Heat Pump Systems

Quantification of energy savings

By implementation of StratiFlex™

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1 Executive summary

This paper investigates the importance of thermal stratification in a storage tank connected to a heat pump system. The correlation between thermal stratification and the COP of a heat pump and thus the cost of heating is outlined as:

Improved thermal stratification

↳ reduced average bottom temperature in tank

↳ reduced average feed temperature to the heat pump

↳ reduced necessary working pressure for the compressor

↳ reduced electricity cons. by the compressor

= improved COP and reduced cost of heating

The investigation consists of two parts, a theoretical and experimental part:

1. Theoretical and experimental research done by, among others, the recognized SPF Institute in Switzerland, explains how stratification efficiency is decisive for the overall system performance of heat pump system. Calculations based on their theoretical and experimental research has been used to determine the energetic and economic impact of thermal stratification in a heat pump storage system.
2. The second part of the work included in this paper is a comparable test setup, which was developed in order to determine the impact of thermal stratification in a heat pump system. A test system was set up with the possibility of testing two different technical approaches. One conventional heat pump system with a fixed inlet, and one with the stratification system from EyeCular Technologies installed.

The investigation revealed a significant potential for increasing the COP in a heat pump system, by implementing the thermal stratification system, StratiFlex™, developed by EyeCular Technologies.

The increase of the COP was determined through experimental tests to be 19%, resulting in a significant reduction of the cost of heating by 16%. Ultimately, for a standard 1-family house in Germany, with an average yearly consumption of 15,000 kWh, this means a reduction of the heating expenses of 211 Euro per year.

The results are significant, and implementing the thermal stratification system, StratiFlex™ in heat pump systems, will have a major impact, not only on the heating expenses for the end user, but also for the environment and future generations.

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2 Introduction

One of the leading scientist in Europe states:

> *”For more than 30 years thermal storage stratification and its impact on the efficiency of hot water storage systems has been a topic of investigation. In particular, for combi-storages that provide domestic hot water and space heating from one device, stratification efficiency is decisive for the overall system performance.”*
>
> (Michel Haller et. al., 2015)[1].

As stated above, thermal stratification is one of the most important factors for highly efficient hot water storage systems. It is scientifically proven that thermal stratification can lead to a significant increase of a heat pump system’s COP and sCOP. As stated by Jean-Christoph Hadorn;

> *“As a general rule of thumb, a decrease of the temperature difference between the evaporation and the condensation by 1K leads to about 2-3% increase of the COP”*
>
> (Jean-Christoph Hadorn et. al., 2015)[2].

Rephrasing the quote by Jean-Christoph Hardon, it is apparent that, 1K reduction in the feed temperature to the heat pump results in an increase of the COP by 2-3%.

This paper demonstrates, explains, and quantifies the impact of thermal stratification in a heat pump system by implementing StratiFlex™.

2 Basics of thermal Stratification

The density of water is a function of its temperature - see figure 1. When water is warmer than 4°C it gets less dense for each increment in degree Celsius. This allows for thermal layering; where warmer water is stored on top of colder water – defined as “thermal stratification”.

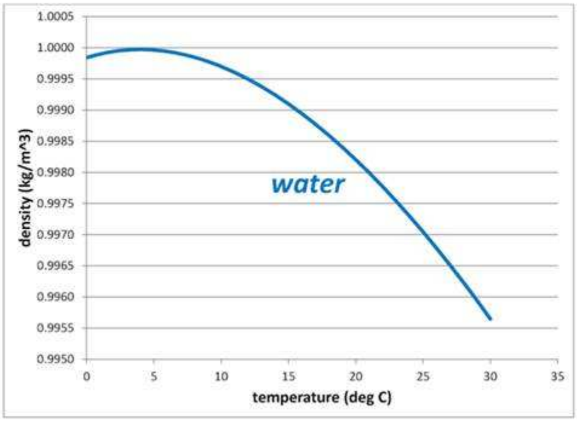


Figure 1 – Water Density as Function of Temperature

Thermal stratification is possible as water becomes less dense when heated, meaning water weighs less per unit volume. Therefore, warmer water will be lighter and colder water will be heavier. Due to this, there will always be a level of “self-induced” thermal stratification in a water storage. However, this can be greatly disturbed by undesirable and uncontrolled water flows, which stirs the otherwise thermally separated layers together and mixes them into a uniform temperature.

