CONVECTION EFFECTS ON STRATIFICATION DURING CHARGING OF A HOT WATER STORE

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1. INTRODUCTION

In domestic hot water stores the preservation of hot water layers is essential for the effective operation. Such stores are operated intermittently: when hot water is taken from the store, cold water is fed into it, so that part of the water in the store is hot and part of it is cold. These two parts should not mix, because this would deteriorate the efficiency of the store.

A simple example shall demonstrate this:
When no mixing occurs, the store has to be heated only to the temperature which is needed for discharge. When we assume for discharge that the hot water is fully displaced in a piston-like flow by cold water, then the hot water carries the entire energy which was fed into the store minus the heat losses to the surroundings.

When mixing occurs between the hot and cold parts, the hot water temperature is decreased. Thus, the store has to be heated to a temperature above the needed temperature from the very beginning. With higher temperature, heat losses are also larger. More heat has to be fed into the mixed store than into the stratified when the same amount of heat shall be taken out with the same amount of water.

Consequently, the energetic store efficiency as the ratio of heat taken from the store to heat fed into the store is less when the store temperature is higher.

Thus, the store with no mixing is the best store. It is an ideal case, of course, but by preserving thermal stratification we can approach this case.

The example was given for the discharge process. Mixing of different temperature water layers also occurs during charging, i.e. heating, of the store. This shall be demonstrated for a conventional domestic hot water tank as shown in FIGURE 1. This is a store of the "4-port displacement" type: a cylindrical container with openings near the top and at the bottom for water inlet and outlet, for the domestic hot water supply, and a heat exchanger to heat the water in the store. The heat exchanger often is a coiled finned tube in order to provide a large heat transfer area.

For charging, a heating fluid is pumped through the heat exchanger, the water in the store heats up and rises by natural convection as long as there is a temperature difference between the heat exchanger and the stored water.

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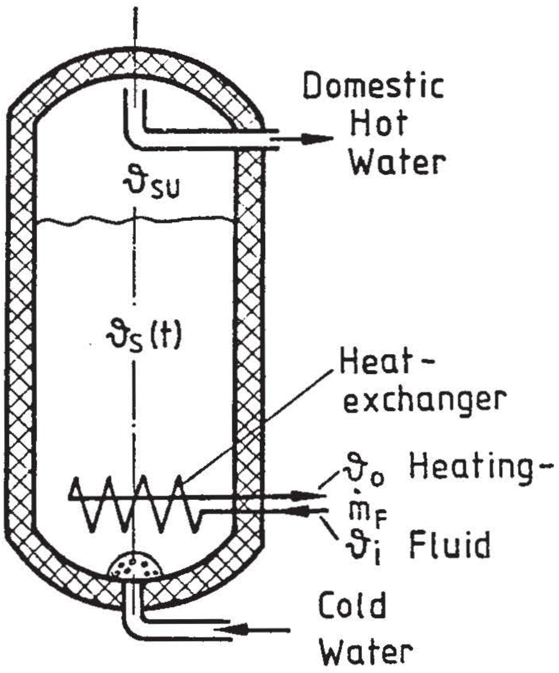

FIGURE 1. Domestic hot water tank; 4-port displacement type

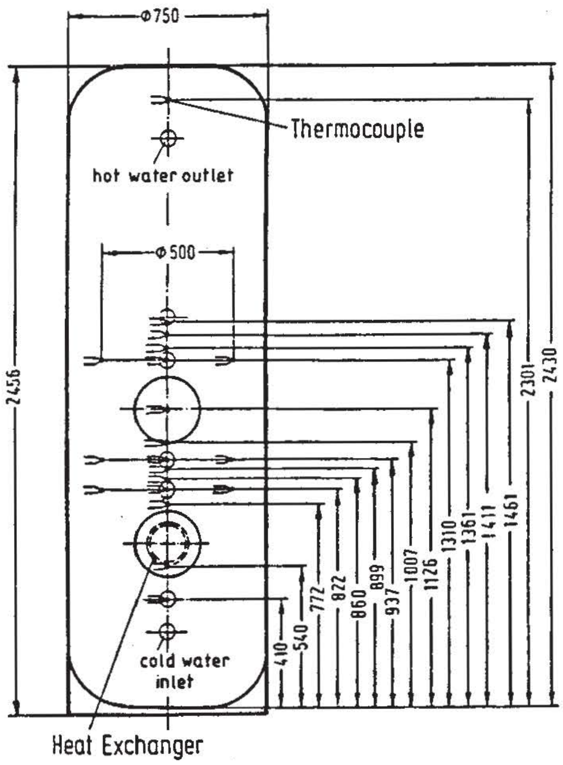

FIGURE 2. Domestic hot water store (1000 l) with thermocouples' position

For discharge, cold water is fed into the bottom part of the store and displaces hot water through the top part.

In a partially charged store, there will be a hot top layer of water, a cold bottom layer and an intermediate layer with a pronounced temperature gradient in between.

In all such stores, great care is taken to keep the hot top layer from mixing with the colder layers below. A temperature decrease due to thermal conduction is inevitable, but there also occur convection flows, during the displacement process and during charging. The former can be suppressed by specially formed inlet caps which diminish the momentum and spread the incoming cold stream equally across the bottom. The convection plumes, on the other hand, rise freely and may disturb a thermal stratification in the store.

In order to learn about the effects of such convection flows, systematic experiments were carried out with a domestic hot water store shown in a cross-section drawing in FIGURE 2.

2. EXPERIMENTAL SET-UP

The hot water store has a volume of 1000 dm^3, it is made of 2.5 mm stainless steel plates and it is insulated by 100 mm PU-foam. The internal heat exchanger is made of a finned tube, 9.04 m long with an outside surface of 2.5 m^2, wound in a coil of 0.5 m length.

