TEMPERATURE AND VOID FRACTION DISTRIBUTION IN A SIDE WALL HEATED TANK

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1. Introduction

Storage tanks for fluids are widely used industrial facilities. As a consequence of an external fire, the heat-up of the inventory may lead to the evaporation of the liquid and to release of significant quantities of dangerous gases into the environment. Comprehensive experiments were performed, to investigate the heating up processes. The experiments have shown that the liquid inventory behaves very differently depending on the mode of heating. Bottom heating leads to an irregular thermoconvective motion of the liquid, which causes good mixing, so that saturation is reached at all points inside the tank approximately at the same time. The maximum enthalpy of the liquid always remains close to the average value. If the vessel is heated from the side, stable temperature stratification is observed leading to large temperature gradients. Evaporation can start much earlier than the average temperature reaches saturation. The scenario is very realistic for cylindrical barrels, which are exposed to an external fire. In the paper, the experimental results of the tests with side wall heating are presented and the observed phenomena are described.

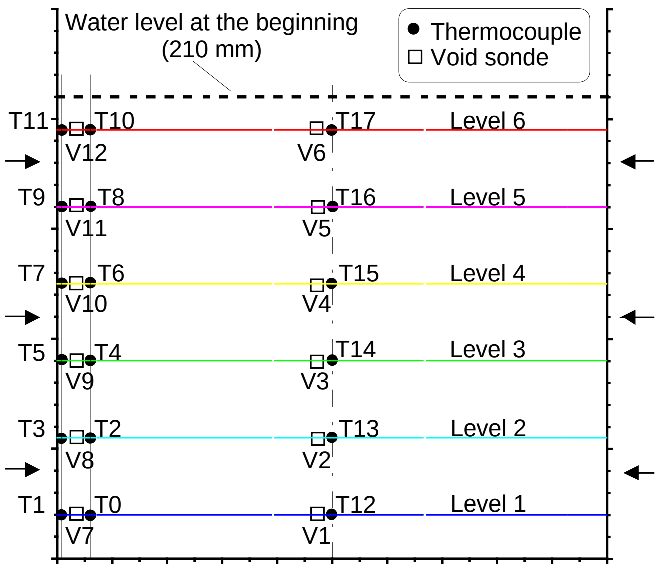

Fig. 1: Test arrangement and localisation of the measuring probes

Table 1: Localisation of the measurements

Level	H [mm]	Near the Wall			Centre of the tank	
		(1mm)		(10mm)		
		Temp.	Void	Temp.	Temp.	Void
6	195	T11	V12	T10	T17	V6
5	160	T9	V11	T8	T16	V5
4	125	T7	V10	T6	T15	V4
3	90	T5	V9	T4	T14	V3
2	55	T3	V8	T2	T13	V2
1	20	T1	V7	T0	T12	V1

The first experiments were performed with temperature measurements only [3-5]. In order to clarify the physical nature of the details of the heating up process in simple geometrical boundary conditions, a two-dimensional mathematical model was developed, which also includes evaporation and two-phase flow. The calculated results of the model essentially contributed to the understanding of the phenomena observed during the tests. It was found that two-phase processes play an important role. Therefore, the tests were repeated, in which the local void fractions were measured too (see Figure 1).

2. The experimental test arrangement

The experimental test arrangement consisted of a cylindrical tank with a diameter of 0.25 m and a height of 0.25 m (see Figure 1). On the side walls, heating elements with an overall power of 4 kW are arranged, so that the heating power was equally distributed over the wall. During the tests, the tank was equipped with thermocouples and with conductivity probes for measuring the local void fractions at different locations. The measuring devices were arranged in certain heights over the bottom in the centre of the tank and near the walls (see Figure 1 and Table 1).

3. The experimental results

Different experiments were performed with different distances of the needle shaped void fraction measurements from the side wall between 1 mm and 5 mm. The experiments showed qualitatively the same behaviour of the fluid during the heating up process. The time dependence of the temperatures measured in different heights from the tank bottom is shown in Figure 2 for the thermocouples in the centre. Temperature and void fraction signals for the different levels are shown in Figure 3a to 3f. During the experiment the void fraction probes V7 through V12 had a distance of 1 mm from the wall.

