Experiments with Vertical Plates for Temperature Stratification in a Heat Storage Tank

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Advanced storage concepts for solar and low energy buildings

Project Report D2 of Subtask D

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Inlet Port design with Vertical Plates for Enhanced Temperature Stratification in a Water Heat Store

by

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A technical report of Subtask D

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Summary

Experiments were carried out to test an inexpensive set-up to enhance temperature stratification in water heat stores or water heater stores. The set-up essentially consists of an arrangement of two vertical parallel plates open to the storage volume on all or most sides with the inlet flow entering the gap between the plates through a flange on one of them. . Any difference in temperature or density between the entering flow and the fluid in the store will allow it to propagate vertically between the plates in reaction to the differing buoyancy of the respective fluids. When the rising or sinking flow attains a surrounding fluid with equal density to itself then flow in the horizontal direction towards the plate edges and the storage volume fluid occurs. To reduce unwanted mixing at the edges of the plates where the incoming flow makes contact with the storage fluid on its buoyant journey up or down, the gap between the plates is made relatively small to increase drag and hence decrease velocity and the likelihood of turbulence.

The store wall could be used to take on the function of one of the plates. Several plates could be used in parallel.

It was demonstrated that even a simple set-up consiting of one gap constructed by a pair of plates spaced roughly can be very effective.

For a maximum temperature difference between the water entering the tank and the water in the tank of 40 to 50 K the optimal plate spacing is about 3 to 4 mm. This is a considerably smaller gap size than what is currently being used in similar arrangements (usually with concentric perforated cylinders) which are marketed by a variety of manufacturers.

A single gap is compatible with a flow rate of around 100 litres per hour. For higher flow rates several gaps could be used. It should be investigated whether multiple parallel plates (and gaps) are advantageous for low flow rates too.

The results obtained, suggest that further investigation, application and optimization of stratifiers with vertical plates would be beneficial. The relatively simple and inexpensive design seems to be particularly interesting for small solar heating systems with solar loops of the drainback type. The application of vertical plates where the return from the space heating enters the heat store might be technically simple and economically feasible.

Video sequences of the experiments described in this document are accessible to the public in a freely available presentation which includes comments [2].

Contents

1 INTRODUCTION

A high degree of temperature stratification in the heat store is important for the performance of solar heating systems. An effective and common way to build up temperature stratification in a store is achieved by removing energy from the store: When hot water is removed from the top of a hot water store, it is replaced by cold water at the bottom. The cold inlet flow stream is almost always colder than any of the water in the store. The same simple principle can be used when charging a store with fluid which is (almost always) hotter that the hottest fluid in the store. Increasingly, a variety of stratification devices are used to promote temperature stratification in a more complicated situation: In circumstances where the temperature of the incoming flow stream is variable and often intermediate with respect to the temperature in the store. In this case, the fluid which enters the heat store is directed to the appropriate level in the store by means of a special device (in the following called an inlet stratifier or simply: stratifier). Ideally an inlet stratifier perfectly directs the incoming flow to the level in the tank which has the same temperature as the inlet flow stream. Figures 1.1. through 1.3. show 3 other types of inlet stratifiers than the design for which experiments are described in the following sections.

Figure 1.1 shows the device often referred to as the Solvis stratifier [8]. This stratifier consists of a rigid tube with openings along its vertical extension. Each opening is fitted with a light flap which acts as a check valve. It lets the fluid leave the pipe at the levels of corresponding temperatures, but prevents it from exiting the pipe elsewhere. The Solvis stratifier has moving parts (the flap valves). Also, its working principle is rather different from the design with vertical plates

Another example of a stratifier is the multi-layer fabric pipe of figure 1.2. This technique functions on account of the throttling effect a fluid with velocity induces when travelling in a pipe. The buoyancy resulting from the density difference between incoming and storage fluids creates a velocity profile across the section of fabric pipe In response to the increase in velocity a pressure drop (from throttling effect) within the pipe collapses the fabric pores, deterring any porosity. When the buoyancy force and velocity of fluid travel within the fabric pipe decreases so too does the pressure difference, which opens the pores and allows transfer to the storage volume at a point of corresponding temperature. [6].

