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Experimental Investigation and CFD Modelling of Storage Tank Breathing

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Experiments were performed with a 200 m^3 air filled storage tank to collect experimental data for validation of literature models and for development of a new CFD model with improved accuracy. The literature models by Fullarton et al. (Fullarton et al. 1987) and Moncalvo et al. (Moncalvo et al. 2016) were chosen for the validation against experimental data. The validation study and experimental results are summarized in this paper, since the full study will be submitted to the International Journal of Loss Prevention in March 2022. In addition, this study compares the experimental data with the results of the new CFD model ARTEM (Advanced Reactor and Storage Tank Emission Model).

1. Introduction

Liquid products, such as gasoline, oil or other chemicals are stored in large-volume storage tanks under atmospheric conditions. These tanks are usually designed with very thin walls to minimize investment costs. Only slight over- and under pressure in the tanks is permissible, as otherwise a risk of bursting or buckling and implosion exists (Fullarton et al. 1987). A vacuum inside the tank is generated whenever the pressure or the temperature inside the tank drops suddenly, e.g. during unloading or a sudden heavy rain event. Increasing ambient pressure must also be considered. In case of undersizing of the vacuum valve, the pressure compensation is insufficient and the breathing volume flow is too low to maintain the minimum design pressure of the tank. A risk of buckling arises or even a loss of containment. In case of hazardous substances, a release leads to a potential hazard to persons and the environment.
The breathing flow rate for sizing of tank breathing valves for non-condensable gases is determined sufficiently accurate with current models, if all required boundary conditions are estimated conservatively (Schmidt et al. 2019). These boundary conditions include the rain intensity on the tank roof or the heat transfer coefficient on the inside and outside of the tank walls. Several models are available for calculating the breathing flow rate of atmospheric storage tanks. Breathing, considering solely gas inside the tank, is determined by the contraction of the tank internal gas phase assuming a constant tank pressure. The calculated breathing volume flow rate in each literature model is based on the mass balance adapted to the tank atmosphere (Foerster H. et al. 1984; Fullarton et al. 1987; Moncalvo et al. 2016; Sigel 1980; Holtkoetter 1994). To complete the differential equation system, energy balances are needed to couple the tank atmosphere with the environment (Schmidt et al. 2019).
In this study, a measurement campaign is presented which was performed to collect experimental data for the validation of literature models and for the development of a new CFD model with improved accuracy. The literature models by Fullarton et al. (Fullarton et al. 1987) and Moncalvo et al. (Moncalvo et al. 2016) were chosen as the reference model for the validation. Moncalvo et al. (Moncalvo et al. 2016) extended Fullarton's model by assuming different temperatures between the incoming free jet and the tank atmosphere, and by incorporating a liquid as storage medium in the energy balance. A constant thickness for the rain film was considered and heat conduction in the tank wall was generally neglected. A detailed overview of common models for the sizing of tank breathing valves during the cooling of storage tanks is given in (Schmidt et al.

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2019). The results from the comparison with experimental data here are transferable to the other literature models given in (Schmidt et al. 2019) as they are similar in structure.

The validation study and experimental results are summarized in this paper, and the full study will be submitted to the International Journal of Loss Prevention in March 2022. In addition, this study compares the experimental data with the results of the new CFD model ARTEM (Advanced Reactor and Storage Tank Emission Model).

