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Correlation of design, material, flow conditions and the thermodynamic losses in hot water storage tank

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CORRELATION OF DESIGN, MATERIAL, FLOW CONDITIONS AND THE THERMODYNAMIC LOSSES IN HOT WATER STORAGE TANKS

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1 Introduction

Hot water storage tanks (HWST), integrated in heat or cold supply systems in an optimal way, contribute to the reduction of installed capacity, fuel and operation costs. By smoothing peak loads and equalising the throughput in pipeline systems they increase the lifetime of the components. Furthermore, storage tanks help to reduce return pipe temperatures and thus energy consumption of circulation pumps and heat losses in district heating networks while the power output of combined heat and power generation (CHP) plants is increased at the same time.

The spreading integration of sustainable sources of energy in conventional heat supply systems makes high demands on design, dimensioning and operation of hot water storage tanks.

A pronounced thermal stratification positively influences the efficiency of solar collectors, condensing boilers and the COP of heat pumps, connected to the storage tank. The size of the mixing layer affects the volumetric efficiency of the tank and thus economics of investment and operation.

The design of inlet pipes in tanks with external heat exchanger and the operation temperature as well as the flow rate of charging and discharging have an effect on formation and temporal stability of the mixing layer. In storage tanks with internal heat exchangers the duration of charging and the developing of return pipe temperature from the heat exchanger depends on dimensioning and configuration of this component.

Improper designed storage tanks can cause increased return pipe temperatures and heat losses, higher pumping work and a more frequently switching of controllers and heaters. The latter effect reduces the efficiency and lifetime of these components.

In this paper a method of correlating exergetic losses of hot water storage tanks to the tank design and operating conditions is presented.

2 Theoretical approach

Internal exergetic losses in HWST are caused by temperature equalization processes within the tank without any heat loss to the ambience. The extension of these losses is influenced by the design and material properties of the tank as well as operation parameter like temperature levels and flow rates. Aim of the examination is to quantitatively and qualitatively describe these influences. For that reason dimensionless key numbers have been developed to deliver information about tank design and intended operation conditions.

The correlation of the key numbers and the losses in the tank were investigated in experimental tests and numerous numerical computations. The CFD-Code Fluent was used to compute flow and heat transfer in the tank. The simulations focused on storage tank volumes between 160 and 4300 l.

2.1 Dimensionless key numbers describing design and operation conditions

The Richardson-number is the relation of buoyancy force to inertia of an inlet flow. It contains information of storage tank design and operation conditions (temperatures ϑ_{tank}, ϑ_{in}, flow rate). Thus it is appropriate for description of mixing losses.

$$Ri_H = \frac{g \cdot \beta \cdot \left(\vartheta_{in,max} - \vartheta_0\right) \cdot H}{c_{in}^2} = \frac{Gr_H}{Re_H^2} \tag{1}$$

The capacity factor, meaning the relation of heat capacities, is defined as the quota of heat capacity of the storage medium and the total heat capacity of the storage tank including tank wall and internal masses such as heat exchangers.

$$f_{cap} = \frac{C_{sm}}{C_{sm} + C_{wall} + \sum_i C_{internal\ mass,i}} \tag{2}$$

Storage tanks with a high capacity factor will respond very dynamically to charging and discharging. That means there are no significant delayed temperature exchange processes between storage medium and other masses inside the tank just after stopping charging or discharging.

The factor f_{cond} describes the intensification of vertical temperature equalization due to vertical heat conduction in tank wall and internal devices additional to heat conduction in the storage medium itself. Convection is induced by wall heat conduction. A theoretical approach to be evaluated is

$$f_{cond} = max\left\{1, \frac{(aA)_{sm} + \xi_{wall} \cdot (aA)_{wall} + \sum_i \xi_i \cdot (aA)_{internal\ device,i}}{a_{sm} \cdot \left(A_{sm} + \xi_{wall} \cdot A_{wall} + \sum_i \xi_i \cdot A_{internal\ device,i}\right)}\right\}. \tag{3}$$

2.2 Evaluation of thermal stratification

The thermal stratification can be measured by the vertical temperature profile in the tank. Two approaches have been tested. A mixing layer is defined as the zone between hot and cold regions in the tank. This layer can be described by the share with a temperature range in respect to minimum and maximum temperature, such as

$$T_{min} + 10\% \cdot \left(T_{max} - T_{min}\right) < T_{ml} < T_{min} + 90\% \cdot \left(T_{max} - T_{min}\right). \tag{4}$$

Otherwise the mixing layer can be approximated by a tangent on the maximum gradient of the temperature profile. This method was preferred as more applicable. A volume segment of 3 % of the total storage volume is considered. The change in temperature of this segment is measured either during tapping or with sensors inside the tank. To compare experiments with simulations the course of temperature was determined by thermocouples of a vertical probe in the tank.