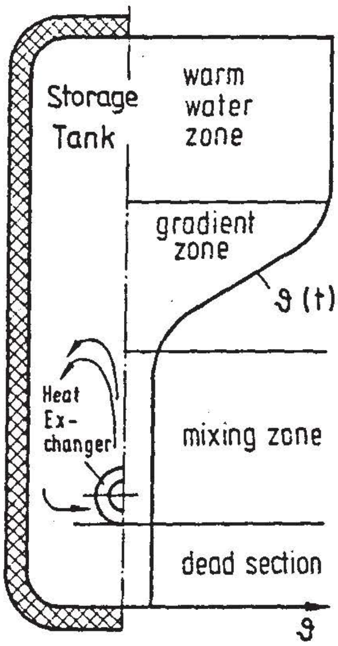

FIGURE 3.
Temperature distribution and respective regions in a partially charged domestic hot water store during charging

Inside the store 20 thermocouples were placed in various heights and across three different levels.

For the experiments a definite temperature distribution of a partially charged store was built up, with the upper part at a higher temperature than the lower part. Thus, we obtain four temperature regions as shown in FIGURE 3.

Below the heat exchanger, there is a region which is heated only by heat conduction. This "dead section" is not affected by thermal convection, at all. Around and somewhat above the heat exchanger, there is the "mixing zone", the region which is most affected by the convection. As an intermediate layer towards the top "warm water zone", there exists a so-called "gradient zone", a region with temperatures varying along the height.

Care is taken that for all experiments the distribution of these zones is as equal as possible. The heat loss rate of the store and heat losses of pipes were measured.

The experiments are performed in the following way: after the stratification is accomplished by heating and cooling, heating water is circulated through the heat exchanger with constant inlet temperature. Two different volume flowrates, $\dot{V}_F$ = 500 l/h and 1000 l/h, were applied.

3. EXPERIMENTAL RESULTS

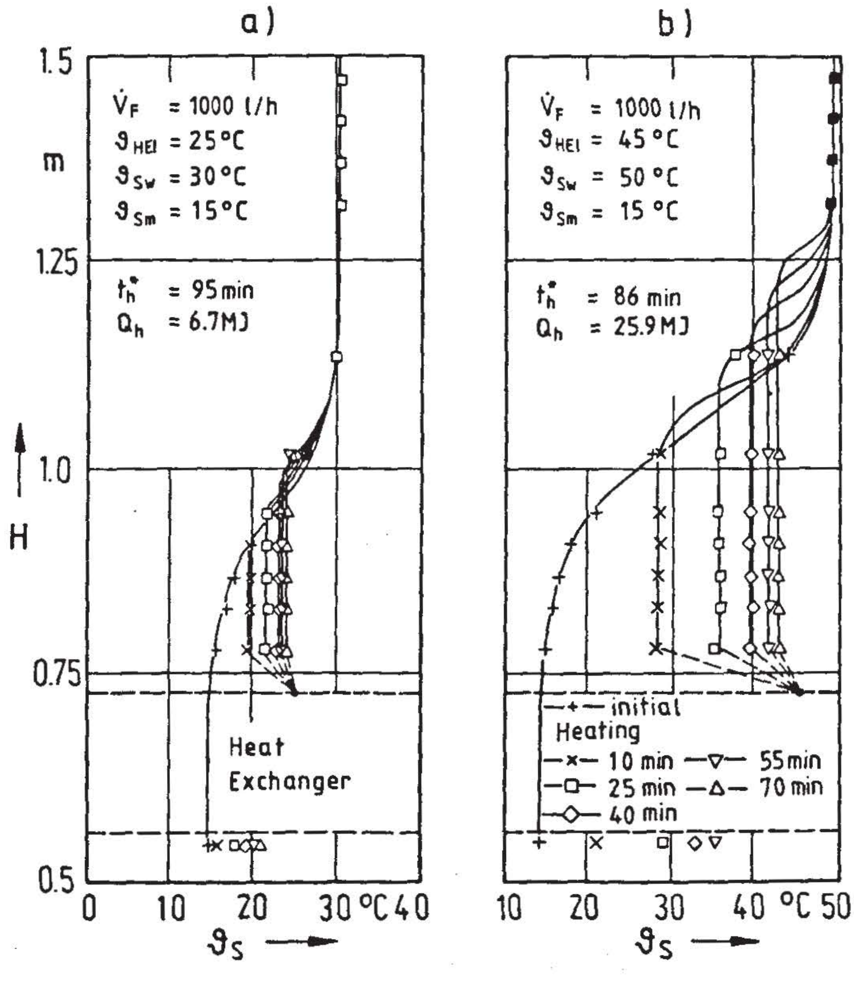

FIGURE 4. Storage temperature in various tank heights for various times

It is easy to conceive that the disturbance of thermal layers depends on the temperature of the heating fluid, on the temperatures of the mixing zone and warm water zone, or on the temperature difference of these. Correspondingly, the differences were varied. Two obvious groups appear:

- heating temperature below the temperature of the warm water zone;
- heating temperature above the temperature of the warm water zone.

Heating at temperatures below the warm water temperature: Results are presented in FIGURES 4 to 6. The temperatures of the water in the store are plotted for different heigths starting from 2 cm below the heat exchanger to 75 cm above it. The common parameter is the time when measurements were taken, e.g. at the beginning, after 10 minutes, 25 minutes, etc.

In all experiments of this series the temperature difference $\vartheta_{HEi} - \vartheta_{Sw}$ between heating water inlet and warm water zone was the same: -5 K; but the temperature levels were changed.