The principle of the inlet stratifier shown in figure 1.3 is basically the same as the design with vertical plates: There are no moving parts and the velocity of the inlet flow stream is limited by exposing the flow stream to a large surface. In this case, spheres were suggested instead of plates to make the surface sufficiently large [7].

Figure 1.1.
Inlet stratifier with
flap valves.

Figure 1.2.
Multi-layer fabric
inlet stratifier.

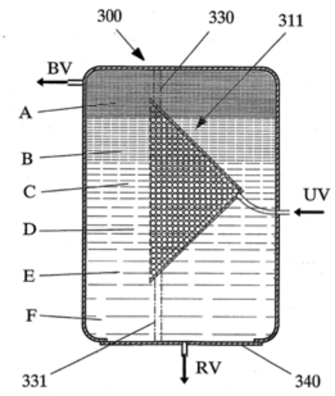

Figure 1.3.
Inlet stratifier with spheres.

2 SCOPE AND CONTENTS

This report summarizes work carried out by Michael Cinelli in his diploma thesis [1]. Besides this report, the work is also published as a presentation including short video sequences. The sequences show the most interesting and illustrating experiments [2]. The same experiments are described in this report in the same order. Therefore, both publications (this report and the presentation) can be consulted for better understanding.

In the framework of IEA SH&C Task 32 a combined solar heating system – called the MaxLean system – was studied. Figure 2.1 shows the schematics of the MaxLean system concept. Detailed performance simulations were carried out by Martino Poretti [3] and Robert Haberl [4]. Both reports quantify the benefits associated with the various specific features of the MaxLean concept including the benefits associated with inlet stratification. According to Poretti, perfect inlet stratificiation at both the solar loop supply and the space heating return – compared with a fixed inlet port at a reasonable position – improves system efficiency notably: Inlet stratification saves approximately 1% of auxiliary energy (natural gas in that case) at either port[1]. Another simulation study [5] quantifies the benefits of stratification for both the solar supply and space heating return inlets. It covers different system concepts, applications and system dimensions. It is generally accepted that this is beneficial for the system's energy performance. On the one hand, stratification is beneficial in terms of energy savings. On the other hand, any device which serves inlet stratification must be inexpensive if it has to be economically feasible. The heat store of the MaxLean system concept is

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[1] The simulations were carried out for: climate: Zurich; hot water load: 3000 kWh/a; space heating load: 8400 kWh/a; solar collector area: 12 m^2; store volume: 0.8 m^3. The total fuel consumption amounted to 8400 kWh/a. The fuel saved due to inlet stratification at both ports amounts to approximately 2% of 8400 kWh/a (or 170 kWh/a). In this case, in a service life of 20 years, perfect stratifiers at both inlet ports save approximately 3500 kWh of auxiliary energy.

charged by solar energy from the collectors through an inlet port without any heat exchanger. Also, the space heating return is directly connected to the store. In many innovative solar heating systems the solar loop is operated at a low flow rate. In the MaxLean concept, both the circuits for solar charging and space heating are operated at a low flow rate. At the inlet ports of both circuits stratification may be applied. This report describes the results from experiments which were carried out in the search for a stratifier which is particularly well suited to be used in the MaxLean system concept. The results are very promising and suggest the optimization and application of the principle for low-flow circuits with variable inlet temperature connected to a heat store. The principle is, of course, not restricted to the MaxLean system concept.