When referred to a stratified storage tank, it is meant that thermal stratification is actively maintained – thereby no mixing of the thermal layers occurs**.** It requires a stratification device to achieve this, and EyeCular Technologies has developed a relatively cheap and very effective stratification device - StratiFlex^{TM}.

Figure 2 shows an equal amount of energy stored inside two different tanks. The first tank is thermally stratified, and the other is fully mixed. These two temperature profiles are an example of how a stratification device will affect the energy distribution inside a storage.

The first temperature profile depicted in figure 2 will yield better working conditions for a heat pump system (see chapter 4.1), even though both tanks have an equal amount of energy.

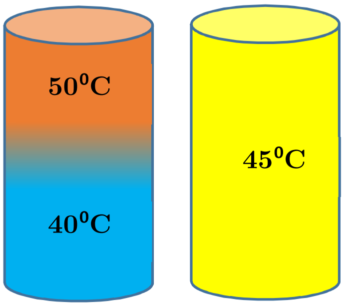


Figure 2 – Stratification vs. fully mixed tank

3 Mixing

There are two main reasons for mixing of thermal layers inside a water storage; mixing due to forced flow called inlet jet mixing, and mixing due to the buoyancy driven effects from natural convection called plume entrainment.

1. **Inlet Jet Mixing**

   A jet refers to a water flow driven by outside forces (pump). Having a jet leads to turbulence, and the higher the velocity of the water the more turbulence.

   When forcing a water flow through a fixed inlet connection, a jet will be created inside the tank. The higher the velocity of the forced jet, the more mixing will occur. This inlet jet mixing causes the inlet water to affect the thermal layers both above and below the fixed inlet connection – regardless of the temperatures in the thermal layers and inlet.

Figure 3 – Inlet jet Mixing

2. **Plume Entrainment**

   When warmer water is positioned below colder water, the warmer water will force its way upwards through the layer of colder water, due to the density differences explained in chapter 2. In the process the warmer water is being mixed with the colder water (entrainment). The phenomenon is similar to when a plume of smoke from an open fire is being mixed with the colder air surrounding the fire pit. This buoyancy driven water flow, is referred to as plume entrainment.

   When heating water by a coil heat exchanger in the bottom of a tank, the water closely surrounding the coil will be heated up faster than the water further away. This introduces warmer water close to the coil than the water above the coil, and will create a thermo siphoning effect and cause plume entrainment.

   Fixed inlet connections are by accident (as temperature profiles in hot water tanks change often) or deliberately (in order to preserve warm water zones) often letting in warmer water below colder water. This is another known source of plume entrainment.

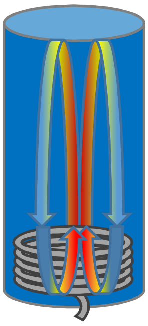


Figure 4 – Plume entrainment

4 Heat Pumps – Briefly

A heat pump has two energy sources; the external (air, water or geothermal) and an electrically driven compressor. A simplistic diagram of a heat pump system is shown on figure 5. The evaporator is where the system is collecting the energy from the external energy source, the “free energy”. The condenser is where the energy is transferred to the secondary side of the system.