In FIGURES 4 and 5 the span between the temperatures of the mixing zone ϑ_{Sm} and the warm water zone ϑ_{Sw} was investigated at different temperature levels. The temperature distribution obtained for a span of $\vartheta_{Sw} - \vartheta_{Sm}$ = 35 K (FIG. 4b) is basically the same as for 15 K (FIG. 4a), only the temperature

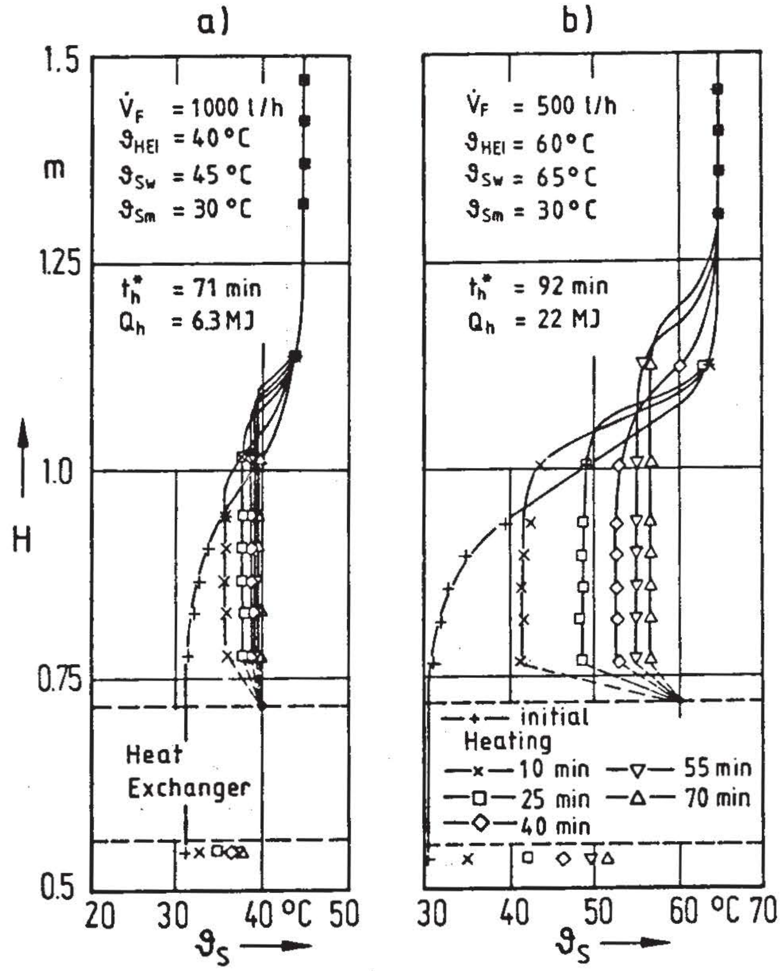

FIGURE 5. Storage temperature for various times in various tank heights

distribution lines are farther apart.

The most interesting feature is the "overshoot" of rising colder liquid into the layer of warmer liquid and the consequent depression of temperature there. If we follow the temperature curve for 25 minutes' heating in Fig. 4b, we observe that the temperature in the height of 1.125 m has been lowered by about 6.5 K compared to the 10 minutes' heating. Progressing in time, similar results are obtained. Although the picture shows that the thermocouple spacing according to FIGURE 2 is not close enough for quantitative calculations, it clearly can be observed that the "overshoot" causes a mixing of different temperature layers and a deterioration of the stratification in the store.

As a criterion for the duration of the charging process, a heating time t_h was introduced. This is the time, when the mixing zone reaches the top of the storage tank; the gradient zone has then disappeared and there exists one uniform temperature above the heat exchangers. The heat transmitted during this time was also measured and is given as Q_h.