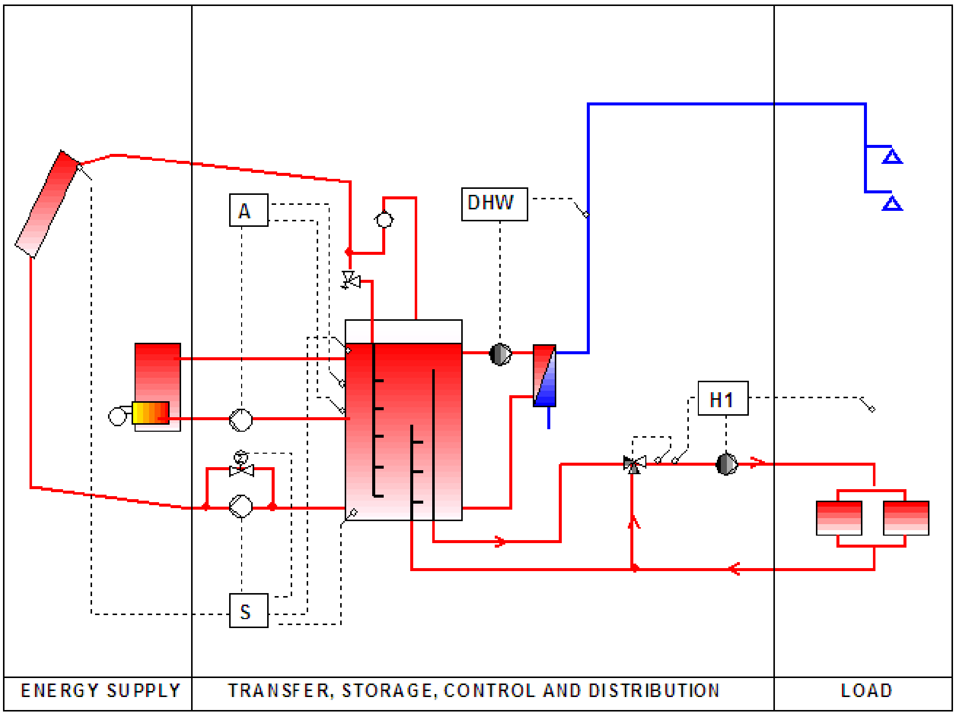

Figure 2.1. Schematic of the MaxLean system concept. The concept is described in detail in the specific technical report (Haberl, [4]). The direct connection of the space heating and solar loops suggests the use of inlet stratifiers. One of the core ideas of the MaxLean system concept is to reduce the amount of material used, which suggests a non-pressurized store with potentially flat walls. A stratifier which consists of parallel plates could implement the wall as one of the plates is it is flat. The evaluation of the MaxLean system concept presented the incentive to study the possibility and potential of an inexpensive stratifier made of essentially parallel plates. However, the use of this type of stratifier is not restricted to one particular system concept.
Schematic adopted from [4] with kind permission by Thomas Letz, INES, Le Bourget du Lac, France.

3 DESCRIPTION OF THE EXPERIMENTAL SET-UP

3.1 Description of the vertical plate stratifier

Figure 3.1. Initial design of the experimental stratifier: two parallel plates made of PMMA with a thickness of 5 mm each. The gap around the plates is open on either side, the top and the bottom.

Figure 3.2. Modified design. On one side the gap is closed, the inlet is positioned near the closed side but vertically centred. Traverses assure flatness of the plastic material.

Figure 3.3. The modified design viewed from the side. The supply pipe is made of copper, with an outer diameter of 12 mm, insulated with EPDM foam.

The plates and the insulated supply pipe were immersed into the open cylindrical glass tank shown in figure 3.4. During the course of the (many) experiments the set-up was modified to test the effect of various designs or solve particular problems. Only the most interesting experiments are described in this report.

3.2 Description of the test equipment

Figure 3.4. The open glass cylinder used for the experiments has a height of 1.5 m and an inner diameter of 380 mm.

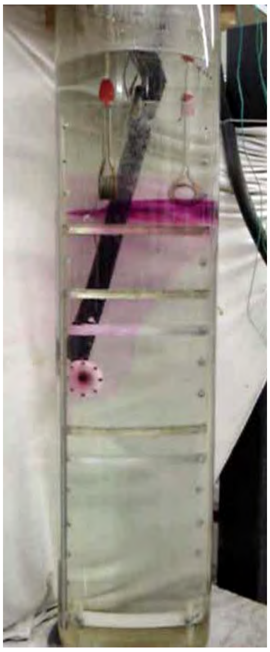

Figure 3.5. Heating for initial temperature profile: To establish the desired initial temperature distribution the tank was first filled with water from the tap. Immersed electrical heating elements were then used to heat the water. During the process the elements were positioned at different levels to establish the desired temperature profile. (Suspending the electrical heaters directly at their cables raised a discussion about electrical safety in the lab).