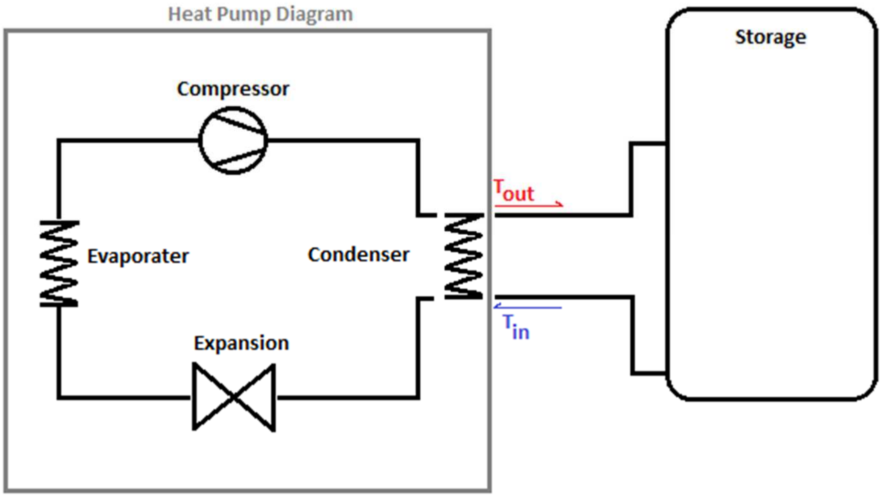


Figure 5 - Heat Pump Diagram with Storage

A heat pump is regulated after a fixed temperature difference (e.g. 5-7°C) between T_{in} and T_{out}. High operating temperatures, hence a high T_{in}, have a significant impact on the working conditions for the heat pump. The higher the operating temperatures, the more the compressor has to work in order to lift the temperature 5-7°C (See chapter 4.1). More work means increased electricity consumption by the heat pump, and therefore a reduction of the COP.

The COP is used to describe the correlation between energy transferred to the storage system and energy consumed through the work performed by the electrical compressor.

$$COP = \frac{\dot{Q}_{out}}{W_{comp.}} \qquad \text{eq.12}$$

In order to improve the COP of a heat pump system with a given and specific $\dot{Q}_{out}$, the necessary work from the compressor needs to be reduced. A high efficient stratified system will significantly reduce the average T_{in}, which then leads to less work required and less electricity consumed by the compressor. Ultimately, this results in a significant increase of the COP and a significant reduction of the heating expenses.

4.1 Why Stratification has an Impact on the COP

When having a system with several processes, improving any of the processes can improve the overall system performance. The interest here is improving the water dynamics inside the storage tank, which will improve the heat distribution inside the storage, ultimately resulting in full utilization of the energy delivered from the heat pump in every cycle.

The work needed from the compressor is dependent on the working temperatures, influencing the required working pressures. The relation between the pressure and temperature of evaporation of a refrigerant is shown on figure 6.

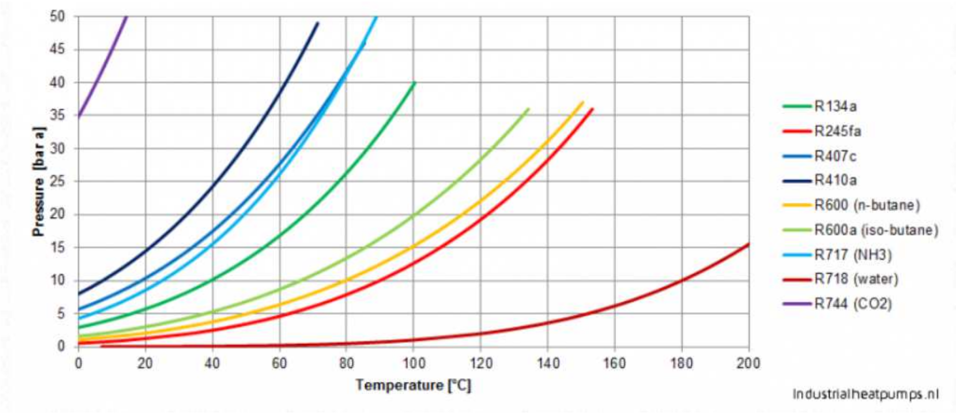


Figure 6 – Pressure and Evaporation Temperature Relation for Refrigerants[3]

Figure 6 shows that the required evaporation pressure increases exponentially with the temperature. This means higher working temperatures demand exponentially higher working pressures from the compressor. For each time the temperature increases one degree, the pressure needed from the compressor will increase exponentially. Therefore, it is very desirable to maintain the working temperatures (bottom temperatures in the storage) as low as possible. Lower working temperatures leads to lower necessary working pressure to reach the same temperature increase between T_{in} and T_{out}.

