NUMERICAL INVESTIGATION OF TEMPERATURE DISTRIBUTIONS IN LARGE STORAGE TANKS

S. Schmelter[1], R. Model[1], G. Wendt[2], M. Bär[1]
[1]Physikalisch-Technische Bundesanstalt, 10587 Berlin, Abbestrasse 2-12, Germany
[2]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Bundesallee 100, Germany
sonja.schmelter@ptb.de, regine.model@ptb.de, gudrun.wendt@ptb.de, markus,baer@ptb.de

Abstract

Using storage tanks for commercial transactions, the precise determination of the quantity of the liquid stored in the tank is required. Whereas the identification of the actual volume is realized by measuring the filling height by level gauges, for mass calculations the mean temperature of the liquid has to be additionally known. To ensure the reliable conversion of the liquid volume measured into mass temperature are investigated by numerical simulations for different fluids employing time-dependent boundary conditions and considering various initial situations. For all boundary condition studied the temperature inside the tank always exhibits a stratified distribution. Consequently, temperature measurements by one vertical sensor chain should be sufficient in practice. After the container was filled with fluid exhibiting a large temperature difference to the already storage fluid our simulations show that it will take hours until measurements by one chain of temperature sensors yield the correct average temperature.

1 Introduction

Large storage tanks are used in a wide range of industrial applications for different kinds of liquids, e.g. mineral oil and its products, liquid food, colors, chemical and pharmaceutical products. For commercial transactions the precise determination of the mass of the actual tank content and the transferred amount of the liquid is of considerable importance. The aim of the investigation is a detailed examination of standard measurement practices. The actual volume may be identified by level gauges which are usually installed inside the tanks. For the geometrical calibration of the tanks, approved rules and regulations are permanently improved [1]. Moreover, for the correct mass determination the mean temperature must be additionally known in order to assign the current mean density of the liquid. At present, the measurements are performed by temperature sensors located along one single vertical chain with a subsequent averaging of the temperature values for each time.

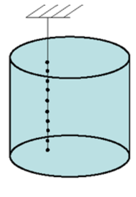


Figure 1. Schematic diagram of a tank with a sensor chain

Because of the high dimensions, e.g. a tank diameter up to 30 m, the tanks are located outdoors and often subjected to one-sided solar radiation potentially causing large temperature gradients. Therefore the question arises how many temperature sensors and what kind of geometric arrangement are needed to represent the average tank temperature. Specifically, it is of great practical interest whether one chain of sensors is sufficient for the task if the right position in the tank is chosen (see Fig.1). Another question concerns specific filling situations, e.g. if hot fluid is refilled into the cold tank fluid. In this case, as expected, a hot fluid region arises inside the storage tank. The question is how long it will prevent a sufficiently accurate measurement of the average temperature of the fluid for a given temperature sensor configuration. Generally, inhomogeneous initial or boundary conditions for temperature cause turbulent natural convection, which then leads to temperature equilibration.

In parallel to the simulations presented here, extensive measurements were performed within the framework of the project "T-distribution in large storage tanks". Temperature measurements were carried out at more than 120 different positions inside a 2440 m3 water-filled tank throughout a whole year. Additionally, the outside conditions were registered in detail. The complete description of these experiments will be published elsewhere and is not included here but preliminary experimental results are in line with the main conclusions drawn from the presented simulations presented here.

The investigation was focused on computational fluid dynamics (CFD) for approximately realistic weather and filling conditions. Usually turbulent flow simulations are characterized by turbulence models and wall functions with a set of individual parameters more or less suitable for a concrete flow situation. Therefore, comparisons with detailed measurement data are a prerequisite for reliable simulations. For simplicity a two-dimensional cavity is concerned advantageously for comparisons with published measurement data for a differentially heated cavity [2]. The mathematical and numerical model was tested and verified by this data set and the application provides a first insight into the convective flow in storage tanks [3].

In the next section the models are outlined. In Section 3 the time-dependent temperature distributions for different weather condition are discussed. An extreme situation for a filling process is treated in Section 4. Finally the results are summarized in the conclusions.