A simple method using electrical heating elements was used to establish an initial temperature profile (see fig. 3.5).
The water supplied to the stratifier through the insulated pipe was conditioned in external buckets to the desired inlet temperature. The volume in the pipe, pump and flow meter connecting the buckets with the stratifier inlet port comprised of approximately 0.2 litres. The temperature of this small volume could not be conditioned.
During the experiment no water is removed from the tank. Therefore, the surface of the water shifts up during each experiment.

4 EXPERIMENTS

Table 4.1. gives an overview of the experiments. Each experiment is described specifically in the respective section.

Table 4.1. Overview of experiments.

Number and Name	Short description
1, without stratifier	Reference test without stratifier. Hot water is supplied to the uniformly cold tank.
2, large gap	Uniform 6 mm gap open all around. Hot water supplied to the stratified tank.
3, one side closed, narrow gap on other side	The gap size is substantial (4 mm) on the side (inlet side), which is not open to the tank, narrow (1 mm) on the other side (outlet gap). Hot water is supplied to the stratified tank.
4, one side closed, moderate opening on other side	The gap size is substantial (4 mm) on the side which is not open to the tank (inlet side), moderate (3 mm) on the other side (outlet gap). Hot water is supplied to the stratified tank.

4.1 Experiment 1 – without stratifier

In the first experiment hot water was supplied to the uniformly cold tank. This reference test demonstrates that without any stratifier – the inflowing water mixes almost completely with the water above the inlet port. Table 4.2 and figure 4.1. describe the parameters of the experiment.

Table 4.2. Parameters of experiment 1, without strarifier.

Initial tank temperature	15 °C
Inlet flow temperature	59 °C
Inlet flow rate	70 l/h
Inlet port position (from bottom of tank)	0.5 m
Inlet water volume	12.8 l

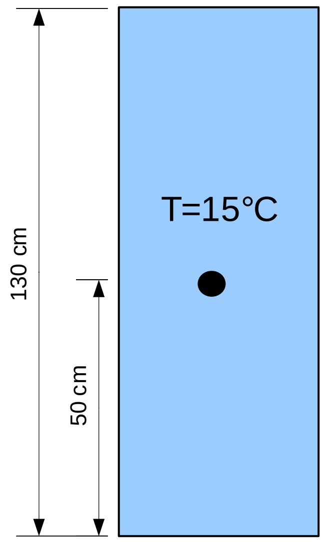

Figure 4.1. Initial tank temperature of experiment 1, without stratifier

Figure 4.2a. Start of experiment 1, without stratifier

Figure 4.2b. Final state of experiment 1, without stratifier

Event though at the beginning of the experiment there is some buoyancy induced drift of the hot water in the tank after leaving the port without a stratifier (figure 4.2a.), the experiment results in a fully mixed volume above the inlet port (figure 4.2b.).

4.2 Experiment 2 – large gap

In the second experiment a basic design of the stratifier was examined. The stratifier consisted of two parallel plates of rectangular shape. Spacers alongside the edges hold them at a distance of 6 mm. Hot water was supplied to the tank. The initial temperature profile is given in figure 4.3. Table 4.3 states the other parameters of the experiment.

Table 4.3. Parameters of experiment 2, large gap.

Initial tank temperature	17-60 °C
Inlet flow temperature	52 °C
Inlet flow rate	70 l/h
Gap width /plate spacing:	6 mm
Inlet water volume	20 l

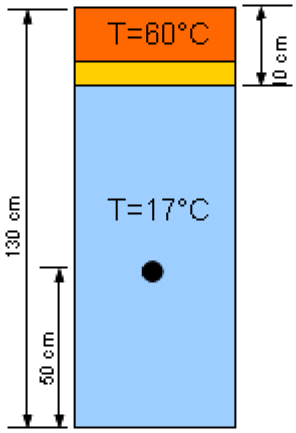

Figure 4.3. Initial tank temperature of experiment 2, large gap

Figure 4.5a. Experiment 2, large gap: soon after it's begun

Figure 4.5b. Experiment 2, large gap: intermediate state

Figure 4.5c. Final state of experiment 2

The coloured inflowing fluid proceeded mostly within the plates towards the top of the tank. Stratification was much improved compared with the first experiment. However, the thickness of the coloured layer reveals that stratification was far from being perfect. The shift of the water surface upwards due to the water volume added during the experiment is much smaller than the thickness of the coloured layer. (Compare the position of the surface and the thickness of the coloured layer between figures 4.5a. and 4.5c.). The shape of the plume moving upwards indicates that there was substantial turbulence which undoubtedly caused mixing and thus reduced the effectiveness of the installation. However, it is remarkable that the hotter top layer remained mostly unaffected by the coloured fluid.