The maximum $\left(\frac{\Delta\vartheta}{\Delta z}\right)_{ml,max}$ is used to calculate the vertical extension and the volume share of the mixing layer:

$$\Delta z_{ml} = \frac{\vartheta_{charge} - \vartheta_{discharge}}{\left(\frac{\Delta\vartheta}{\Delta z}\right)_{ml,\,max}} \quad \text{and} \quad \Psi_{ml} = \frac{V_{ml}}{V_{tank}} \approx \frac{\Delta z_{ml}}{H_{tank}} \qquad \text{(5) and (6)}$$

2.3 Evaluation of internal losses and entropy production

Irreversible losses produce entropy in the system „storage tank“. The entropy balance includes the integrated entropy of all volume or mass segments in the tank and the fluxes through the system boundary. There is entropy flux coupled to mass flow in and out of the tank. An additional entropy flux occurs with heat transfer at the walls. In Fluent the integration of entropy in the modelled domain is easy to postprocess. Tank walls had been considered as adiabatic in all simulations of internal losses.
The entropy production $S_{irr,12}$ during the process from start (1) to end (2) is

$$S_{irr,12} = S_2 - S_1 - S_{Q,12} - \int_1^2 \dot{m} \cdot \left(s_{in} - s_{out} \right) \cdot dt \qquad \text{with} \qquad S_{Q,12} = \int_1^2 \frac{dQ}{T} \qquad (7)$$

3 Experimental investigations

3.1 Test facilities

A test rig was set up with several hot water storage tanks. Thermal analysis of tank operation was done with a commercial 1000 l storage water heater. A smaller special designed tank for heating-circuit water (150 l) and a Plexiglas storage tank model with a volume of 175 litres were used for examination of internal losses such as mixing and heat exchange processes.