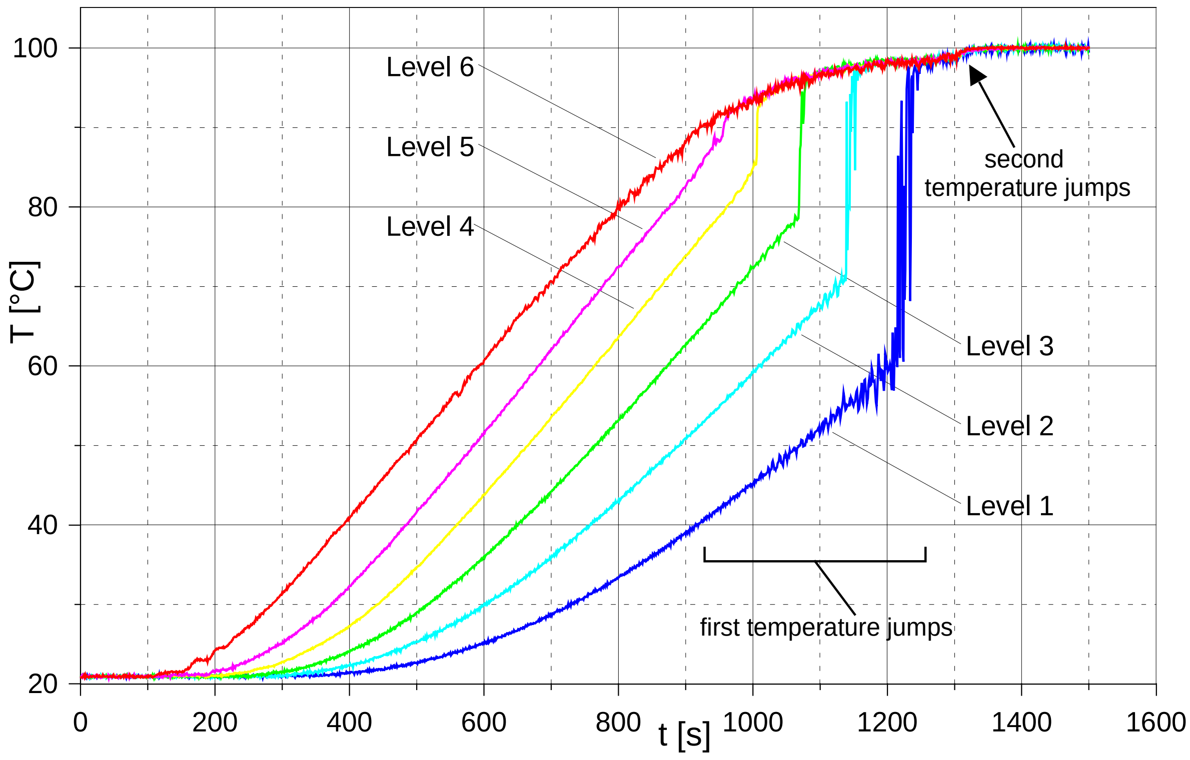

Fig. 2: Experimental results of the temperature measurements in the centre of the tank (T12 through T17)

Already some hundreds of seconds after the beginning of the heating a strong temperature stratification occurs. Temperature differences up to 50 degrees between the 1st and the 6th height level are observed (see Figure 2 after about 1000 seconds). The different temperatures of the thermocouples at 1 mm and at 10 mm distance from the wall show, that already shortly after starting the test a small boundary layer of only a few millimetres is established with up to 7 °C higher fluid temperature (see Figure 2 and 3a to 3f).