2 Mathematical model and numerical approach

The mathematical basis for our fluid dynamic problem provides the incompressible Navier-Stokes-equations (NSE) for the conservation of mass and momentum which is extended by the energy equation. Because the flow inside the tank is buoyancy-driven the Boussinesq approximation is assumed.

Then, the model equations result in

$$\begin{gathered} \frac{\partial}{\partial t}\boldsymbol{u} + (\boldsymbol{u}\cdot\operatorname{grad})\boldsymbol{u} + \frac{1}{\rho_0}\operatorname{grad} p = \nu\Delta u - \boldsymbol{g}\beta T \\ \operatorname{div}\boldsymbol{u} = 0 \qquad (1) \\ \frac{\partial T}{\partial t} + \boldsymbol{u}\cdot\operatorname{grad} T = \alpha\Delta T \;, \end{gathered}$$

where $\boldsymbol{u}$ is the velocity field, p the pressure, T the temperature, $\rho_0$the reference density of the fluid, ν the kinematic viscosity, and t the time. Furthermore for the temperature dependency the gravitational acceleration $\boldsymbol{g}$**,** thermal expansion coefficient β, and the thermal diffusivity α are need.
For the numerical solution of flow problems the finite-volume method is proven to be convenient due to its conservation properties. Because of the high computational expense the direct numerical simulation (DNS) of the model (1) is restricted to moderately turbulent flows in spatial domains of not too large size. Generally, many turbulence models based on time or space averaging are available and are still objects of research. For our buoyancy-driven flow an unsteady Reynolds-averaging Navier-Stokes model (URANS), the Shear Stress Transport (SST) model by Menter [4] was chosen since it turns out to be more robust for our application than others like, e.g., Reynolds stress models.
For the two-dimensional treatment of the tank a standard size with a width of 14,928m and height of 14.021 m was chosen and the related grid contains 100489 elements. Near the walls the grid is rigorously refined because the convective flow is fastest there. Hence, the width of a finite volume in the middle of the domain is 450 times larger than the smallest at the wall. Time steps keep constant at 0.5 s, larger step often leads to instabilities. For differentially heated cavity with time-constant boundary conditions a stationary solution could not be reached by a stationary integration method since even for long simulation times the fluid flow is moderately varying around a kind of "average solution" [3].
The numerical simulations presented here were carried out using the commercial software ANSYS CFX®. On a computer cluster about 30 processors were used.

3 Results for different weather boundaries

The problem of convective heat conduction in cavities is well known by the Rayleigh-Benard cells where a hot bottom and a cold top cause rotating cells [5]. In this section two extreme weather situations are chosen in order to check whether a one chain measurement is possible. For comparison we create two chain positions: x = - 4 m and x = 4 m. The centre is characterized by x = 0 m. Every chain contains five equidistant located sensors. Furthermore, the simulation provides the average temperature over the whole tank.
The first situation describes the cooling down of water at night and the second one the temperature distribution during a hot summer day for four different liquids: water, naphtha, diesel or heavy gas oil.

3.1 Cooling down at night

Since the temperature differences overnight are relatively small a simplified model with constant boundary conditions was used. Assume that in the late evening the sun has disappeared and the temperature around the tank is nearly constant at 5°C. Throughout the day the fluid in the tank has been warmed up and holds a constant temperature of 15°C in the evening (initial condition). The bottom of the tank holds the temperature of 15°C throughout the whole night because the ground below keeps the warmness of the day.
In a transition time (about 6 h) different temperature patterns are observed as shown in Fig. 2 for one, two, three and six hours, but later the temperature is almost constant in the whole tank. It can be expected that in the