Higher average operating temperatures are found in heat pump systems with low stratification efficiency. As explained in chapter 3, when mixing occurs in a storage tank, the hot zone is mixed with colder water, either due to inlet jet mixing and/or plume entrainment. As mixing results in a more uniform temperature distribution inside the storage tank, the working temperatures (and required pressures) will be averagely higher, leading to a higher consumption of electricity by the compressor. Furthermore, as the hot zone is degraded, a reheating of the hot zone is required. The reheating will be performed at high operating temperatures, resulting in even higher heating expenses.

Recapping the example from figure 2 (Chapter 2), where two tanks had the same energy content but very different temperature profiles. The thermally stratified tank would have a continuously lower bottom temperature, as a result of an effective and continuous heating cycle with active stratification of the heated water from the heat pump. This will allow the heat pump to add the same amount of energy to the storage, but with less energy consumed by the compressor.

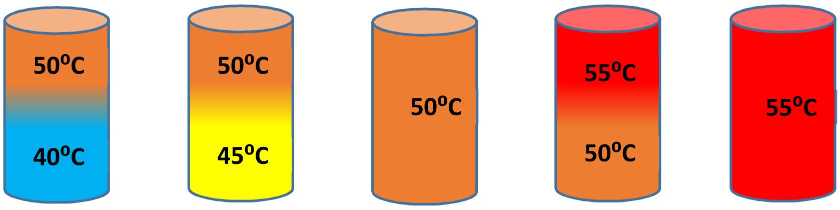


Figure 7 - Heating Cycle with Active Stratification

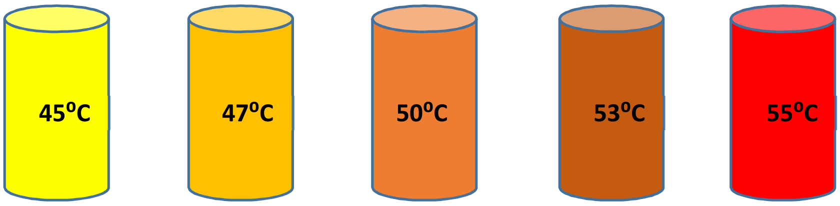


*Figure 8 - Heating Cycle with**out** Active Stratification*

Figure 7 and 8 shows an example of how a heat pump system could reach the same end result; fully charged tank at 55°C, with and without stratification during the charge cycle.

With stratification (figure 7) the bottom temperature during the charge cycle is in average 46¼ °C. Without stratification (figure 8) the bottom temperature during the charge cycle is in average 48¾°C. In this example stratification reduces the bottom temperature 2½°C, which would give the compressor improved working conditions, thus reducing the energy consumed by the compressor.

5 Lab Tests

The tests described in this section investigate how much the COP of a heat pump system can be improved by implementing thermal stratification. As stated earlier, low operating temperatures are crucial for the heat pump system performance.

5.1 Equipment

The test facility is equipped with 24 temperature sensors (thermocouples), positioned with a vertical distance of 50mm figure 9. Temperatures are logged every 10 second by a data logger (Agilent 34972A LXI).

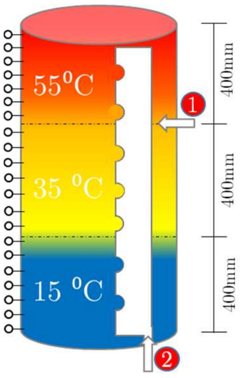


Figure 9 - Starting Conditions

5.2 Test Setup

There are two test setups. The tests will be performed separately, but performed with the same starting and operating conditions. This will ensure comparable test results, and enable quantification of the difference between the COPs of the two given system designs.

Setup 1:

Standard fixed connection placed in a vertical height of 800mm.