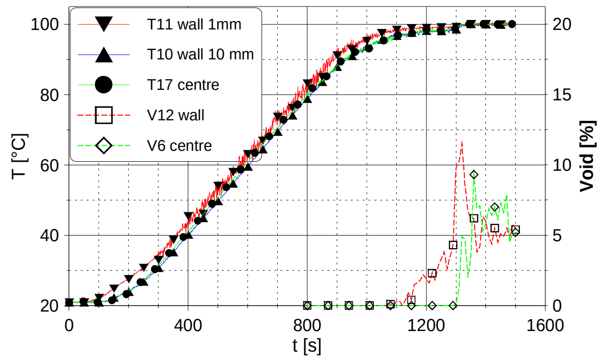

Fig. 3a: Level 6, H = 195 mm

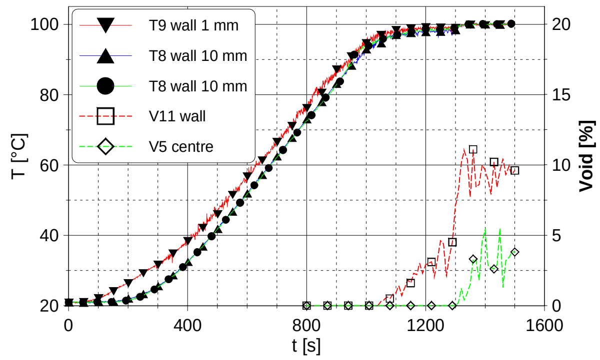

Fig. 3b: Level 5, H = 160 mm

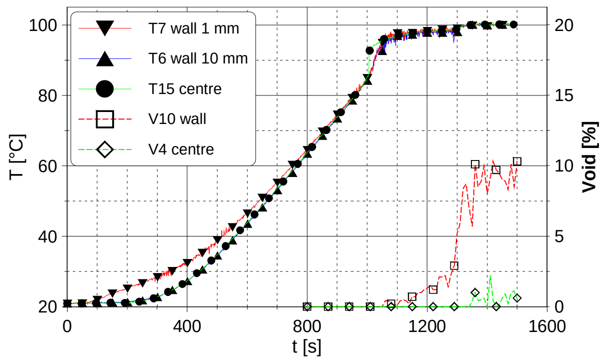

Fig. 3c: Level 4, H = 125 mm

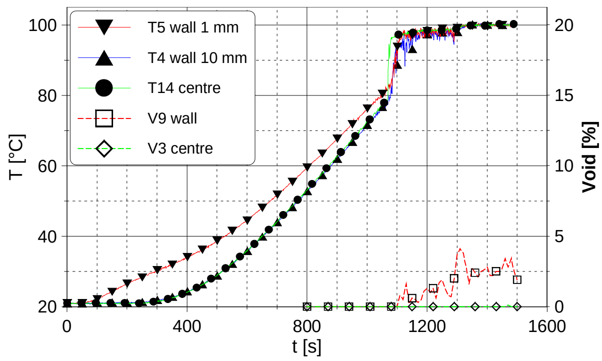

Fig. 3d: Level 3, H = 90 mm

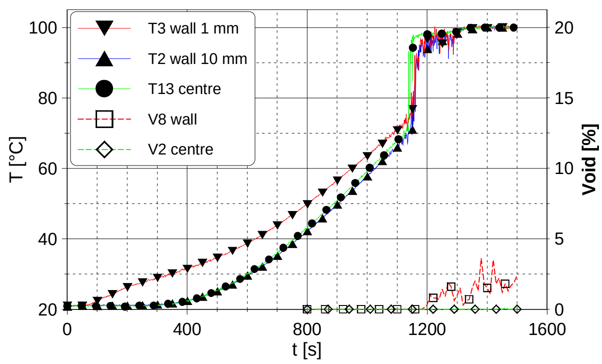

Fig. 3e: Level 2, H = 55 mm

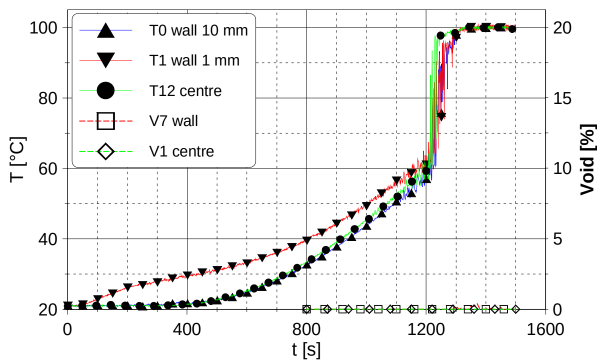

Fig. 3f: Level 1, H = 20 mm

Fig. 3: Fluid temperature and void fraction courses at different height levels in the tank