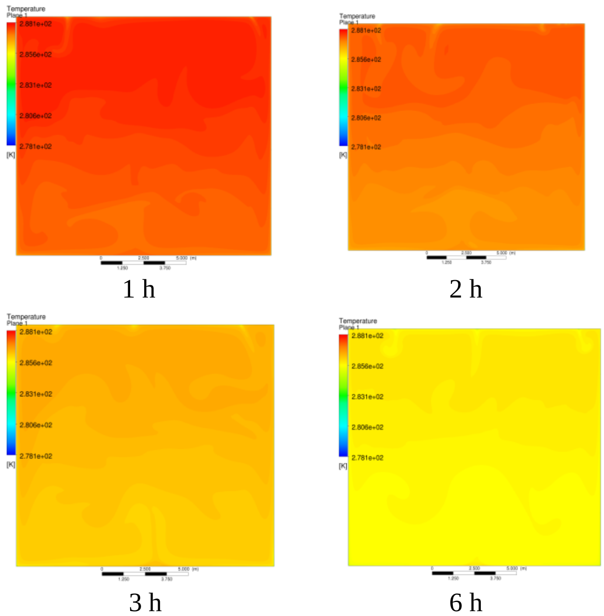


Figure 2.Temperature distributions after one, two, three, and six hours for the cooling down configuration.

later time the average tank temperature can be reproduced quite well by one vertical sensor chain. Nevertheless, also during the cooling down process in the first few hours, the difference between the vertical sensor chains and the average tank temperature is very small, which can be seen in Fig. 3 top.
Furthermore, all the time differences between the average temperatures of the whole tank and the chains are smaller than 0.07 K, see Fig. 3 bottom. It could be expected that in three dimensions a quite similar stratified temperature distribution is formed. Therefore, in this cooling down si-

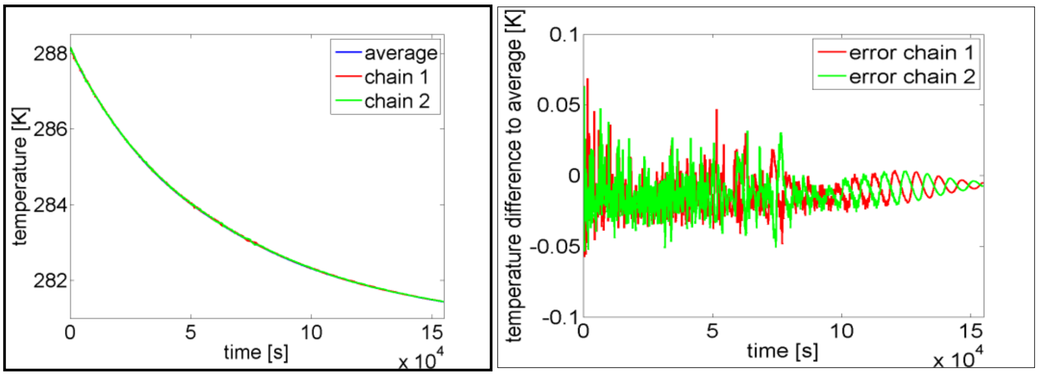


Figure 3.Left: Average tank temperature (blue line) in comparison with average temperature derived by the two chains (red and green lines). Right: Difference bettween the average tank tempe-rature and average chain temperature.

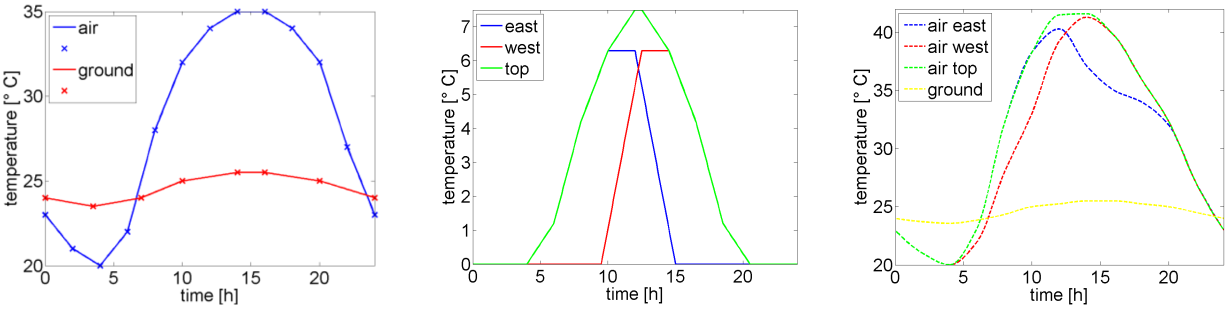


Figure 4. Left: Temperature profile in the air and at the ground, middle: temperature rise at the tank walls due to solar radia-tion, right: boundary conditions for the simulations as smoothed sum of the corresponding curves of the left and middle picture.