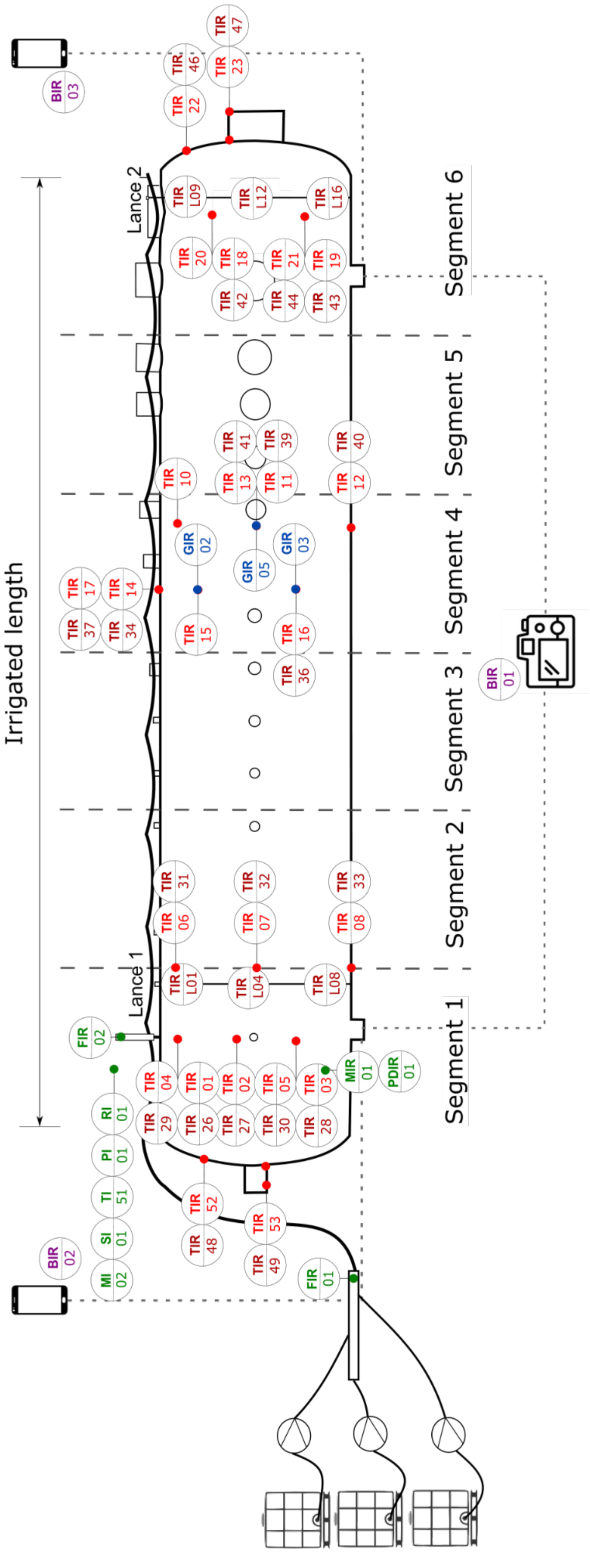

Figure 1: Experimental setup scheme of the tank.

2. Experimental setup and procedure

To investigate global phenomena of tank cooling, an experimental campaign was performed on a horizontal storage tank with a total volume of 191 m^3 and a weight of approximately 25 tons as shown in Figure 1. The tank was located on a paved windless courtyard on two bearings with a distance from vertex to ground of 13 cm. The total length of the tank amounted 20.5 m with 16 vertical and 15 lateral flanges on top and front side. The diameter of the tank was 3.6 m with a wall thickness of 1 cm. Five vacuum support rings were attached to the outer tank wall at a distance of 3 m each, which divided the tank into 6 segments. The first nozzle on the top at a size of DN25 was selected as inlet for all experiments. For cooling, 3 Intermediate Bulk Containers (IBCs) filled with tap water were used. Around the tank, three infrared cameras were placed to record the unsteady temperature distribution on the tank surface during the experiments. One high-resolution infrared camera BIR-01 was located at the frontside of the tank perpendicular to the nozzles, and two low-resolution cameras on smartphones (BIR-02 and BIR-03) were placed laterally at an angle of 55° each to the back of the tank, so that almost the entire tank surface was visualised by the infrared cameras. Each camera was aligned with a temperature sensor mounted on the tank wall so that the thermal image could be recalibrated.

Prior to the start of the experiments, the gas phase inside the tank was preheated with an electric heater for 3 hours. Subsequently, the tank surface was heated externally for 20 minutes with hot water from a sprinkler system consisting of 8 dripping tubes at a temperature of 60°C. The hot water was prepared in three additional IBC tanks by heating with immersion heaters. After the IBCs containing the hot water were emptied, the tank was sprinkled from the three cold IBCs.