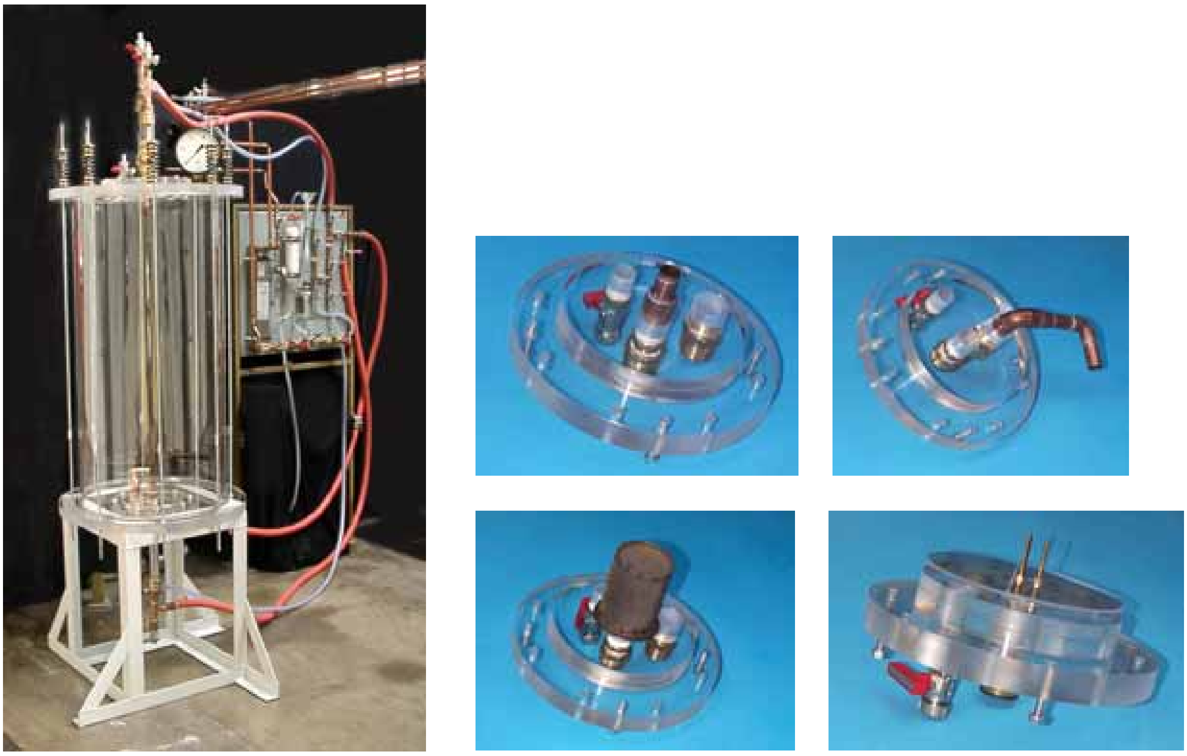

Figure 1: Test rig "Plexiglas storage tank model" – tank design (left) and inflow devices in the removable lids (right)

The Plexiglas storage tank model has removable lids at the top and at the bottom. Thus, different inflow devices could be mounted and tested with a number of thermal and fluidic boundary conditions. Plexiglas – as transparent as window glass – is appropriate for visualization of inlet flow and mixing patterns in the tank. By dyeing the inflowing water the necessary contrast is made to keep track of the way and the mixing process of the inflowing water. Pipes, baffles and screens were tested and later compared to simulation results. Heat conduction in metal walls and heat storage in the tank wall are further objects of examination.

3.2 Influences of design details

The influence of a tank wall made of metal was reproduced with a 3 mm steel plate of 300 mm height and 150 mm width. Its backside was insulated with PE and equipped with thermocouples. The plate was fixed in the lid of the tank via a thin rod. The temperature field in the plate could be measured. The convection patterns were visualized with a coloured mixing layer.

Figure 2 shows a standstill test with the metal plate. The mixing layer was created by discharging the 50 °C warm tank with 10 °C cold water and a flow rate of 350 l/h until the colder water reached the height of the plate. After 90 s first convection effects had moved away a part of the green coloured water from the plate.

As a contrast the path lines of a simulation are shown on the right side of Figure 2. A 2D-domain of 200 mm x 100 mm was simulated assuming a temperature drop between the upper and the lower part at time zero. On the left border of the domain there is a 5 mm steel plate. It conducts heat from the upper warm region to the lower cold region and induces vortices as seen in Figure 2. The flow field after 40 s of standstill is shown.

