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STRATIFIED OPERATION OF A 500 M^3 TEST PIT

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ABSTRACT

In this paper the results of measurements and simulations during stratified operation of a 500 m^3 heat storage test pit are summarized. The test pit is located in the test area of the Thermal Insulation Laboratory at the Technical University of Denmark.

Measuring equipment and its application for recording temperatures during a 126 hour charge and a subsequent 261 hour discharge of the storage are described. The recorded measurements comprise the forward temperature and the flow as well as the temperature distribution in the center of the storage.

In order to allow simulation of the experiment, the original computer model describing the thermal behaviour of the test pit has been further developed to take into account the stratification of the water temperatures. The results of the simulations for the charge as well as for the discharge sequences have been compared with the measurements during similar actual operations.

Good agreement between measurements and simulations was found and it may be concluded that the applied computer model may be used during simulations of the thermal behaviour of this type of storage pits.

1. INTRODUCTION

As a joint venture between the Danish Government and the European Economic Communities a test storage pit was constructed in 1982 in the area of the Technical University of Denmark designated for outdoor testing of solar energy equipment, etc. Studies of simulated operations have been in progress for the last three years. This work has been reported in [1], [3],[4], and [5].

During the operational studies in 1984 it was decided to study the temperature variations in the test pit (540 m^3) during stratified operations. The storage was charged during 126 hours and immediately after discharged for 261 hours.
The above mentioned measurements during charging and discharging of the storage have been compared with simulations in a computer model.

2. STRATIFICATION

During stratified operations the storage is in principle charged by conducting water with a temperature of $\nu_o+\Delta\nu$ to the top of the pit while a similar volume of water is extracted from the bottom of the pit at a temperature of $\nu_o-\Delta\nu$. The border line (thermocline) between the hot and cold water moves during the charging of the pit from the top to the bottom of the storage, see figure 1.

In principle the storage is discharged similarly by conducting water with a temperature of $\nu_o+\Delta\nu$ from the top of the storage, while a similar volume of water is replaced in the bottom of the pit at a temperature of $\nu_o-\Delta\nu$. The thermocline hereby moves from the bottom to the top of the pit.

Theoretical considerations concerning heat losses and stratification may among other references be found in [2] and [6].

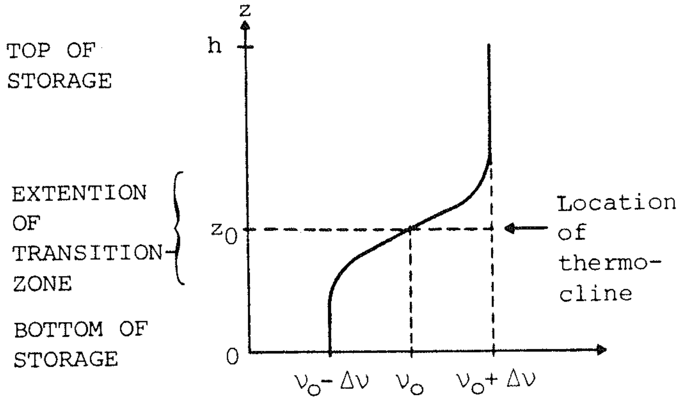

Figure 1. Temperature variation in stratified storage with vertical sides.

3. ARRANGEMENTS AND MEASUREMENTS

Figure 2 shows in principle the operation of the storage during a stratified charging of the storage pit. The gas boiler is via the heat exchanger capable of supplying 52 kW which, with a bottom temperature of 32°C and a volume flow of 64 l/min, makes a forward temperature to the top of the storage of about 44°C possible.