tuation one sensor chain would be sufficient to reproduce the average tank temperature

3.2 Hot summer day

Next, we consider the case of time-varying thermal boundary conditions, which vary over 24 hours. At first, a mathematical model was created which describes the influence of the heating up and cooling down of the tank walls during a hot and sunny summer day.
From the weather database for the German town Dort-mund the 28 June 2011 was chosen as a sunny day with large temperature variations which are illustrated in Fig.4.
Fig. 4 left shows the prescribed temperature profile for the air and the ground. The values for the air temperature were chosen according to the values read off the data-base. The ground values are assumptions. The middle picture shows the assumed temperature rise due to solar radiation. For example, the midday sun at noon cause a rise of 7°C on the top tank surface corresponding to the peak in the green line. The east wall is heated up more in the forenoon (blue line, overlapped with part of the green line) whereas the west wall more in the afternoon (red line). The smoothed sum of these curves with the tem-perature profile for air (blue line in the left picture) rep-resents the effective temperature at the corresponding tank sides used for the simulations, see Figure 5 right.

The ground temperature is unaffected by solar radiation. The initial temperature was assumed to be 25°C.
In this simulation series four materials were tested: wa-ter, diesel, naphtha, and heavy gas oil as examples, see Table 1. The temperature dependency was considered in the simulations. For all materials the temperature dis-tributions show a stratified distribution over the whole 24 hours. Fig. 6 shows the resulting distributions for noon.

date for 30°C	**water**	**naphtha**	**diesel**	**heavy gas oil**
kin. Vis-cosity [mm^2/s]	0.801	0.5627	3.601	7.967
therm. exp. coeff. [10^{-3}/K]	0.303	1.13	0.73	0.7
therm. Diffusivity [mm^2/s]	0.148	0.0837	0.0572	0.0528
Reyleigh number	1.50 e15	1.40 e16	2.07 e15	9.72 e14
Reynolds number	1.66e7	4.57e7	5.73e6	2.54e6

Table 1. Material and flow properties.

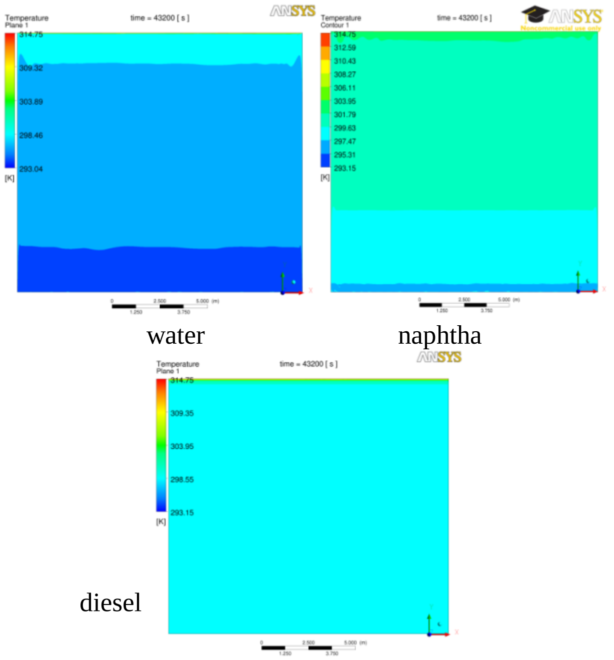


Figure 5. Temperature distributions for water, naphtha, and diesel at noon 12 o'clock.

The same effect was observed for constant boundary conditions, where the left wall was hot, the right wall cold, and the top and bottom walls were adiabatic [3]. Because the density difference caused by a temperature difference immediately induces a convective flow, the temperature gradient in a horizontal plane is almost zero.