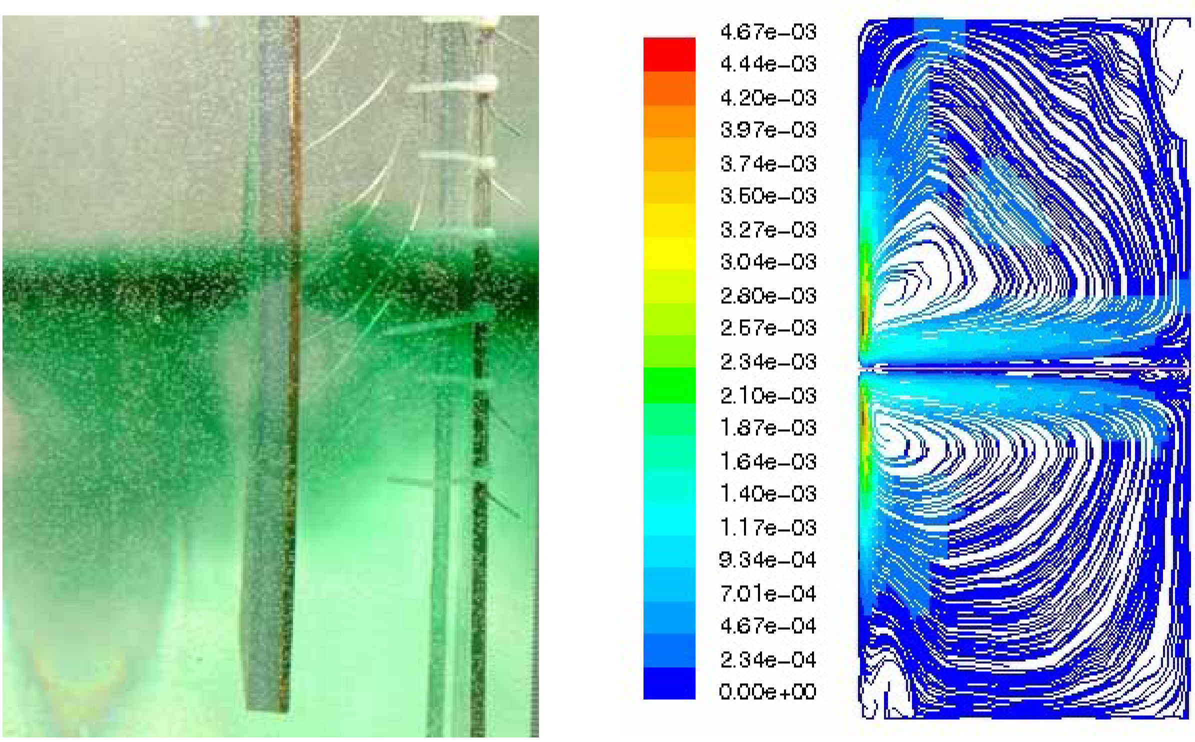

Figure 2: Convection near the metal plate in height of the mixing layer, left: mixing layer (50/10 °C) after 90 s standstill in experiment, right: path lines of convection in a simulated 2D-domain with 5 mm steel wall on the left border, 40 s heat exchange

The influence of heat exchange between storage medium and other masses in the tank is of importance, if charging and discharging occur frequently. During discharge heat is transferred from the hot wall to the storage medium, which is displaced upward. During charging the process works vice versa: Heat is transferred from the storage medium to the wall. In large storage tanks with a relatively thin wall this heat exchange process causes only a marginal loss. But especially in smaller tanks this effect should not be neglected. Figure 3 shows the decrease of maximum vertical temperature gradient in the mixing layer for two different cases described below.

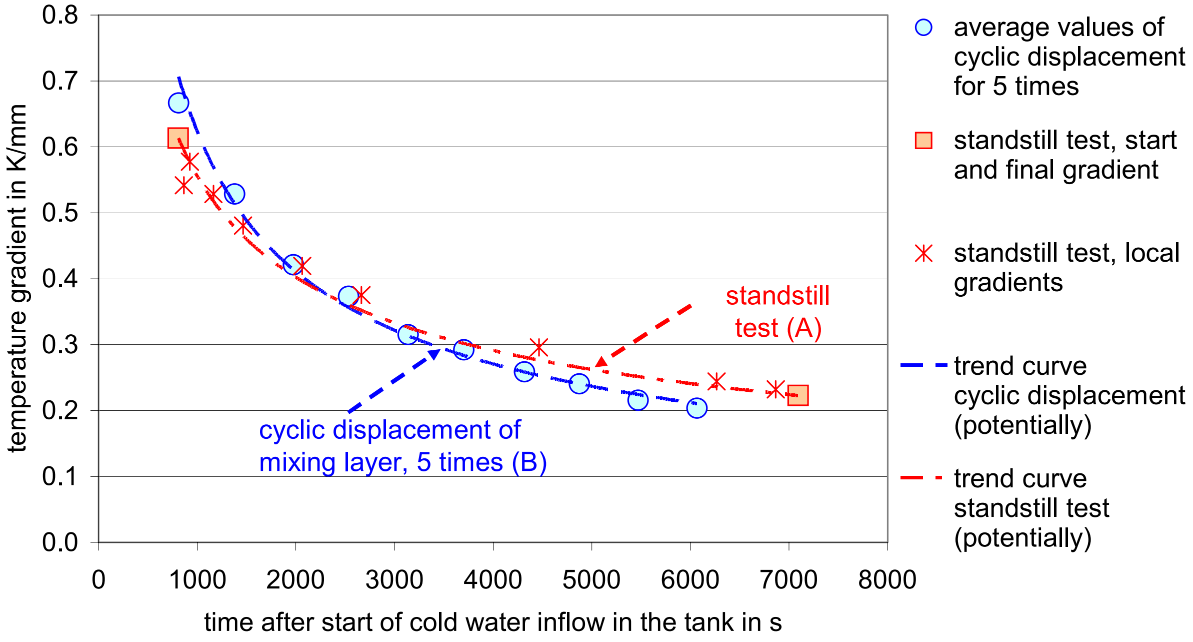

Figure 3: Decrease of maximum vertical temperature gradient in the mixing layer at standstill (Test A) and at cyclic partial charging and discharging (displacement of mixing layer 2 x 5 times, test B).