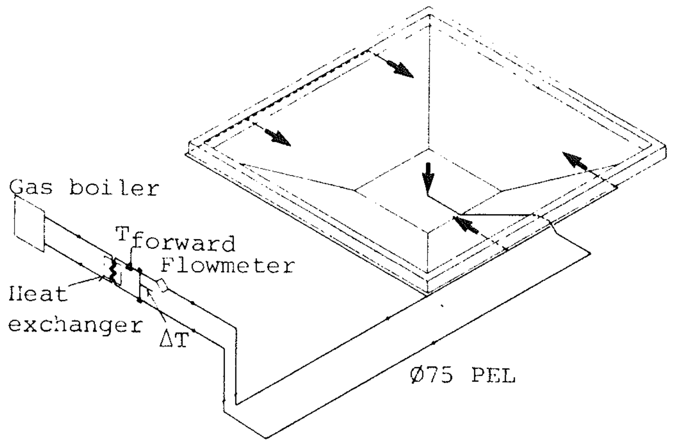

Figure 2. Charging (stratified).

Figure 3 shows in principle the operations of the storage during a stratified discharging of the storage pit. The air cooler is via the heat exchanger capable of cooling 25 kW (the maximum is somewhat dependant on the ambient temperature) which, with a top temperature of 43,5°C and a volume flow of 37 l/min, makes a return temperature to the bottom of the storage of about 34°C possible.

The details of the operational equipment can be seen in [1] and consequently will not be described further in this paper.

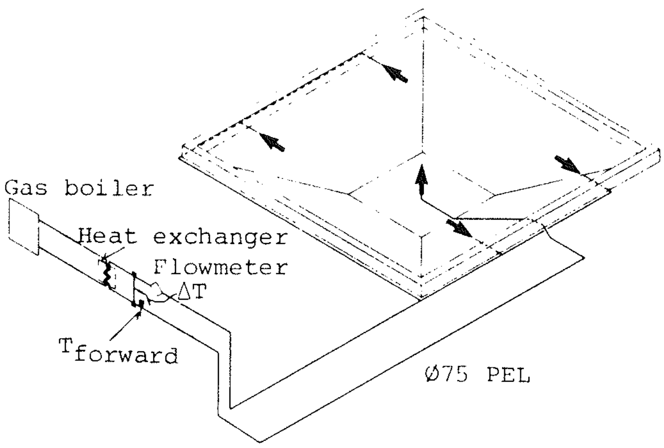

Figure 3. Discharging (stratified).

3.1 Measuring Equipment

As indicated in figure 1, the extention of the transition zone is limited. Consequently the distance of 700-900 mm between the points of temperature measurements in the storage water previously applied [1] would not be feasible for a reasonable registration of the temperature variations in the transition zone between the hot and cold water volumes.

As it was judged desirable partly to maintain all 51 thermocouples previously placed in the soil surrounding the storage and partly to maintain one of the existing measuring chains in the center of the water volume (5 thermocouples) as well as one existing measuring chain near the storage wall (3 thermocouples), it was decided that a movable vertical measuring rod equipped with 14 thermocouples spaced at 100 mmm (see figures 4 and 5) should be used.

