m^2 h) was recorded in Holt, MO in June 1947 (Cerveny et al., 2007).

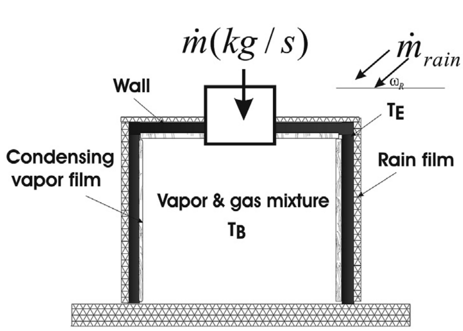

Fig. 1. A tank exposed to a rain fall.

3. Results and discussion

For a given tank size, wall thickness and specified ambient temperature and rain intensity and incidence, Eqs. (1)–(3) can be integrated numerically to estimate the temperature profiles of the bulk product, the walls and the rain film as well as the in-breathing flow rate as a function of time. For vapors of a pure component a direct formula for the condensed vapor flow rate is presented by the authors in function of the temperature difference between wall and product as well as on behalf of the saturation curve, see Eq. (5). This formulation transforms the energy balance for the walls in Eq. (2) in a linear PDE. Similarly, the energy balance in Eq. (1) can be considered as a linear PDE, since in the practice the change in heat capacity of the bulk product is often marginally affected by vapor condensation.

$$\dot{V}_{cond} = \beta 1\big/p_B \quad dp_{sat}/dT|_{T_E}[T_B - T_E]A \tag{5}$$

Fig. 2 shows the calculated in-breathing flow rate in function of time for a 2651 m^3 tank at an initial temperature of 120 °F (49 °C). The tank is filled with dry air saturated with steam (humid air) in one case and with heptane vapors in a second one. No liquid level is initially present in the tank, since tanks containing only gaseous phases due to the low thermal capacity experience the strongest cooling, most condensation and consequently have the largest in-breathing requirement than liquid filled tanks. The rain incidence angle is independent from rain intensity and set equal to 68°, which seems an acceptable value based on the work of Gabriels at al. (Gabriels et al., 1995). The calculations are performed assuming constant density, specific heat and thermal conductivity in the gaseous phase. The fractions of condensable vapor in the gaseous mixture are determined on the base of the initial partial pressures, resulting in about 11.7%-vol. for steam and 18.1%-vol. for heptane vapors.

The choice of steam as condensable phase in the gaseous mixture has a relevant practical aspect in tank storage due to tank failure during product change-over, when cold liquid is erroneously or unintentionally injected during steam sterilization. Despite the dramatic consequences, this occurrence is often underestimated during plant risk assessment (Sanders, 2004). Despite the similarity with condensation caused by rainfalls, condensation caused by liquid injection is much more rapid due to the direct heat and mass