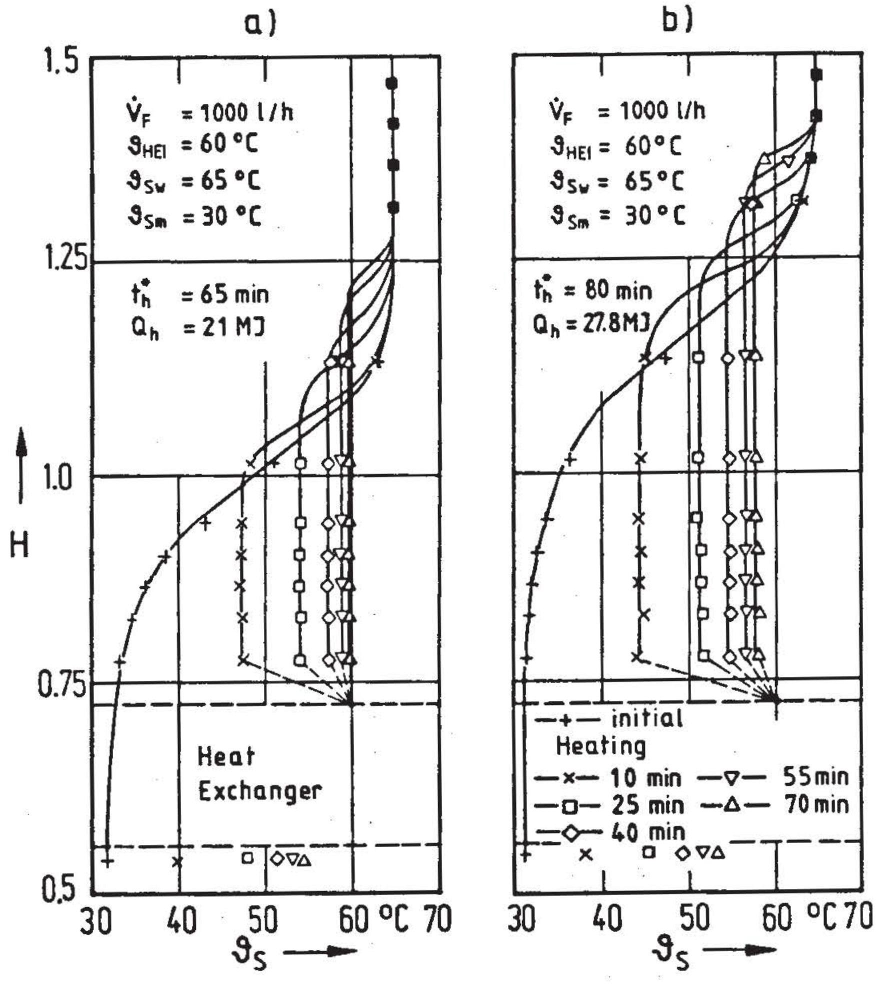

FIGURE 6. Storage temperature for various times in various tank heights

When, however, the heating water temperature is below the warm water zone temperature (FIGS. 4 to 6), a uniform temperature did not occur; there remains a warm water layer on top, and a colder below. In this case, a pseudo-heating time t_h^* is defined when the colder layer reaches a temperature 3 % below the heating fluid inlet temperature.

Comparison between FIGURES 5b and 6a shows the effect of the flow rate through the heat exchanger: With $\dot{V}_F$ = 500 l/h the heating time is 92 minutes; with 1000 l/h (FIG. 6a) it is only 65 minutes. The heat transferred during this time is about the same, 22 MJ or 21 MJ, respectively.

The heat transferred into the store depends very much on the initial temperature distribution within the store. This is shown in FIGURES 6a and 6b. The gradient zone in the case of FIGURE 6a is shorter, the heat contents is larger. Consequently, less heat has to be added in the case of FIGURE 6a, e.g. Q_h = 21 MJ instead of 27.8 MJ in FIG. 6b and the pseudo-heating time is shorter t_h^* = 65 minutes instead of 80 minutes. This effect of initial temperature distribution demonstrates the difficulty for comparison and evaluation of partially charged stores.

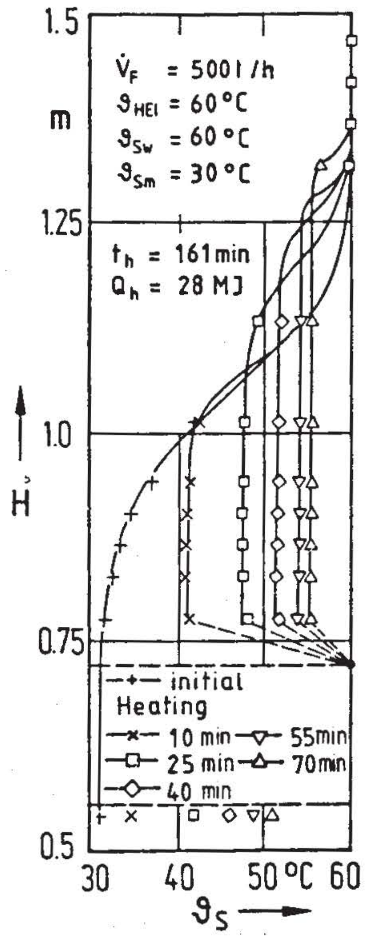

FIGURE 7.
Storage temperature for various times in various tank heights

In the case of FIGURE 7 the heating fluid inlet temperature equals the warm water zone temperature. After 161 minutes the store was charged to this temperature. This long heating time is not only a consequence of the equality of heating- and warm water-temperatures, but is also due to the initial

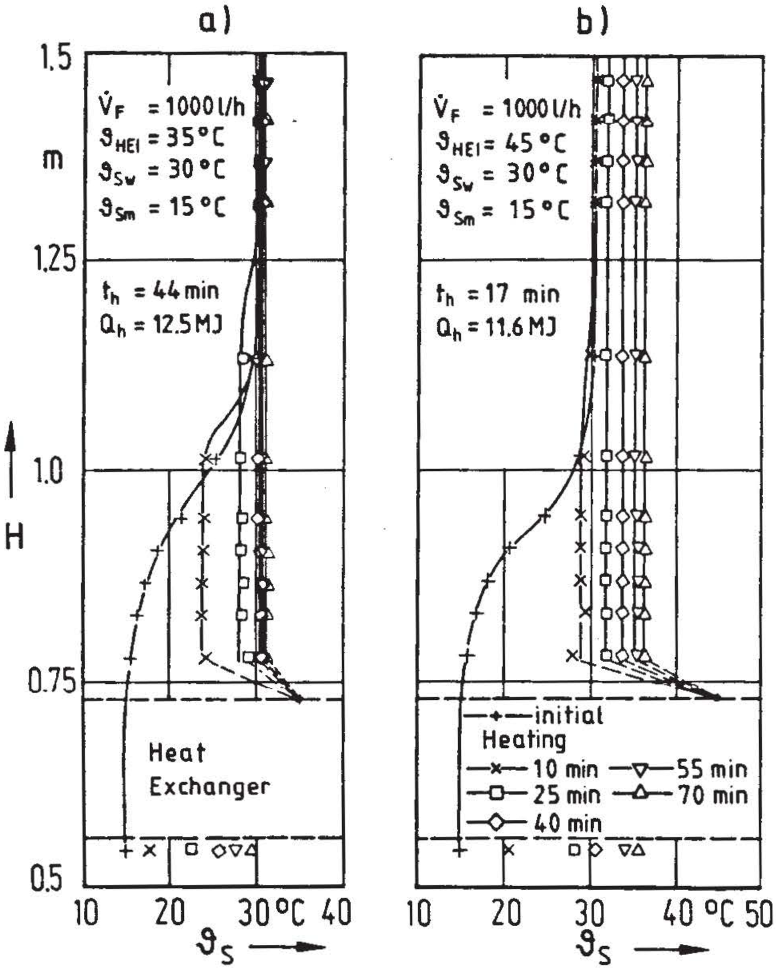

FIGURE 8.
Storage temperature for various times in various tank heights

temperature distribution. The case of FIGURE 5b could be compared to FIGURE 7 in this respect. The temperature of the warm water zone is 65° in FIGURE 5b instead of 60° in FIGURE 7 other data are equal. Nevertheless, the heat delivered to the store under the conditions of FIGURE 7 is larger Q_h = 28 MJ, than under condition FIGURE 5b Q_h = 22 MJ.