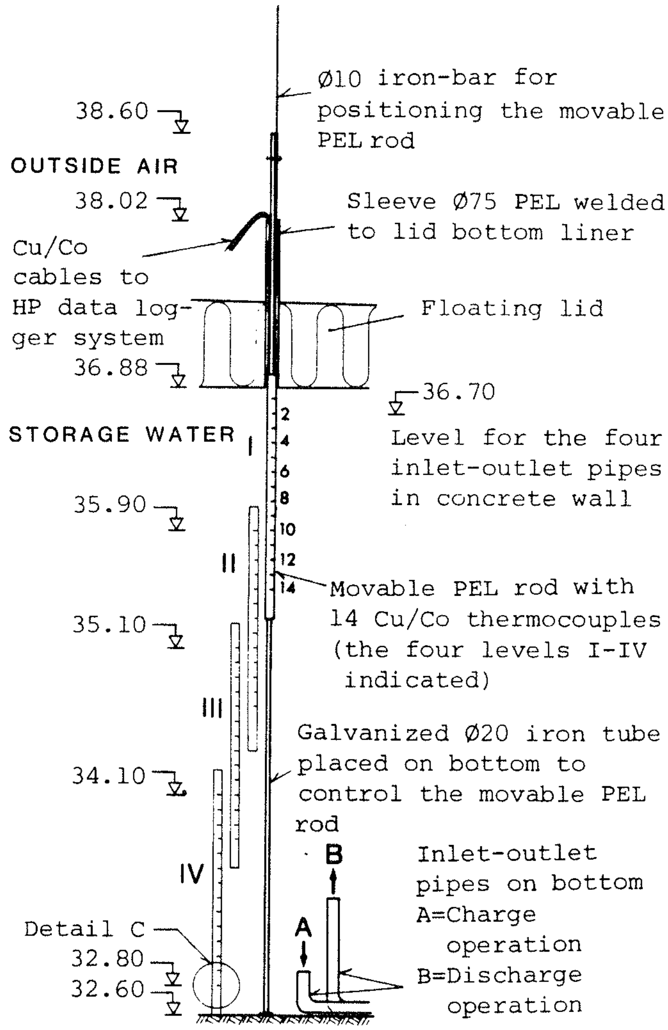

Figure 4. Measuring arrangement for study of temperature stratification during loading and unloading of underground topinsulated heat storage.

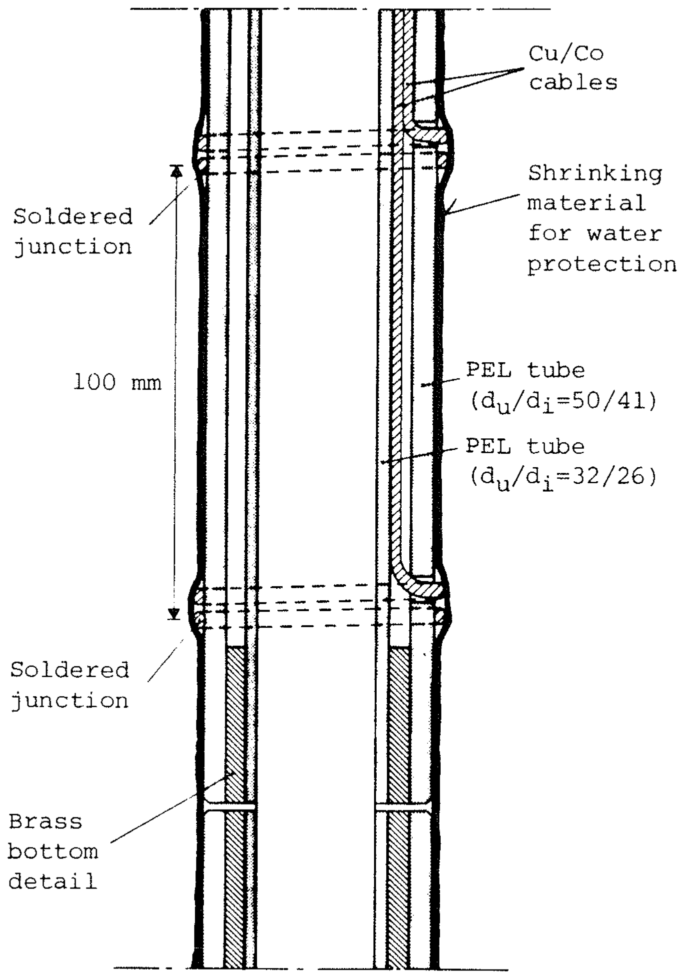

Figure 5. Detail C from figure 4.

A galvanized steel pipe placed on the bottom of the storage allowed the measuring rod to be placed in 4 locations according to the movement of the thermocline. After each movement of the measuring rod 4 or 5 thermocouples, depending on the position of the rod, could be located at identical levels compared to the previous position of the rod.

The measuring rod and the guiding steel pipe were placed in the storage through a 75 mm pipe originally built into the floating lid of the storage, to allow charge of hot water in the center of the lid, (figure 6).

4. MEASUREMENTS

All thermocouples in the soil as well as in the water were scanned automatically once an hour applying a Hewlett Packard 3054A datalogger system. Only the temperature difference over the inlet/outlet of the storage side of the heat exchanger and the forward temperature of the water flowing into the storage were scanned every second minute. Every hour the data logger system printed on paper all soil and water temperatures as well as the average temperature difference, forward temperature and volume flow during the hour, and recorded the values on magnetic tape for later transfer to the main computer at the University.