After about 1100 seconds first boiling is detected by the void probes near the wall at the levels 6 to 3 (see Figure 3a to 3e). During the time period from 900 to 1200 seconds temperature jumps to about 98 °C are observed. The jump is only small in the level 5. The jumps for the levels 4 to 1 are clearly to be seen in Figures 2 and 3c to 3f: in level 4 at 1000 seconds, level 3 at 1080 seconds, level 2 at 1130 seconds and finally in the lowest level 1 the largest jump (approximately 40 °C) at 1220 seconds. In the lower levels temperature oscillations are observed shortly before the jump. During this period no steam is detected in the centre of the tank (see Figure 3). Shortly after the last jump at level 1 a second temperature jump from 98 °C to 100 °C is observed for all thermocouples at about 1300 seconds (see Figure 2).

Simultaneously with the second temperature jump the needle probes V9 to V12 near the wall indicate a clear increase of the void fraction. Only after that steam was detected in the levels 6 to 3 in the centre of the tank (see Figure 3a to d). As an additional effect the void fraction detected by the wall probe at the highest level 6 decreases (see Figure 3a).

The needle shaped probes during the experiments yielded reliable signals, but problems occurred because of the probe size. The probes had a diameter of 1 millimetre. Therefore, they are not capable of detecting bubbles with a diameter smaller than about 1.5 mm. During the tests small bubbles were seen at the wall already after about 950 seconds. Also the typical noise at subcooled boiling was heard. The probes detect first boiling only after about 1100 seconds.

4. A numerical model

In order to clarify the physical nature of the details of the heating-up and the evaporation process in simple geometrical boundary conditions, a two-dimensional mathematical model was developed. The flow in the vessel was approximated by a two-dimensional flow in a rectangular area in Cartesian co-ordinates. It was assumed that neither temperature nor gas fraction influences the density of the liquid in the mass conservation equation and in the inertial term of the momentum equation. The changing density was taken into account only at the volume force term in the momentum equation (Boussinesq-approximation). This simplification leads to simpler calculation of the velocity field of liquid phase: when actual temperature and gas fraction distributions are given over the time, the volume force term can be determined explicitly and the motion of the liquid can be further calculated independently from the gaseous phase. For the gaseous phase, a constant bubble rise velocity was assumed. The vector of the gas velocity results from the liquid velocity by adding a constant value to the vertical velocity component.

Caused by these simplifications, the momentum of the gaseous phase is neglected and there is no need to solve a second momentum equation. The model is therefore restricted to low gas densities. This condition holds in the majority of practical applications.

So the model consists of four main equations [7]: the energy conservation equation, the momentum and mass conservation equation for the fluid and the mass conservation equation for the gaseous phase. The continuity equation was considered for each phase. The transport of the gaseous phase was described by a mass conservation equation that contains an empirical bubble diffusion coefficient. The energy conservation equation was simplified to the heat transport equation, which includes an effective thermal conductivity coefficient. The momentum equation was considered only for the fluid phase. A constant turbulent viscosity represented turbulence.

The phase transition due to evaporation and condensation was modelled assuming thermodynamic equilibrium. The mass source of steam was computed from the superheating or subcooling of water. The heating power was considered by the source term in the heat transport equation. The heat is added to the cells near to the heated wall. The time dependent power derived from the measured heater sheet temperatures is shown in Figure 4.