Note that the area close to the inlet port is brighter than the area further away. This was caused by the plastic plate’s flexing. The plates suffered deformation in this area (moved closer together) as a result of difference in temperature or hydrodynamic pressure This deformation persisted after the flow was stopped. The distance between the plates at the position of the inlet port ended up being less than 3 mm. (It was meant to be 6 mm everywhere). As a consequence, traverses were installed in subsequent experiments to improve the rigidity and flatness of the plates.

4.3 Experiment 3 – one side closed, narrow gap on other side

In the third experiment the plate spacing was (intentionally, this time) non-uniform. Also, on one side of the plates the space between the plates had no opening to the tank. The inlet port was moved to that side. The plate spacing on the port side was 4 mm, the spacing on the other side (which is open to the tank volume) was only 1 mm. Some traverses made of aluminium where fixed to the outside of each plate to stiffen them. Compared to the experiments described above, the flow rate was slightly higher (100 litres per hour). The temperature of the incoming fluid was moderate (40 °C). Table 4.4. and figure 4.6. summarize the parameters.

Table 4.4. Parameters of experiment 3, one side closed, narrow gap on other side.

Initial tank temperature	15, 35, 62 °C
Inlet flow temperature	40 °C
Inlet flow rate	100 l/h
Gap width, plate spacing (inlet side / outlet gap):	4 / 1 mm
Inlet water volume	20 l

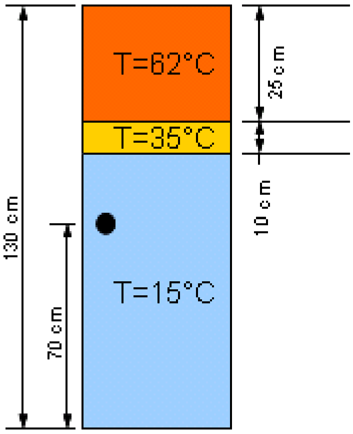

Figure 4.6. Initial tank temperature of experiment 3, one side closed, narrow gap on other side

Figure 4.7. Tank at the beginning of experiment 3. Note that the plates extend to nearly to surface of the water

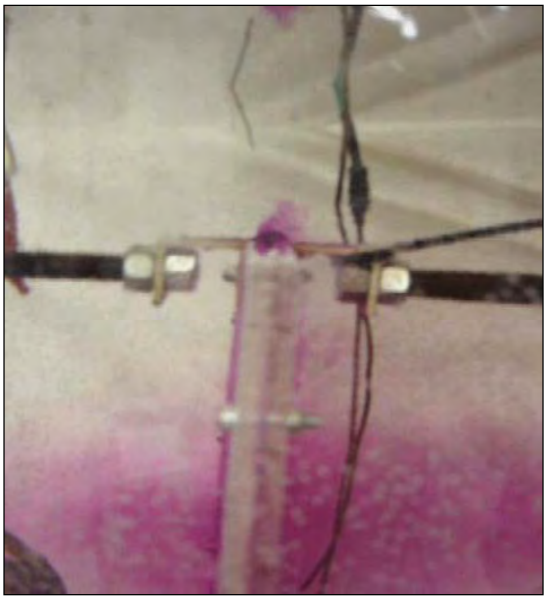

Figure 4.8a. Experiment 3, one side closed, narrow gap on other side. The picture shows the uppermost portion of the plates. Coloured water exits the space between the plates at their top edge.

Figure 4.8b. Experiment 3. Final state of the experiment.

The gap width of only 1 mm was much too small to achieve good stratification. Even though all coloured water should have exited the space between the plates at the right side of the plates (see figures 4.7. and 4.8b.), much of it passed through the gap at the top (figure 4.8a.). There, on the port side (the left side in the figures 4.7. and 4.8b.) the gap was considerably wider (4 mm) causing less friction.
This result (and that of other experiments not documented herein) make clear, that a continuous and relatively even plate spacing is essential. It is important to equalize friction along any possible trajectory of the water between the plates to prevent the inflowing water from preferring an unfavourable path. Buoyancy and friction governs the path the incoming water takes. Uneven friction corrupts the flow path. Buoyancy rather than friction should direct the fluid. Friction should be even and just sufficient to avoid turbulence.