The heating time will be reduced when the heating temperature is above the warm water zone temperature. This situation is expected; it is demonstrated in FIGURES 8 to 11.

Here also "overshoots" occur with a depression of temperatures in the gradient zone. All heat delivered after the heating time t_h will help to increase the uniform temperature above the heat exchanger. This can be observed from FIGURE 8b: The heating time is 17 minutes; for the following time of observation, the temperature above the heat exchanger increases uniformly. Below the heat exchanger the temperature does not rise accordingly and near the bottom part of the tank (not shown here) the water temperature is not affected, at all.

In most of the levels the temperatures were measured by one thermocouple in the axis of the tank, above the heat exchanger. Does this temperature represent the temperature of an entire level? Measurements taken in three different levels in three different spots show that the temperatures distant from the axis are only between 1 and 1.5 K below the axis temperature.

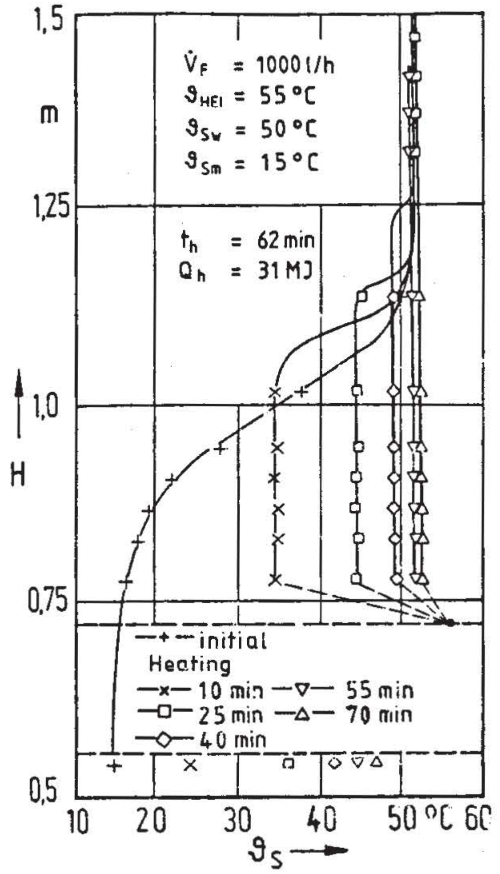

FIGURE 9. Storage temperatures for various times in various tank heights

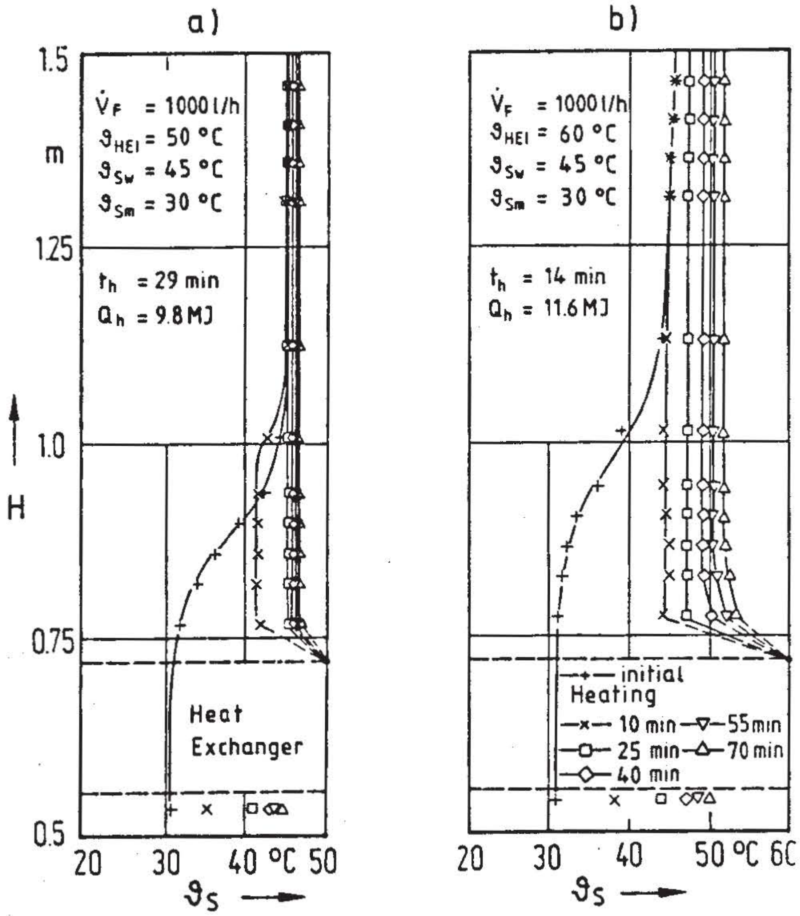

FIGURE 10. Storage temperature for various times in various tank heights

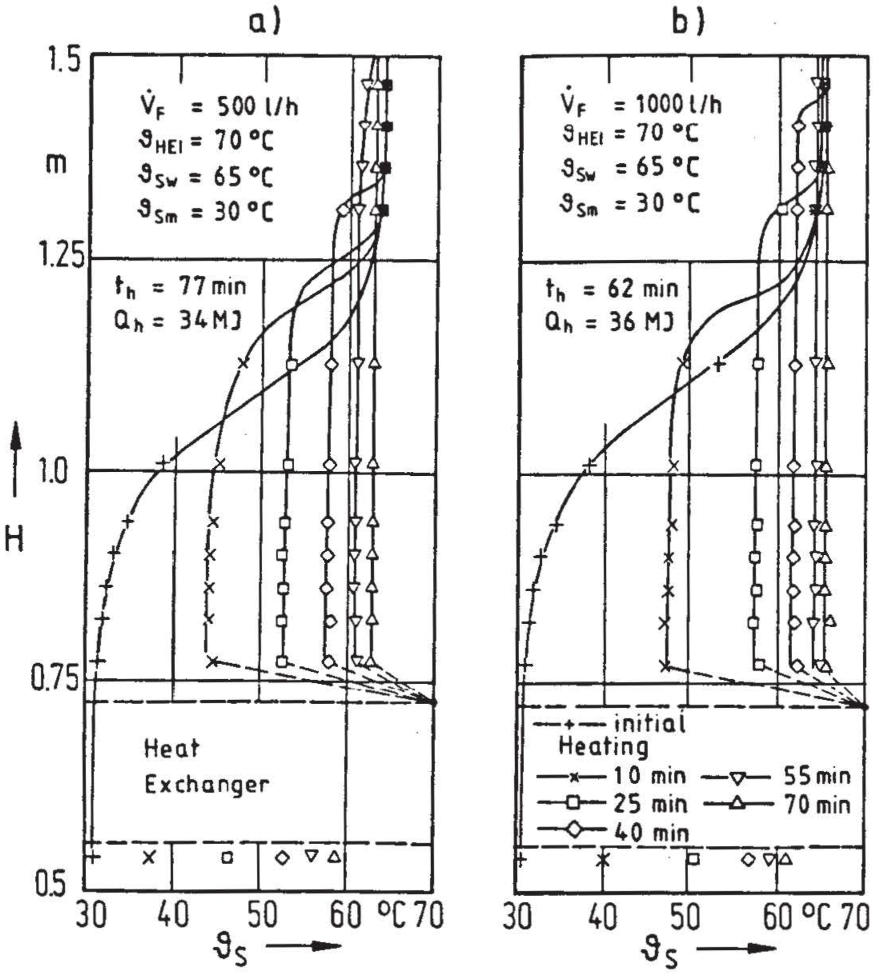

FIGURE 11. Storage temperature for various times in various tank heights

Thus, the measured axis temperatures may serve as good approximations for each level temperature.