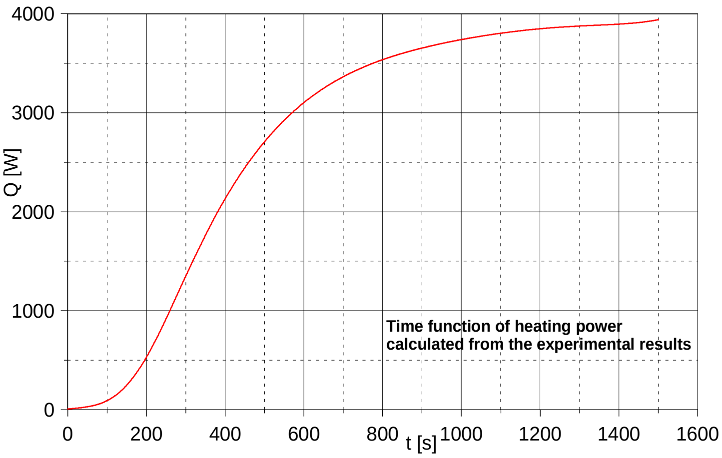

Fig. 4: Calculated time function of heating power

5. Numerical results and physical interpretation of the heating up process

The 2D model described in chapter 4 reproduces the experimental results and all phenomena in good agreement to the experiment (see Figure 5). The simulations enabled to clarify the physical reasons for the occurrence of the temperature jumps, which are explained in the following.

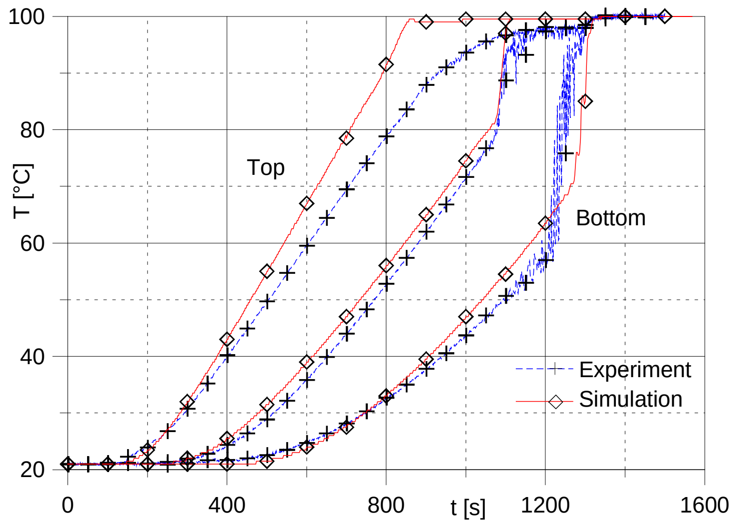

Fig. 5: Calculated and measured time dependence of temperatures. The bottom temperature corresponds to the probe T13, the middle to T14 and the top to T17 (compare Fig. 1)

Figure 6 shows the temperature distribution after 600 seconds. Heating of the side walls leads to significant horizontal temperature and density gradients in the vertical boundary layer. The resulting volume forces impose a strong preference direction of circulation. The result is a stable vortex that transports the warm liquid from the heated wall to the surface. In the bulk, stable temperature stratification develops. As the temperature in the boundary layer increases in time, the liquid arriving at the surface is always piled up at the top. In the bulk a large vertical temperature gradient arises. In the consequence, evaporation starts much earlier than predicted by the average enthalpy. The steam generated in the boundary layer and at the top of the liquid discharges from the vessel. That leads to early mass losses.