The measured temperatures along a vertical line near the center of the storage (figure 6) during 126 hours of charging and 261 hours of discharging are shown in figures 8 and 9.

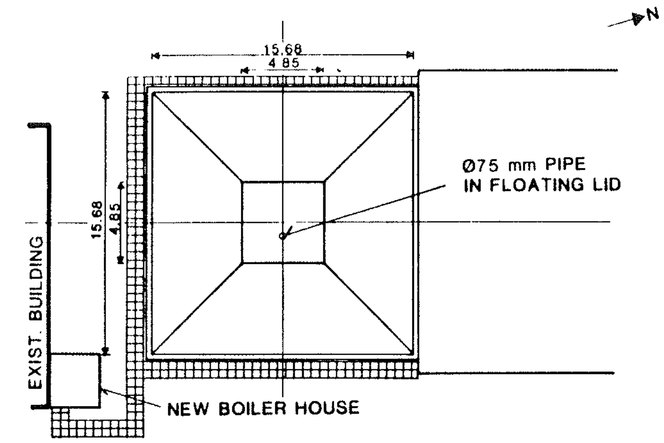

Figure 6. Plan view of pit.

The deviations between the simulated and the measured temperatures are assumed to be almost eliminated if the size of the segments applied (figure 7) in the simulation (0.3 m) was changed to match the distance between the thermocouples on the measuring rod (0.10 m).

5. COMPUTER PROGRAM AND VERIFICATION

5.1 Computer Program

The three-dimensional model for one eighth of the storage (with no stratification) and the surrounding soil is described in [1] and [5]. Thus only the calculations concerning the stratified water content of one eighth of the storage will be dealt with here.

After some consideration the principle of superposition in the calculations of the vertical temperature profile in the water is used.

First the temperature of the water segments upon the convective movement created by the water flow in the time-step Δt is calculated. Subsequently correction is made for the heat flow through the surfaces of the segments (i.e. conduction in the water and heat loss to the surrounding soil).

5.2 The Convective Movement

Knowing the velocity of the flow in the direction of the s-axis, the change of temperature of the water segments in a time-step Δt may be calculated.

The velocity in the direction of the s-axis is for a height of the segments of water of 0.3 m:

$$u(s) = 0.3\,\frac{ds}{dt} \quad \Rightarrow \quad 0.3\int \frac{ds}{u(s)} = \int dt$$

For u(s) is applied:

$$u(s) = \frac{\dot{v}}{A} = \frac{\dot{v}}{\frac{16}{25}\,s^2}$$

where $\dot{v}$ is the flow through the storage (figure 7) and A is the variable cross-section.

During charging of the storage $\dot{v}$ is negative and during discharging $\dot{v}$ is positive.

This is undertaken for all water segments and for all time-steps.

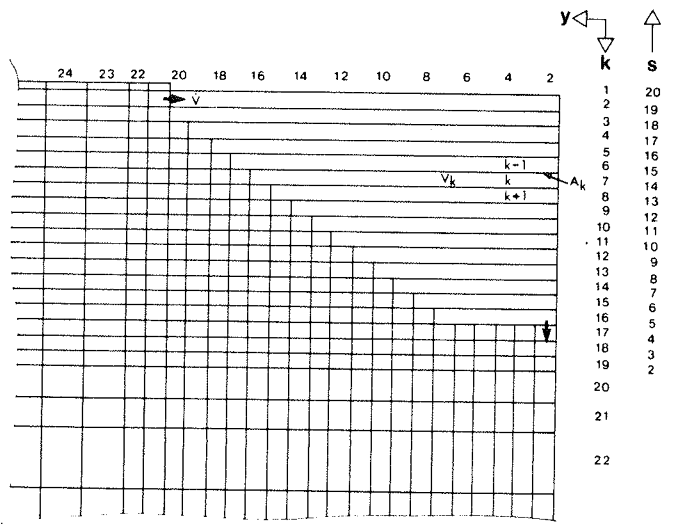

Figure 7. Part of the segmentation.