From the "overshoot" it can be observed that convective flows deteriorate the efficiency of the store, but so far, no clear quantitative criteria can be defined, because results could not be based on equal initial conditions (e.g. the same temperature distribution) and the temperature distribution could not be determined accurately enough.

An improved experimental set-up was used to find such criteria. The thermocouples in the tank were closer spaced and the procedure to obtain the same initial temperature distribution was changed: The stored water was heated up to the desired temperature and circulated through the store, so that it obtained a homogeneous temperature. Then a certain amount of cold water was fed from the bottom into the tank. The gradient zone could be reproduced very well in both position and gradient by this procedure. Besides, the heating condition was changed: from constant temperature heating before, now a constant heat flux was transferred from the same heat exchanger as before. It has to be noticed that under these conditions the heat exchanger temperature will rise when the storage temperature rises.

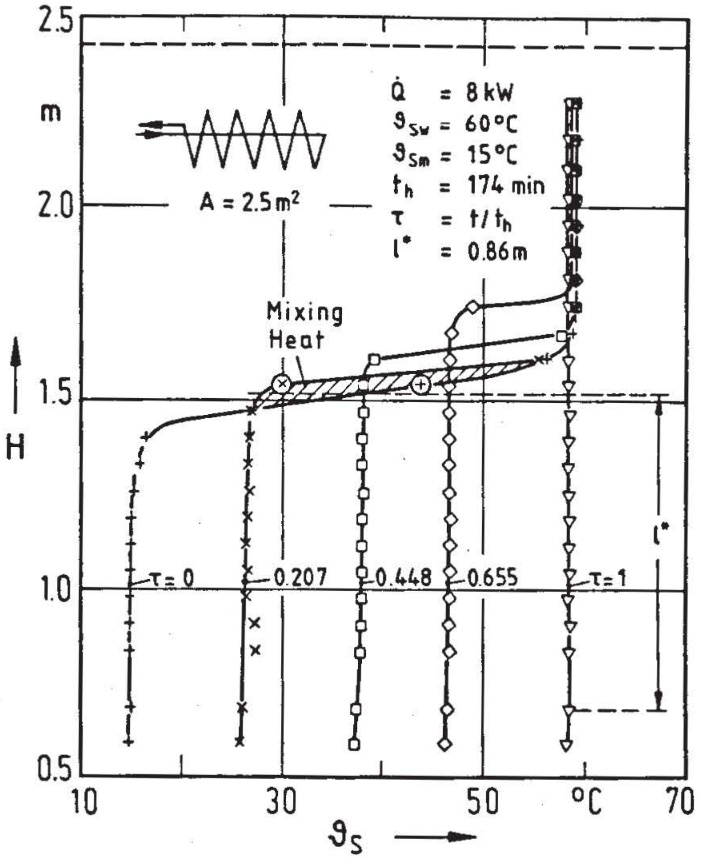

FIGURE 12. Storage temperature for various times in various tank heights in an improved measuring arrangement

The natural convection heat transfer coefficient on the outside of the heat exchanger increases when the temperature level increases due to the favourable combination of thermal properties in the Nusselt and Rayleigh numbers. Formerly, with constant temperature heating, this heat transfer coefficient remained nearly constant, because of the counteracting effects of decreasing temperature difference and increasing storage temperature.