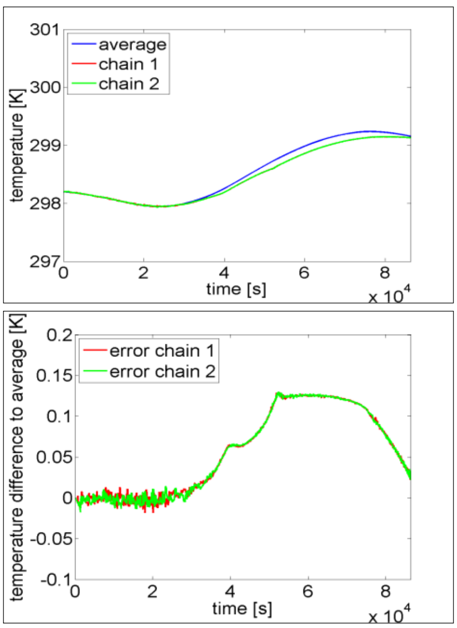


Figure 6. Top: Average tank temperature (blue line) in comparison with temperature derived by two different vertical chains (red and green line) for diesel filled tank, Bottom: Difference between the average tank temperature and the average chain temperature.

There arises the question whether the small temperature variations in a horizontal plane have a significant influence on the measurement results. Indeed, the effect is weak for all materials over all 24 hours.

The error between the average tank temperature and the temperature derived by the two chains is smaller than a possible measurement uncertainty. The maximum error observed is 0.07 K for water, 0.13 K for diesel, 0.06 K for naphtha, and 0.06 K for heavy gas oil, see as example Fig. 6 for diesel.

In summary, it was found that also the temperature distributions for all considered liquids are stratified for the case of time-varying thermal boundary conditions modeling a hot und sunny summer day and that the potential measurement error caused by a one-chain measurement is insignificant.

4 Secial tank filling situation

The weather conditions stand for one influencing factor generating the temperature distribution inside the tank. In the previous section the simulated examples suggest that independent of the outside temperature including sunshine or not the temperature distribution inside turns to stratified or homogeneous pattern. Filling a tank with the same fluid but subjected to different temperature a considerable disorganization of this pattern is expected. Consequently, the question arises, how long is the time delay till an one-chain measurement gives the correct result.

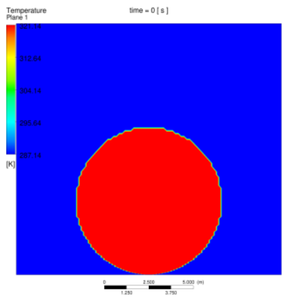
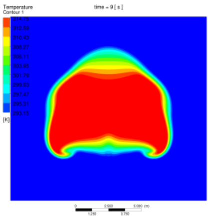


Fig. 7. Initial condition.

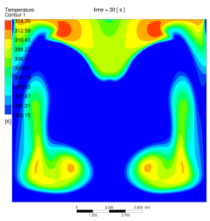
For a principal test an oil company proposes the following situation: the temperature of the tank content is 14°C, of the infilled fluid 48°C and the pumping capacity is 3500m^3/h.

For the simulation a five-minute infilling is assumed corresponding to a volume of 291.7 m^3. This could be a sphere with a radius *r* of 4.1 m. Then the initial condition for the 2D-Simulation is as follow: in a circle with radius *r* in the low region 48°C and 14°C elsewhere as illustrated in Fig. 7. The walls satisfy isothermal boundary conditions with 14°C. As tank liquid diesel was chosen because it was the worst case for the summer day.

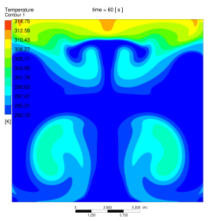
Over time the both fractions, warm and hot diesel, mix relatively fast but after two hours a broad layer of warmer temperature than elsewhere still remains at the top of the tank, see Fig. 8. After ten hours this layer is After ten hours this layer is smaller but still exists there. The error between the average tank temperature and the temperature derived by the two chains is larger than in the two cases of the previous section.