5.3 Heat Balance

When all the temperature changes in each segment of the storage originating from the water flow have been found, a thermal balance for all storage segments is established.

The heat balance for the "k^{th}" water segment (see figure 7):

$$V_k \cdot \rho \cdot c_{p,water} \cdot \frac{dT}{dt} = \Sigma A \cdot \lambda \cdot \frac{dT}{du}$$

expresses that the heat change in the "k^{th}" volume segment per unit of time equals the sum of heat flows through the surfaces of the segment.

The programming of the equation is in principle:

$$V_k \cdot \rho \cdot c_{p,water} \cdot \frac{T_k^{t_1+\Delta t} - T_k^{t_1}}{\Delta t} =$$

$$A_k \cdot \lambda_T \cdot \frac{T_{k-1}^{t_1} - T_k^{t_1}}{\Delta z} + A_{k+1} \cdot \lambda_T \cdot \frac{T_{k+1}^{t_1} - T_k^{t_1}}{\Delta z} +$$

$$\Sigma \Delta x \cdot \Delta z \cdot \frac{T_{j1+1,k}^{t_1} - T_k^{t_1}}{M} +$$

$$\Sigma \Delta x \cdot \Delta y \cdot \frac{T_{j,k+1}^{t_1} - T_k^{t_1}}{M}$$

The first two expressions on the right hand side of the equation express the heat conduction in the water, and the last two expressions the heat loss to the soil segments.

5.4 Additional Input Data

In order to simulate the temperature changes in the stratified water volume the geometrical data for the eighth of the storage dealt with by the computer program must be available as V_k and A_k for each segment of the volume (see figure 7). The physical and geotechnical data were unchanged from the original simulations of the temperatures in the soil surrounding the pit [1] and [5].

5.5 Verification of the Simulated Results

Figure 8 shows the measured and simulated temperatures of the water during the 126 hours of charging and figure 9 shows similarly the measured and computed temperatures during the 261 hours of discharging. It should be noted that the simulation results for charging as well as discharging the storage originate from a single simulation.

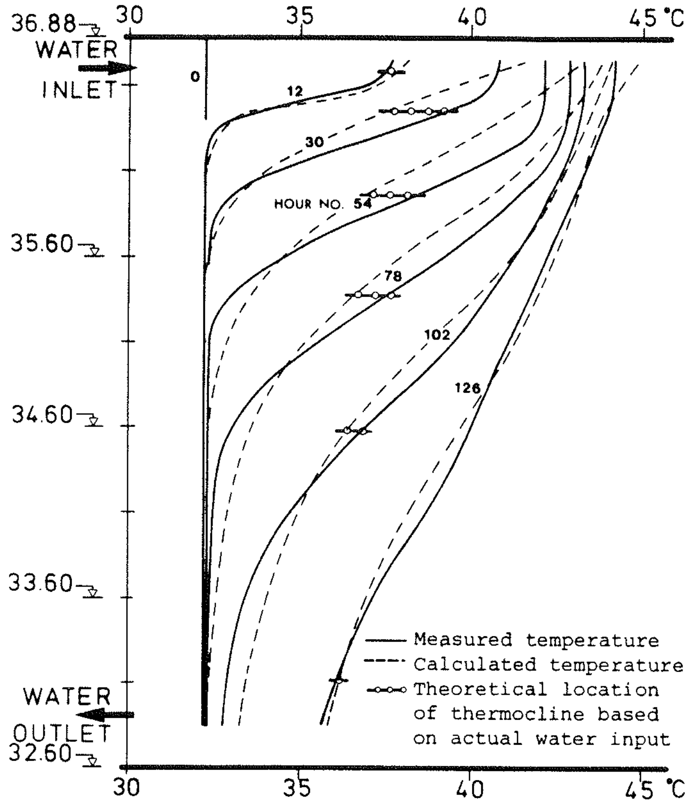

Figure 8. Charge operation. Comparison between measured and calculated temperatures.