Setup 2:

StratiFlex™ is integrated through the bottom of the storage tank.

Starting conditions:

- Top 1/3 volume: 55 °C
- Middle 1/3 volume: 35 °C
- Bottom 1/3 volume: 15 °C

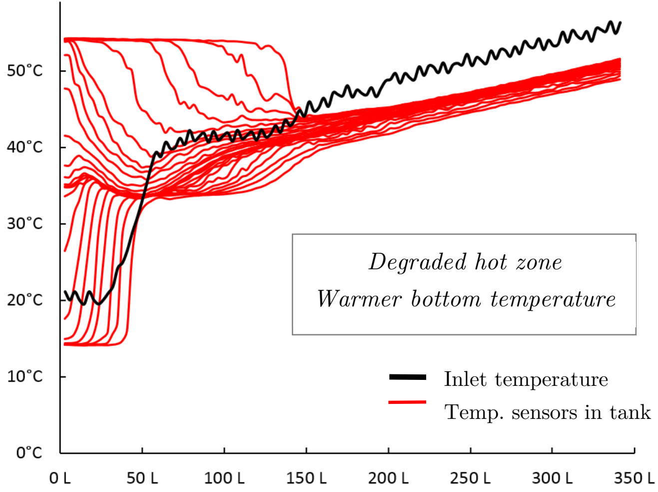
Flow conditions:

- 17.5 l/min
- Circulation our form the bottom of tank
- 6 cycles of △T = 7 K

5.3 Test Results

Below, on *Figure 9 and Figure 10,* the results of the two test setups are shown.

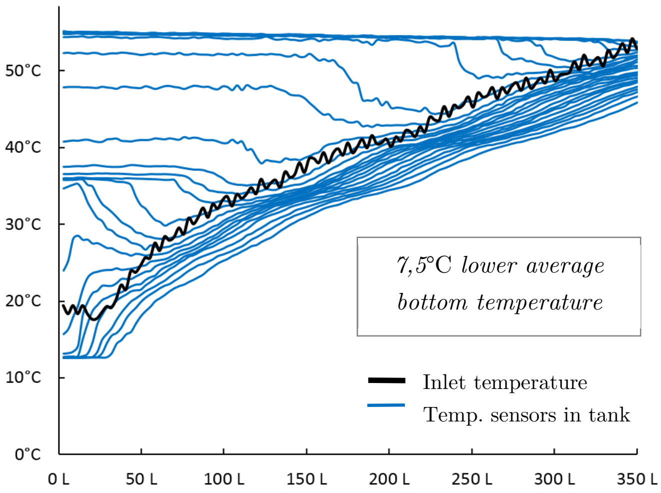
Fixed inlet (test setup 1)



Degraded hot zone
Warmer bottom temperature

Figure 9: Circulation from heat pump at a fixed position ⅔from the bottom of the tank

With StratiFlex™ (test setup 2)



7,5°C lower average bottom temperature

Figure 10: Circulation from heat pump managed by StratiFlex™ installed in the bottom of tank

Each of the colored lines represent a reading of one of the 24 temperature sensors in the tank**.** The black line represents the inlet temperature to the tank. The y-axis is temperature in degree Celsius, and the x-axis is the volume of circulated water in liters.

There is a great difference in both the top and bottom temperatures of the two comparison tests.

In Setup 1 the inlet water is being mixed with the water in the tank, mainly because of jet mixing (see figure 3). But plume entrainment will also occur, since the fixed inlet can result in warm water being positioned below colder water, in this case in the beginning of the test.

As some of the hot zone is mixed into the lower grade layers of water, the average operating temperature for the heat pump is higher throughout the entire duration of the test, compared to setup 2.

In Setup 2 (Thermally stratified by StratiFlex™) the bottom temperatures are kept almost as cold as possible throughout the entire test duration, ensuring the most optimal operating conditions for the heat pump. Plume entrainment is greatly reduced as StratiFlex™ is always positioning the inlet water in the appropriate thermal layer, and jet mixing is also greatly reduced as StratiFlex™ reduces the inlet water velocity to the recommendable range of velocity.