A result of this kind of experiments is shown in FIGURE 12. The initial storage temperatures are ϑ_{Sm} = 15°C in the mixing zone, and ϑ_{Sm} = 60°C in the warm water zone. The gradient zone is 1* = 86 cm above the upper edges of the heat exchanger fins. Heating is performed with 8 kW.

The temperatures are taken at various times and plotted in fractions of the heating time. This is here the time necessary for the stored water above the heat exchanger to obtain a uniform temperature. It is observed that a stratification which persisted in the top part of the store is only deteriorated when the rising water reaches a temperature close (1 to 2 K below) to the top temperature.

As before, overshoots were observed with rising fluid penetrating into the higher temperature layers of the gradient zone. Now, as an indicator for the devaluation of energy, a so-called "mixing heat" is introduced: this heat is shown in FIGURE 12 as a hatched area.

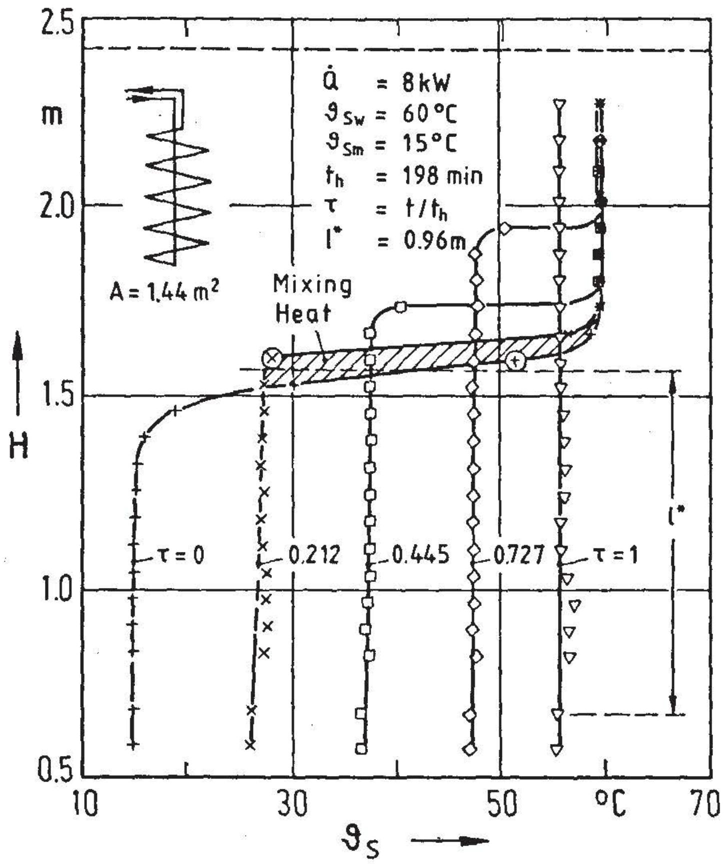

FIGURE 13. Storage temperature for various times in various tank heights in an improved measuring arrangement.

It is dissipated from the gradient zone to the mixing zone during the time interval τ = 0.207. Such "mixing heats" can be calculated for all time intervals in various levels of the store, and they can be summed up for the entire heating time. Apparently, if there is no decrease of temperatures in the gradient zone, there is no devaluation and no "mixing heat", so that a good charging process is characterized by a low "mixing heat".

With another finned tube heat exchanger of 1.44 m^2 outside area, also wound in a coil, experiments were performed in the same storage tank. This smaller heat exchanger could be inserted in the tank in a horizontal and vertical position. Tests were performed in either position.

Results for the vertical position are shown in FIGURE 13. In comparison to FIGURE 12 it can be observed that the top layer temperature is decreased by about 5 K when the store obtains a uniform temperature. This is probably due to the more intensive convection flow in a less extended plume above the heat exchanger. Consequently, the penetration of this flow into the warmer layers of the gradient zone is more pronounced and the mixing heat is larger.

The mixing heat, as a criterion for losses during charging is plotted versus the initial temperature difference between the warm water zone and the mixing zone in FIGURE 14. The mixing heat steeply increases with temperature difference.

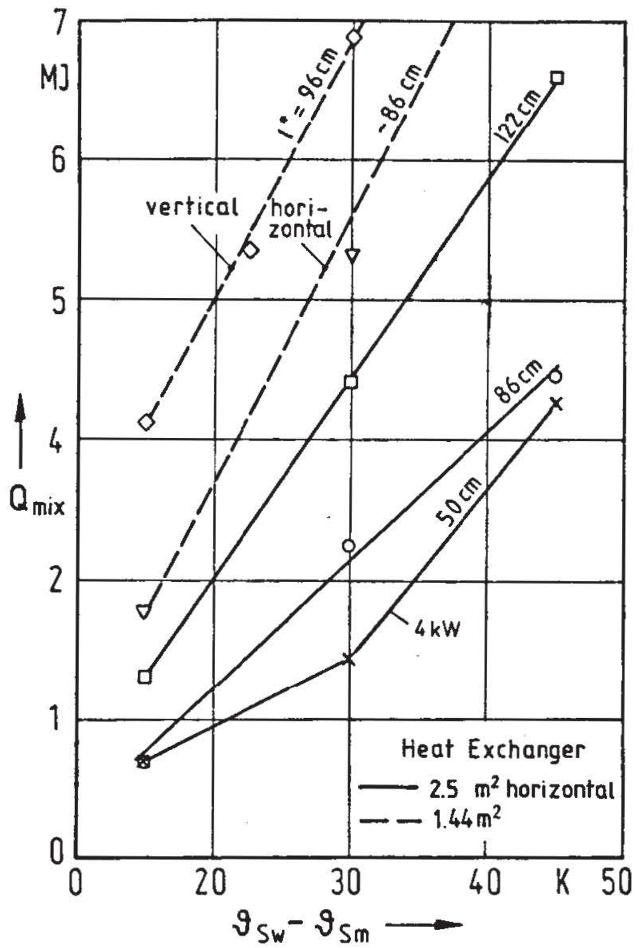

FIGURE 14. Mixing heat vs. initial temperature difference between warm water zone and mixing zone for 8 kW heating power and various positions of the gradient zone (1*)

However, it has to be considered that for larger temperature differences more heat Q_h has to be fed into the store, this yields larger mixing heats.