A total of 9 experiments have been performed. In the first experiment, the breathing rate at a reduced water flow rate was investigated using 2 of the 3 IBCs. In the second and fourth experiment, the maximum possible temperature gradient during cooling was attempted. For this purpose, the IBCs containing the cold water were additionally filled with 100 kg of crushed ice each. The amount of water provided from 3 IBCs was sufficient for an experimental duration of 20 minutes. To ensure that the maximum inbreathing volume flow rate was reached within this time, the cooldown in experiment 5 was conducted using 6 cold IBCs to extend the experimental time to 40 minutes. In experiments 3 and 9, the inlet was closed and the tank slowly cooled down overnight. For experiments 6 and 8, the tank was cooled down with cold water with closed inlet. To perform experiment 7, a tank breathing valve with a set pressure of 13 mbar was attached at a lateral nozzle, therefore the inlet on the top was closed. The environmental conditions in experiments 1-9 were similar, as they were completed within one week. On all days the wind speeds did not exceed 5 m/s, the average ambient temperature was 33°C, the ambient humidity varied between 40% and 50%, the radiation intensity was between 850-950 W/m^2 and the average atmospheric pressure amounted to 1016 mbar.

Table 1: Initial and boundary conditions for literature models of Fullarton et al. (Fullarton et al. 1987; Fullarton 1986) and Moncalvo et al. (Moncalvo et al. 2016) and model parameters for comparison to the results of experiment V004.

Parameter	Description	Value	Unit
Geometry	Sprinkled length of tank surface	19	m
	Tank diameter	3.6	m
	Tank wall thickness	10	mm
	Tank volume	191	m^3
	Sprinkled surface area	225	m^2
Tank conditions	Initial wall temperature	39	°C
	Initial tank temperature	39	°C
	Initial vapor mass	2.2	%
Heat transfer	Internal heat transfer coefficient (bulk-wall)	2.1	W/m^2K
	Heat transfer coefficient (wall-film)	2416	W/m^2K
	External heat transfer coefficient (film-ambience)	2.9	W/m^2K
Ambient conditions	Ambient temperature (rain temperature)	10	°C
	Ambient relative humidity	50	%
	Ambient pressure	1017	mbar
	Effective rain intensity	132	kg/m^2h

3. Comparison of the experimental results to literature models

The results of experiment V004 are compared to literature models of Fullarton et al. (Fullarton et al. 1987; Fullarton 1986) and Moncalvo et al. (Moncalvo et al. 2016). Initial conditions are defined acc. to Table 1. The mixture property data of the humid air mixture including heat transfer for moist air have been taken into account for the model of Moncalvo et al..

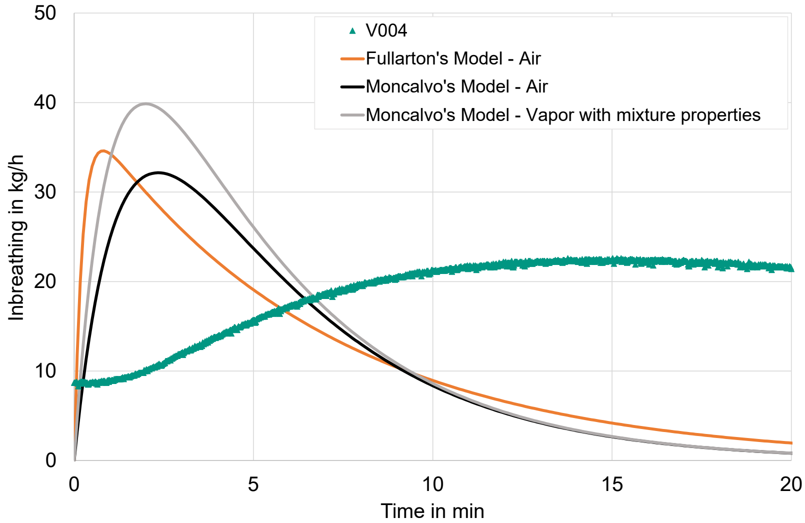

Figure 2: Inbreathing rate over time of experiment V004 (triangled line) and the literature models of Fullarton et al. (Fullarton et al. 1987; Fullarton 1986) (orange solid line), Moncalvo et al. (Moncalvo et al. 2016) for dry air (black solid line) and moist air with mixture properties (grey solid line)

In Figure 2, the calculation results for the literature models are presented (solid lines), the triangled line shows the results of experiment V004. Obviously, none of the literature models represent the course of the experiment with sufficient accuracy. The maximum deviation between the models and the experiments is 39% for Moncalvo's model assuming dry air (black line) and 47% for Fullarton's model (orange line).
Assuming moist air in the tank atmosphere with a mass fraction of 2.2%, the maximum values are additionally exceeded by Moncalvo's model with pure air property data by 20%. The temporal progression of the average tank temperature in the literature models and the experiment show a significant discrepancy of 58% to the end of experiment, see Figure 3. In all models the average tank temperature reaches the rain temperature of 10°C after 20 minutes. During the experiments, however, only a tank temperature of 24°C is reached.