In test A the Plexiglas storage tank model was charged with 50 °C warm water followed by a partial discharge with 10 °C cold water, inflowing at the bottom. Then the temperature of the tank was observed for 110 minutes at standstill. Vertical heat conduction in the water and heat losses to the ambience led to an extension of the mixing layer and a decrease of maximum temperature gradient. Test B started in the same manner but after 5 minutes standstill the water was drained at the bottom of the tank until 300 mm change of height level of the mixing layer were reached. After further 5 minutes cold water entered smoothly at the tank bottom and the mixing layer was displaced 300 mm upward again. This cycle was repeated 4 more times. After total testing time of 100 minutes the maximum temperature gradient in the mixing layer had decreased below the value of test A after 120 minutes. The cold water injection with the baffle at the bottom was done with low flow rate very carefully. Thus the measured difference can mainly be assigned to heat exchange processes between storage medium and tank wall.

4 Modelling with CFD

A large number of interpolation points is necessary to derive semi-empirical correlations between the losses and design data. As the number of experimental tests is limited due to temporal and financial expenses, numerical simulations have been used to generate more data points for the correlations. In the first step the simulation model has to be validated with measurements. Several experimental test sequences were simulated in Fluent and very good results have been achieved.

In the second step flow conditions were changed in the simulations. Later the geometric models in Fluent were scaled and detailed examinations with varying tank materials und wall thicknesses ware executed.

5 Results

5.1 Mixing at inflow in the tank

A correlation for mixing in the tank as function of the Richardson-number was developed from the results of tank inflow simulations with different parameters. Inflow velocity, temperature difference between tank and inflowing water, tank height and height-diameter-ratio have been varied. For inflow with baffles an empirical function for entropy production was derived. It is shown together with the simulation data in Figure 4.

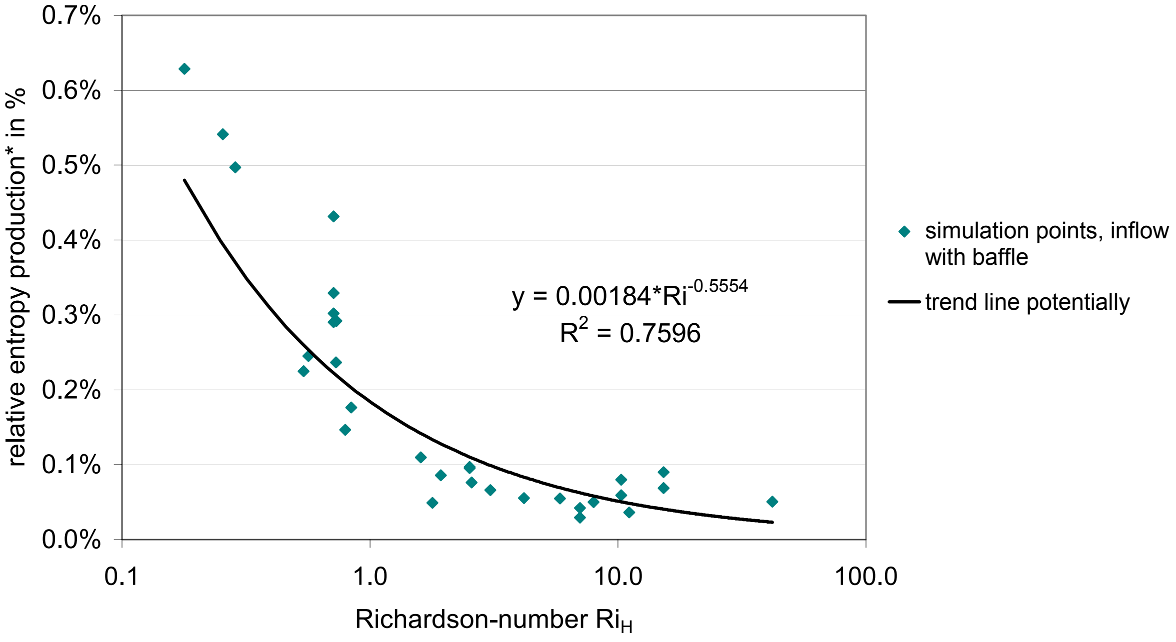

Figure 4: Entropy production at inflow with baffles as function of Richardson-number, relating to entropy difference between fully charged (60 °C) and fully discharged (20 °C) tank, here charging / discharging of one third of tank volume took place