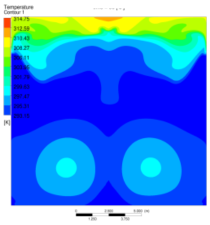
t = 18 s



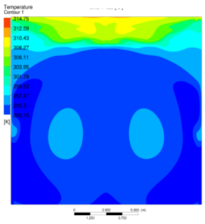
t = 30 s



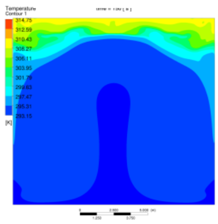
t = 1 min



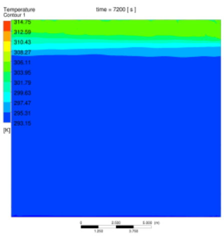
t = 1.5 min



t = 2 min



t = 2.5 min



t = 2 h

Figure 8. Temperature distribution 18 s, 30 s, 1 min, 1.5 min, 2 min, 2.5 min, and 2h after start with initial condition of Fig. 8.

Notably, it takes about three hours to keep this error smaller than 0.5°C and five and a half hours to keep it smaller than 0.25°C, see Fig. 9. Otherwise, the wall temperature would not realistically remain constant and a fluid flow evolves inside the tank reducing the temperature differences. In this way, the simulated example describes a critical case to point to the risk in filling situations.

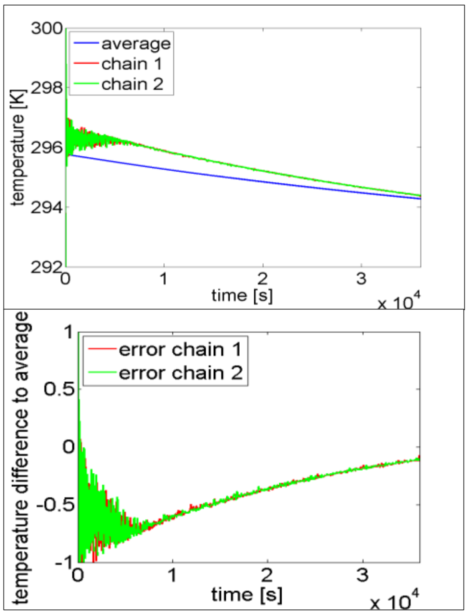


Figure 9. Top: Average tank temperature (blue line) in comparison with temperature derived by two different vertical chains (red and green line) for diesel filled tank, Bottom: Difference between the average tank temperature and the average chain temperature.

5 Conclusion

The goal of our investigations was to evaluate common procedures that are used to determine the average temperature in large storage tanks. In particular, a standard measurement protocol was considered which uses a single vertical chain with several temperature sensors. The mean value of all measured temperature values is then assumed to be equal to the average temperature of the tank content. Fluid flow and heat transfer for two extreme weather conditions (cooling down in the night and a hot and sunny summer day) and for a partial filling situation were numerically simulated, and the mean values of two fictive sensor chains were compared with the average temperature obtained by the complete temperature distribution in the simulation. For the simulations mimicking different weather situations, a single chain reproduces the average temperature quite well, but the results of simulations addressing the filling situation investigated show a sufficient large waiting time is required to obtain reliable measurement results for the average temperature of a fluid in a large storage tank.

This work is part of the PTB-project “T-distribution in large storage tanks” carried out by altogether eight parties representing the appropriate authorities, manufacturers and operating companies as well as the university side.

References

[1] G. Wendt, R. Jost, and D. Werner,“Eichfähige 3D-Vermessung großer Lagertanks mittels Laserscanning“, Technische Überwachung **51**, pp. 38–41, 2010.

[2] Y.S. Tian, and T.G. Karayinnis, “Low turbulence natural convection in an air filled square cavity: Part I: the thermal and fluid flow fields“, Int. J. Heat Mass Transfer,, **34,** 6, pp. 849-866, 2000.

[3] S. Schmelter, G. Lindner, G. Wendt, and R. Model, “Numerical investigation of turbulent natural convection in differentially heated square cavity”, AIP Conf. Proc.,2011, 1389,pp. 106-109.

[4] F.R. Menter, “Two-equation eddy-viscosity turbulence models for engineering application”, AIAA Journal, 32:8, pp. 1589-1597, 1994.

[5] G. Nicolis, “Introduction to nonlinear science”, Cambridge Uni Press1995.