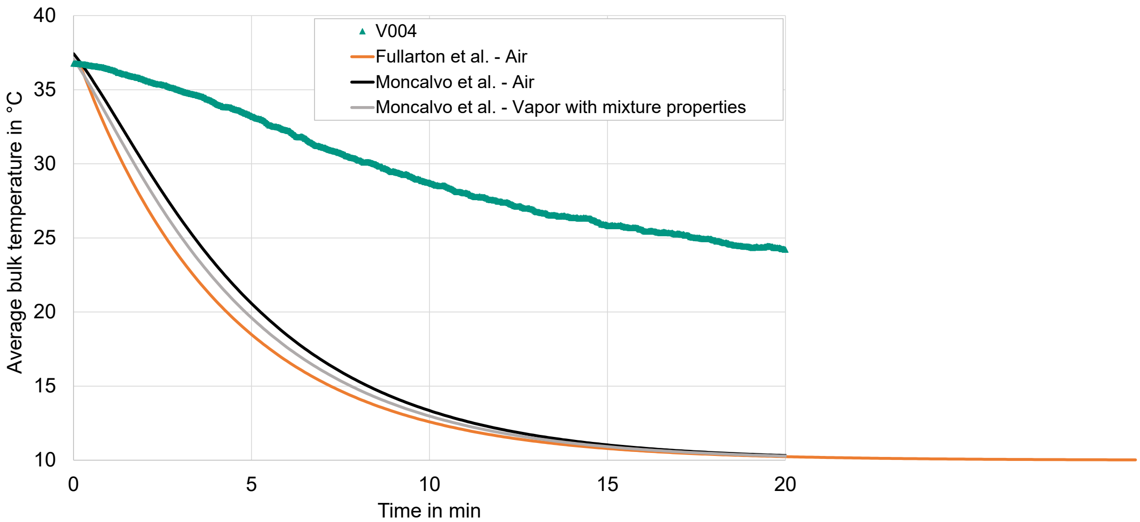

Figure 3: Temporal progression of the average tank temperature of experiment V004 (triangled line) and the literature models of Fullarton et al. (Fullarton et al. 1987; Fullarton 1986) (orange solid line) and Moncalvo et al. (Moncalvo et al. 2016) for dry air (black solid line) and moist air with mixture properties (grey solid line)

4. Numerical simulation of the tank cooling process

For further investigation, the new CFD model ARTEM (Advanced Reactor and Storage Tank Emission Model) was developed to simulate the transient phenomena during cooling of the tank. A CFD model allows to turn on or off single effects and to investigate causes of deviation described above. An ideal gas model was used to simulate dry air inside the tank. Unsteady heat conduction in the tank wall was resolved in detail. The water film on the outside was modelled by a thin film approach. The model was implemented in Siemens Simcenter STAR-CCM+ (Siemens Industries Digital Software 2022).
Initial conditions for the temperature inside the tank were horizontally and vertically interpolated experimental data. The initial pressure was provided by a pressure sensor inside the tank and extrapolated to a vertical pressure profile. The tank venting nozzle was defined as a pressure outlet with ambient conditions where backflow is allowed. An additional pressure loss coefficient of 0.96 was set to compensate for pressure drop in the experimental mass flow sensor.
For the tank wall, an initial temperature profile calculated from infrared experimental data and dry air conditions on the outside were assumed. To represent the experimental sprinkler system from linear tubes on the top of the tank, an inlet edge for the fluid film was defined. Inlet temperature of the film was set to 10°C and the experimental water mass flow was homogeneously distributed along the inlet edge.
Figure 4 shows the simulated mass flow rate of ambient air into the tank in comparison to the experimental result. The simulated mass flow rate matches the experimental values with high accuracy. The maximum value of the simulated mass flow rate deviates from the experimental results by 11%.