In order to relate the mixing heat to the heat delivered, a ratio Q_{mix}/Q_h is formed and plotted in FIGURE 15. All horizontal heat exchangers exhibit a tendency of increase in mixing heat with temperature difference between the warm top layer and the cold mixing layer. For the vertical heat exchanger the adverse tendency is observed.

The smaller heat exchanger gives in either position a higher relative mixing heat than the larger heat exchanger. In vertical position the small heat exchanger causes the largest devaluation of a stratification.

The effect of heating power on mixing heat is shown in FIGURE 16. The highest heating power of 12 kW yields the largest mixing heat, and again the small vertical heat exchanger appears less favourable than the large horizontal heat exchanger. As in FIGURE 15, there also appears to be an effect of the position of the gradient zone.

Measurements are quite difficult, and results are still not sufficient in number.

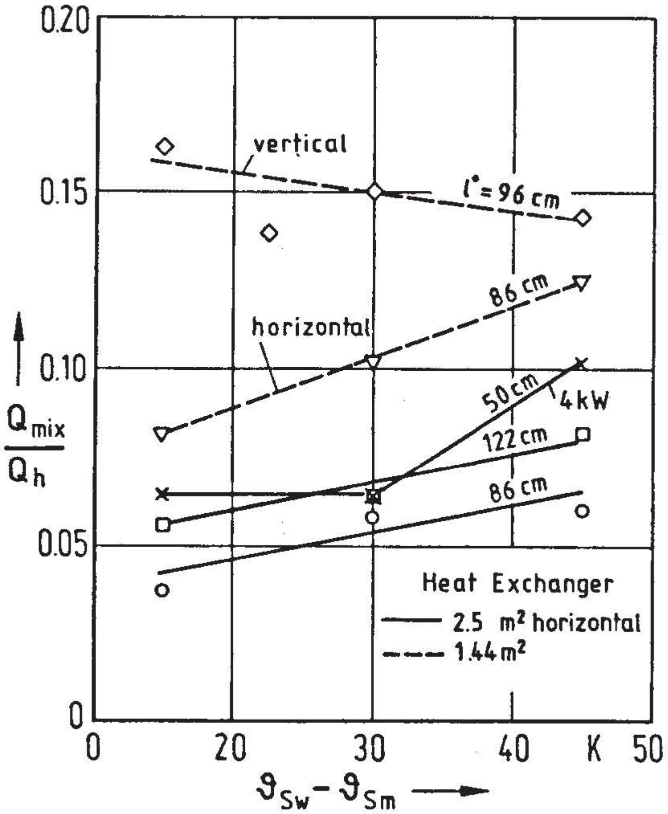

FIGURE 15. Relative mixing heat vs. initial temperature difference between warm water zone and mixing zone for 8 kW heating power and various positions of the gradient zone (1*)

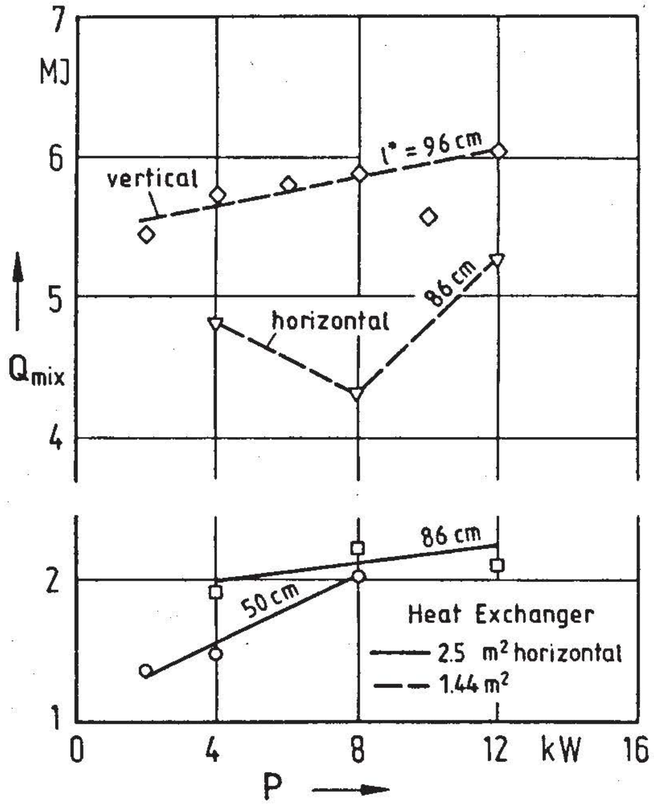

FIGURE 16. Mixing heat vs. heating power for $\vartheta_{Sw} - \vartheta_{Sm}$ = 30 K and various positions of the gradient zone (1*)

Whether the mixing heat concept is the best criterion for a comparison of convection effects in stratified stores cannot be stated as a final result, more and other considerations are needed.

ACKNOWLEDGMENT

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NOMENCLATURE

$\dot{m}_F$	fluid flow rate
$\dot{Q}$	heat flow rate
Q_h	heat input
Q_{mix}	mixing heat
t_h	heating time
t_h^*	pseudo heating time
$\dot{V}_F$	volume flow rate

Greek symbols

ϑ	temperature
τ	time ratio t/t_h

Indices

i	inlet
HEI	heating water inlet
o	outlet
s	store
Sw	warm water zone
Sm	mixing zone
u	upper

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