The example of the 1000 l storage water heater demonstrates the influence of the Richardson-number on thermal stratification. In Figure 5 the vertical temperature profile in the tank at r/R = 0.75 is shown for different Richardson-numbers. The inflow pipe is directed tangentially inclined to the bottom of the tank. Only at Ri > 2 a good thermal stratification is reached. This condition can be achieved using well designed baffles even for high flow rates and low temperature differences. For baffle design following recommendations should be obeyed [1].

Ratio of gap height to diameter of connecting pipe $$\frac{H_{gap}}{D_{pipe}} = 0.25 \quad (8)$$

Ratio of flow path in the gap to gap height $$\frac{L_{gap}}{H_{gap}} \geq 10 = 2.5 \cdot D_{pipe} \quad (9)$$

Dimensioning baffle to achieve a gap exit velocity $$c_{gap,\,out} = f(Ri_{H,ideal} \approx 4) \quad (10)$$

In (10) $Ri_{H,ideal}$ is calculated with the theoretical average exit velocity from the baffle gap. The real velocity profile is taken into account by the higher value $Ri_{H,ideal} \approx 4$.

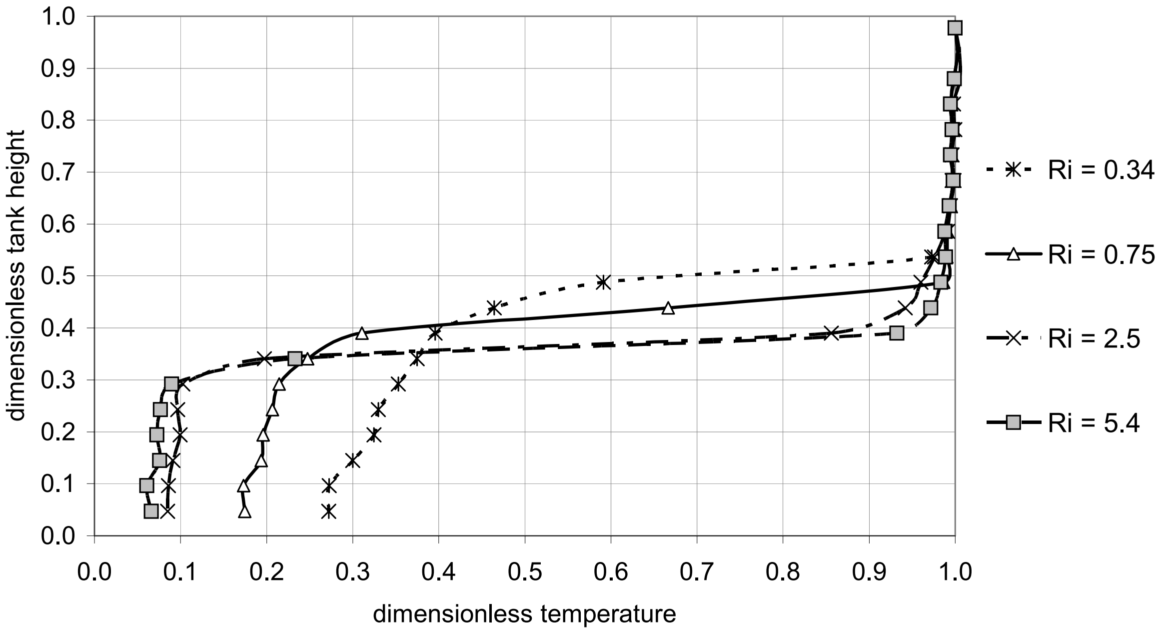

Figure 5: Vertical temperature distribution at r/R = 0.75 in the 1000 l storage water heater after discharge with inclined tangential inflow pipe, one third of tank volume was discharged

Influences of intermittent tapping, inflow in a tank with linear vertical temperature profile and mixing losses in tanks connected in series have been examined numerically and partially in experiment. Further tests and simulations were carried out to quantify convection processes and losses at connecting pipes. This is all described in [1].