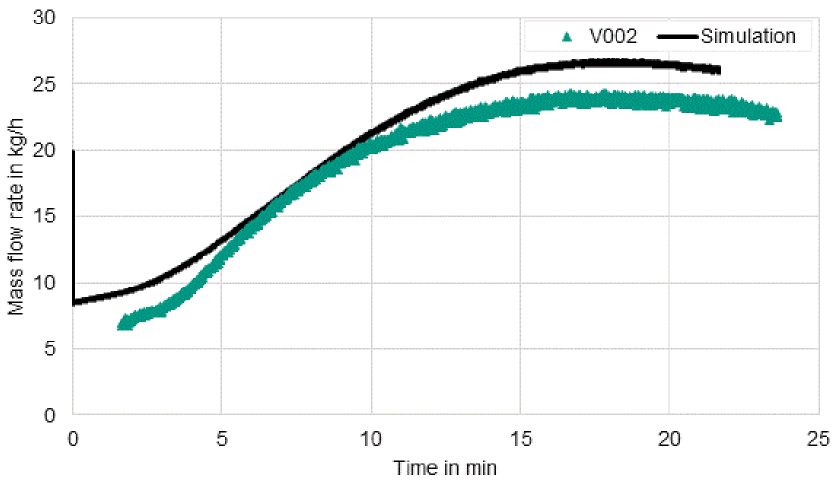

Figure 4: Tank breathing mass flow rate from CFD simulation (black solid line) and experiments (green triangled line).

5. Conclusion

Experiments with 200 m^3 were conducted to validate literature models. Additionally, the experiments were compared to the new, much more detailed CFD model ARTEM. The literature models are too imprecise to adequately describe the real cooling situation. Therefore, they are unsuited e.g. for accident analysis. The main purpose of literature models is to give a conservative result for sizing of tank breathing devices. The data from the numerical simulation of the CFD model ARTEM show that if damping effects of inbreathing flow restrictions are considered, the breathing process is much closer to the experiments. For additional improvements, besides the inbreathing pressure losses, the heat transfer from environment into the water film, the unsteady heat conduction in the tank wall and the mixing of hot ambient air into the tank atmosphere could be included for improvement of simplified models.

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References

Foerster H.; Schampel K.; Steen H. (1984): Atmungsvorgänge infolge von Witterungseinflüssen an Lagertanks für brennbare Flüssigkeiten. PTB-Bericht. Physikalisch Technische Bundesanstalt (Technical Report).

Fullarton, D.; Evripidis, J.; Schluender, E.U (1987): Influence of product vapour condensation on venting of storage tanks. In: *Chemical Engineering and Processing: Process Intensification* 22 (3), S. 137–144. DOI: 10.1016/0255-2701(87)80040-5.

Fullarton, Douglas (1986): Sicherheitstechnische Ueberlegungen bei Atmungsvorgängen in Lagertanks - Einfluß der Kondensation von Produktdaempfen. In: *Chemie Ingenieur Technik* 58 (1), S. 38–40. DOI: 10.1002/cite.330580111.

Holtkoetter, Torsten (1994): Modellentwicklung und experimentelle Untersuchung der Behälteratmung Report - Scanned PDF. Diplomarbeit.

Moncalvo, Davide; Davies, Michael; Weber, Roman; Scholz, Reinhard (2016): Breathing losses from low-pressure storage tanks due to atmospheric weather change. In: *Journal of Loss Prevention in the Process Industries* 43, S. 702–705. DOI: 10.1016/j.jlp.2016.06.006.

Schmidt, N.; J. Denecke; J. Schmidt; M. Davies (2019): Modelling of Breathing Phenomena within Large Storage Tanks During Rapid Cooling with Ambient Rain. ISSN 2199-9244 / Technische Mechanik; 39; 1; 96-112; ISSN 2199-9244. In: *Technische Mechanik* 39 (1), S. 96–112. DOI: 10.24352/UB.OVGU-2019-010.

Siemens Industries Digital Software (2022): Simcenter STAR-CCM+. Version 2022.1: Siemens.

Sigel, Reinhard (1980): Auswertung der Tankabkühlungsversuche 1980 und 1981 im Werk Höchst. Technical Report (Hoechst AG). Höchst.