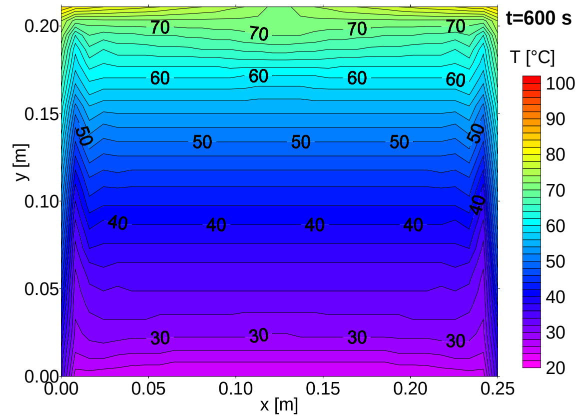

Fig. 6: Calculated temperature field at 600 seconds

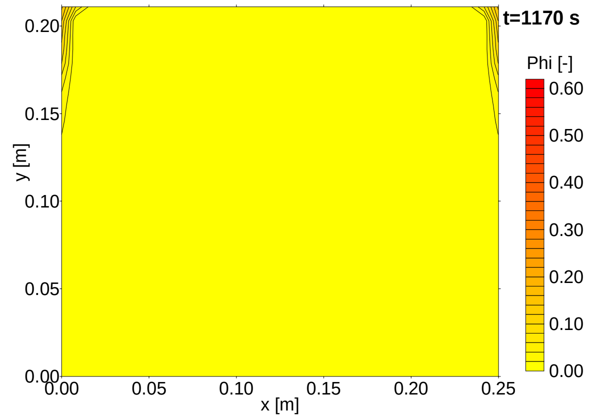

Fig. 7: Calculated void fraction field at 1170 seconds

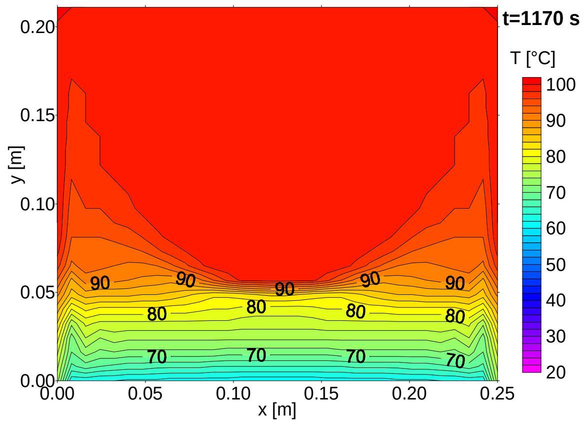

Fig. 8: Calculated temperature field at 1170 seconds

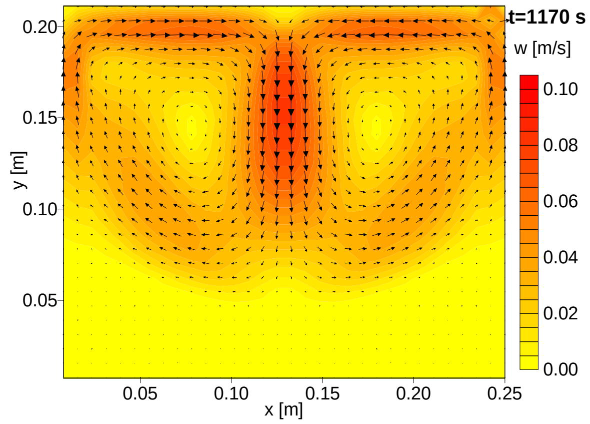

Fig. 9: Calculated velocities at 1170 seconds

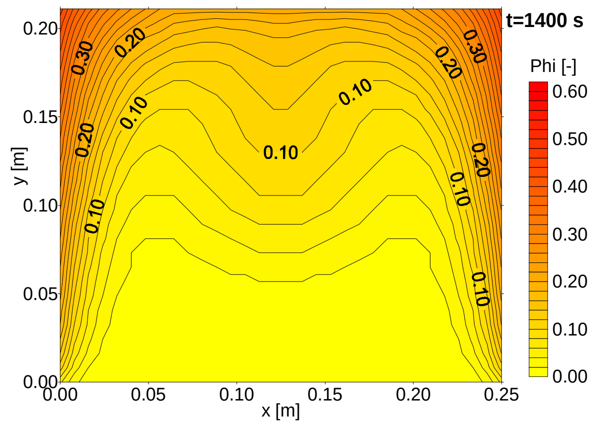

Fig. 10: Calculated void fraction at 1400 seconds

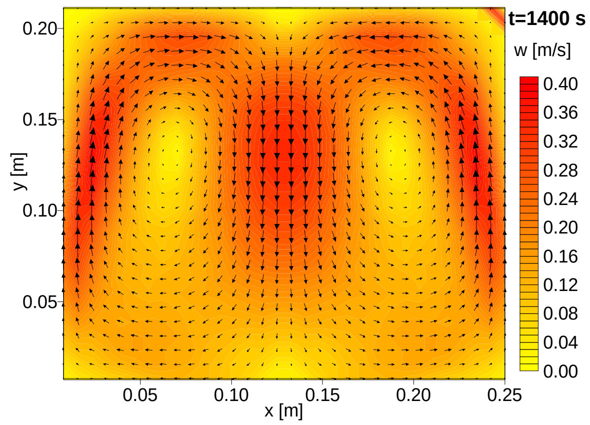

Fig. 11: Calculated velocities at 1400 seconds

The system responds very sensitively to the appearance of steam in the boundary layer. As it is seen also in the experiments, evaporation is first observed in the upper region of the side wall (see Figure 7). There, the buoyancy force caused by the bubbles is much higher than in the region below, where only density differences of the liquid phase drive the circulation. In the result, the upper region is well mixed, while the fluid in the region below remains stratified (see Figure 8 for the temperatures, Figure 9 for the velocities and Figure 7 for void fraction distribution).

The region of good mixing is extending downwards, because the onset of boiling moves down in the boundary layer. When the mixing front reaches the position of a thermocouple, its reading rapidly increases to a value close to saturation temperature. This explains the first successive temperature jumps found in the experiment.

Approaching saturation, the steam generation in the boundary layer gets more and more intensive causing significant mass and energy losses, but also accelerates natural circulation. When the sink velocity at the centre of the vessel becomes greater than the bubble rise velocity, suddenly a part of the produced steam is entrained into the bulk of the liquid. This causes a rapid approach to the saturation temperature in the entire fluid volume. In the temperature measurements this event is seen as the second temperature jump after 1300 seconds (see Figure 2). Figure 10 and Figure 11 show the calculated void distribution and velocities during the period of pool boiling. The described scenario yields the explanation, that during the heating up process before the second temperature jump no steam is found in the centre of the tank. The increased mixture velocity after the second jump causes a decreased void fraction at the upper probe on the wall (V12, see Figure 3a). This effect could be confirmed during several tests.