4.4 Experiment 4 – one side closed, moderate gap on other side

In the fourth experiment the outlet gap was 3 mm (instead of 1 mm in experiment 3). Again the other side (where the inlet port is located, see figures 4.10) was closed. The flow rate was increased in steps from 30 l/h to 100 l/h.

Table 4.5. Parameters of experiment 3, one side closed, narrow gap on other side.

Initial tank temperature	15, 25, 60 °C
Inlet flow temperature	38 – 43 °C
Inlet flow rate, variable and increasing in 4 steps of equal duration	30 l/h, 70 l/h, 85 l/h, 100 l/h
Gap width, plate spacing (inlet side / outlet gap):	4 / 3 mm

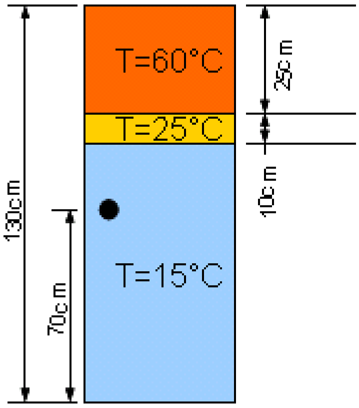

Figure 4.9. Initial tank temperature of experiment 4, one side closed, moderate gap on other side

Figure 4.10a. Experiment 4, one side closed, moderate opening on other side. Picture taken 1:27 minutes after the start of the experiment.

Figure 4.10b. Experiment 4, intermediate state, after 5:45 minutes.

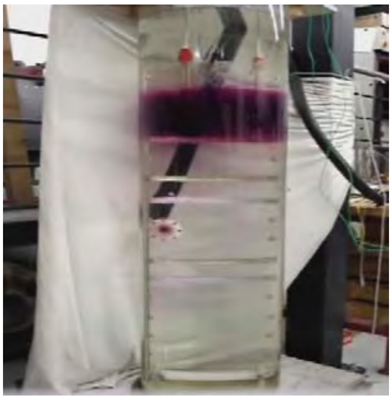

Figure 4.10c. Final state of experiment 4

Figures 4.10. show the process and result of the fourth experiment. Note that the surface of the water shifts from the near top border of the picture taken soon after the start of the experiment (figure 4.10a., left, at this moment, approx. 0.75 litres had been supplied only) to the top border of the picture (figure 4.10c., right) because no water was removed during the experiment. Also note that the camera was located slightly below the coloured layer, which explains the curved shape of it's top and bottom borders.
The size of the coloured layer at the end of the experiment corresponds to a slightly larger water volume than the volume added to the store during the whole experiment (the layer is slightly thicker than the rise of the water level). This good result was achieved only with a roughly optimised design. Also, it is remarkable that the lower border of the coloured layer (which happens to be at the height of the uppermost aluminium traverse in figures 4.10.), stays at virtually the same level throughout the experiment. It is easy to assume that a modified design (e.g. an oval, instead of a rectangular shape of the plates; or a plate spacing which is slightly bigger immediately around and above the inlet port, bigger near the edges but small in the area between the inlet and the edges, with continuous transition between the areas of different plate spacing; or a design with several gaps in parallel) would further improve the performance.

5 CONCLUSIONS

The experiments demonstrate that stratification can be achieved with vertical plates. Even roughly optimised arrangements lead to good results. The plate spacing is the most important parameter. The spacing must be well chosen and precise. The arrangements which performed best had a plate spacing of 3 to 4 mm. (This result correlated with theoretical considerations and calculations carried out before setting-up the experiments.) One important advantage of the concept is its simplicity and the fact that there are no moving parts. Because several plates – constituting several parallel gaps – could be used, a modular design could be developed which would be suitable for a large range of flow rates. The promising results obtained in experiments suggest the further development, application and optimization of the vertical plate stratifier.

6 ACKNOWLEDGEMENTS

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