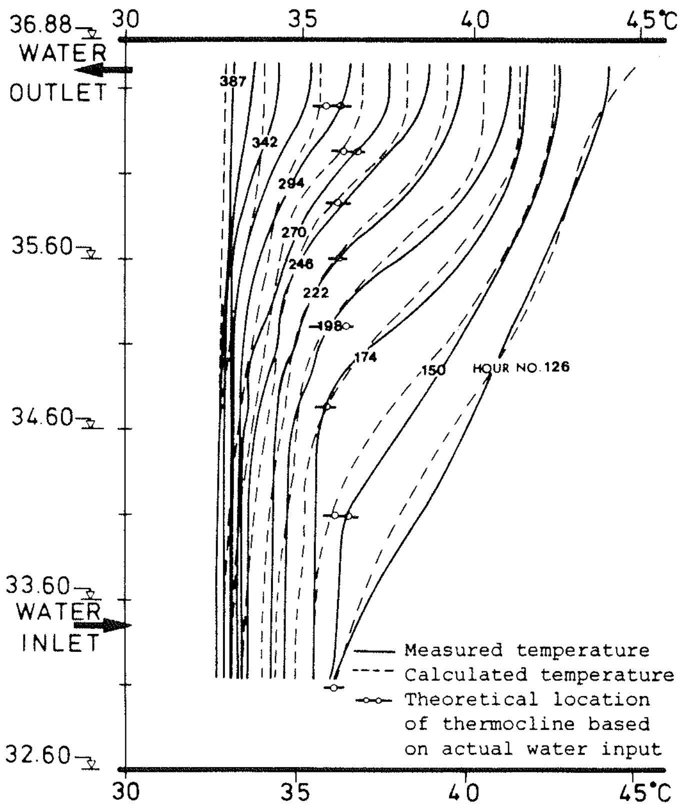

Figure 9. Discharge operation. Comparison between measured and calculated temperatures.

6. CONCLUSION

Based on the above results it may be concluded that the computer program employed during simulation of the thermal behaviour is applicable, permitting prediction of the vertical temperature profile during operation with this type of storage.

7. REFERENCES

[1] Hansen, Kurt Kielsgaard, Hansen, Preben Nordgaard and Ussing, Vagn. 1983. "Seasonal Heat Storage in Underground Warm Water Stores - Construction and Testing of a 500 m^3 Store". Bulletin no. 134 from Thermal Insulation Laboratory, Technical University of Denmark.

[2] Hansen, Preben Nordgaard. 1981. "Analytical Description of the Heat Losses from Underground Thermal Seasonal Heat Stores". Proc. of the US Department of Energy Conference: Seasonal Thermal Energy Storage. Oct. 19-21, 1981, Seattle, Washington, USA.

[3] Hansen, Preben N., Hansen, Kurt K. and Ussing, Vagn. 1984. "Seasonal Heat Storage in Underground Warm Water Stores - Construction and Testing of a 500 m^3 Store". In Solar Energy Applications to Dwellings - Solar Energy R&D in the European Community. Series A, Vol. 4. (Ed. T.C. Steemers and C. den Ouden). D. Reidel Publishing Company.

[4] Hansen, K.K., Hansen, P.N. and Ussing, V. 1984. "Seasonal Storage Test Pit. Testing of a 500 m^3 Store". Proc. of the International Conference: First E.C. Conference on Solar Heating. Amsterdam, April 30 - May 4, 1984.

[5] Hansen, Kurt Kielsgaard, Hansen Preben Nordgaard and Ussing, Vagn. 1985. "Fortsatte målinger på 500 m^3 forsøgsvarmelager (Continued measurements on 500 m^3 test storage pit)". Report no. 85-2, 1985. Thermal Insulation Laboratory, Technical University of Denmark.

[6] Cole, R.L., Bellinger, F.O. 1982. "Thermally Stratified Tanks". ASHRAE TRANSACTIONS, Vol. 88, part 2.