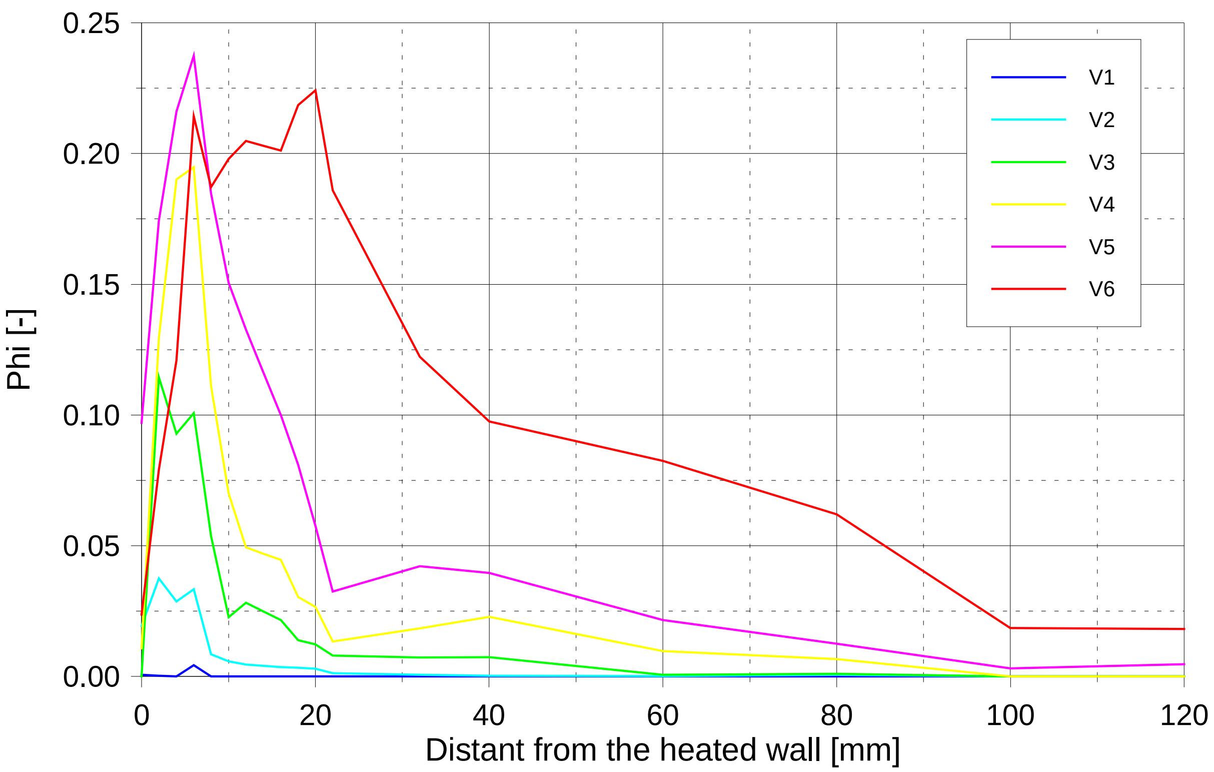

Fig. 12: Measured void fraction profiles after the second temperature jump

Additional measurements during further tests were performed, which aimed at the determination of the void fraction profiles during the period of pool boiling after 1300 seconds. For this purpose, the void fraction measurement arrangement V1 to V6 was moved through the tank in radial direction. The result is shown in Figure 12 and Figure 13. Figure 12 shows the measured void fractions depending on the distance from the heated wall. The figure shows clearly that steam is measured not only near the wall, but also in the bulk. Steam bubbles are carried down in the centre of the tank. The void fraction field in Figure 13 was derived by interpolation of the data of Figure 12. Figure 13 can be compared with Figure 10. The computed void fraction field shows a qualitatively good correspondence to the measured data. During the pool boiling period of the test the void distribution in the tank is very sensitively influenced by the relation of steam degassing from the tank surface and steam entrainment by the downward moving fluid into the centre of the tank.

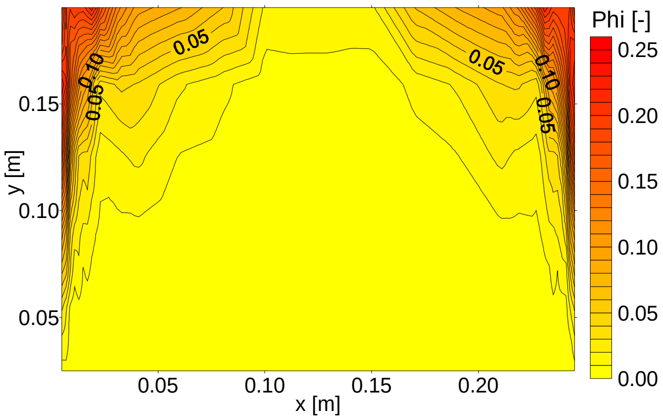

Fig. 13: Measured void fraction field after the second temperature jump

6. Conclusions

The paper presents experimental and numerical investigations of single and two phase heating up processes of tanks with side wall heating. The measurement of the temperature and of the void fraction at different locations in the tank provides deeper insight into the mechanisms of two-phase natural convection in a tank. Despite some simplifications, the numerical 2D-model served as a tool, to understand and explain the observed events.

It was found, that side wall heating yields a considerably non-uniform temperature distribution in the tank. Assessing the numerical and experimental results, it is possible to identify the temperature stratification and the subcooled boiling near the wall as the cause of the first temperature jumps observed in the experiments. The quick transition from slight subcooled to volumetric boiling causes the second temperature jumps and a rapid approach to the saturation temperature in the entire fluid volume. This event was reproduced correctly by the two dimensional model.

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