5.2 Tank wall influences on thermal stratification

The influence of wall heat conduction can be calculated with the help of the factor f_{cond}. This key number is to consider if the vertical temperature field in the tank during a standstill period is determined. The factor is the ratio of the effective thermal diffusivity $a_{tank,eff}$ of the total tank cross section and the thermal diffusivity a_{sm} of the storage medium.

$$f_{cond} = \frac{a_{tank,eff}}{a_{sm}} \tag{11}$$

A similar parameter $\lambda_{tank,eff}$ (effective thermal conductivity) was described by different authors earlier [2]. It had to be determined in experiments and is applied in simulation tools for solar storage tanks. Using $\lambda_{tank,eff}$ or $a_{tank,eff}$ for computing the vertical temperature profile neglecting convection, the same result should be obtained as in a simulation using λ_{sm} or a_{sm} including convection. Measurements in test tanks had approved the theoretical approach in equation (3) as valid for tanks with $f_{cap} > 0.97$.
The coefficient ξ_{wall} in equation (3) can be set to 0.95 to 1.0 for tanks with thin wall. That means a wall thickness of less than 1 % of the tank diameter.
Further empirical correlations for calculating entropy production arising from heat exchange processes with the tank wall or charging with internal heat exchangers are given in [1]. Analytic relationships for the extension of the mixing layer at standstill

and the average return pipe temperature from the heat exchanger are explained in the final report of that research project [1].
The entropy production during charging the tank has the highest share in the internal losses. It is caused by temperature differences at the surfaces in the heat exchanger. The internal losses impact the efficiency of heaters connected to the storage tank.
The other losses – vertical heat conduction, heat exchange with tank wall, mixing at inflow with well designed baffles – are of the same dimension. Therefore, all these aspects should be considered in the design of an optimal hot water storage tank.

6 Conclusion

Comprehensive numerical computations and experimental tests yielded in empirical correlations for determination of internal losses in hot water storage tanks. An improvement of guidelines for optimized storage tank design is achieved by coupling the losses to details of tank design and operation conditions. Calculation of storage tank losses already during tank design contributes to cost reductions and reduces tests on prototype tanks.
The design engineer can easier determine, if a given storage tank is appropriate for an application with given boundary conditions, or if the tank needs to be modified to guarantee an efficient operation.
As recommendations for storage tank design it can be summarized:

- complete insulation of the tank without lacks at connecting pipes
- consideration of dimensionless key numbers for design of inflow devices and baffles
- use of materials with low thermal diffusivity and thin tank walls

The latter aspect will not be realizable in many cases but is worth to be proved.

The inclusion of the warm water circulation system in the design of hot water storage tanks and new concepts for connecting the circulation system to the tank should be object of future research. The strict hygienic demands have to be covered at the same time with reduction of heat losses and use of primary energy. A research project concerning this topic is going on at Technische Universität Dresden.

7 References

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8 Acknowledgements

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Nomenclature

a – thermal diffusivity, m^2/s
A – surface area, cross sectional area, m^2
c – velocity (m/s)
C – heat capacity, J/K
d, D – diameter of a pipe, diameter of storage tank, m
f – factor, key number, function
g – gravitational acceleration (m/s^2)
Gr_H – Grashof-number
H – height (of storage tank, of baffle gap), m
L – length, m
$\dot{m}$ – mass flux, kg/s
r, R – radius, Radius of storage tank, m
Re_H – Reynolds-number
Ri_H – Richardson-number
S – entropy
T – temperature, K
V – volume
z – height coordinate in storage tank, m
β – volumetric expansion coefficient
Δ – difference
λ – thermal conductivity, W/(mK)
ϑ – temperature, °C
ξ – reduction factor
Ψ_{ml} – volume fraction of the temperature mixing layer

Abbreviations and Indices

0 – reference or initial condition
1, 2.. – state 1, 2 ..
cap – capacity
cond – condution
eff – effective
i – running index
in – inflow
irr – irreversible
ml – temperature mixing layer (transition zone from warm to cold region)
sm – storage medium
out – outflow
tank – storage tank
wall – tank wall