5.4 Comparison

Based on the temperature measurements, it can be calculated that the bottom temperature is in average 7.5°C lower in the test setup with the StratiFlex™ (Setup 2) compared to the fixed inlet setup (Setup 1).

Furthermore, the hot zone is degraded at a very early stage in the fixed inlet test setup (Setup 1). As the hot zone is degraded, the heat pump system has to perform a reheating of the degraded hot zone at inefficient conditions (see chapter 4.1). However, the hot zone in the StratiFlex™ setup (Setup 2) remains almost constant over the duration of the test, and no reheating cycle at inefficient conditions is required. The improved operating conditions due to stratification, leads to a significantly improved COP, and reduced cost of heating for the end user.

6 Quantification

The correlation between improved thermal stratification and the cost of heating, can be outlined as follows:

Improved thermal stratification

↳ reduced average bottom temperature in tank
    ↳ reduced average feed temperature to the heat pump
        ↳ reduced working pressure for the compressor
            ↳ reduced electricity cons. by the compressor

= improved COP and reduced cost of heating

Remembering the rule of thumb quoted in the introduction:

> *"a decrease of the temperature difference between the evaporation and the condensation by 1K leads to about 2-3% increase of the COP"*
>
> (Jean-Christoph Hadorn et. al., 2015)[2]

This quantified correlation between the change in bottom temperature of the water storage and the COP of the heat pump will be used in the following chapter of quantification.

6.1 COP Increase

The increase in COP is found in the difference of the average bottom temperature in the two test cases, as 1K reduction in the feed temperature to the heat pump results in an increase of the COP by 2-3%[1]. The percentage used in the following calculation will be 2.5%. It is given that:

$$\mathrm{COP}_{\mathrm{increase}} = \left(\mathrm{T}_{\mathrm{avg.bottom.test.1}} - \mathrm{T}_{\mathrm{avg.bottom.test.2}}\right) * 2.5\% \qquad \text{eq.2 2}$$

Where:

$\mathrm{T}_{\mathrm{avg.bottom.test.1}}$ = Average feed (bottom) temperature to the heat pump from the fixed inlet storage tank (Test setup 1)

$\mathrm{T}_{\mathrm{avg.bottom.test.2}}$ = Average feed (bottom) temperature to the heat pump from the stratified storage tank (Test setup 2)

The average bottom temperatures in the two test cases are as follows:

- Test setup 1, Fixed inlet: 37.5 °C
- Test setup 2, StratiFlex™: 30.0 °C

Applying equation 2 it is found that:

$$\text{COP}_{\text{increase}} = (37.5 - 30)\text{K} * 2.5\% = 18.75\% \cong 19\%$$

In the comparison tests, the average increase of the COP is 19%.

6.2 Quantification of Energy Savings

A common yearly energy consumption in a 1-family house in Germany is approximately 15,000 kWh in a combined DHW and space heating system (5,000 kWh DHW, 10,000 kWh SH).

The average electricity cost in Germany in 2015 was app. 0.295 €/kWh[4].

Based on the electricity prices and the improved COP, the yearly savings by implementing StratiFlex™ can be calculated.

Table 1	**1. Fixed inlet**	**2. With StratiFlex™**
Yearly demand	15,000 kWh	15,000 kWh
COP	3.5	$3.5 * 119\% \cong 4.2$
Electricity consumption	$\frac{15{,}000\text{ kWh}}{3.5} = 4{,}286\text{ kWh}$	$\frac{15{,}000\text{ kWh}}{4.2} = 3{,}571\text{ kWh}$
Cost of heating	$4{,}286\text{ kWh} * 0.295\,\frac{€}{\text{kWh}} = 1{,}264\text{ €}$	$3{,}571\text{ kWh} * 0.295\,\frac{€}{\text{kWh}} = 1{,}053\text{ €}$
Yearly Cost savings	-	**211 €**

For a heat pump system delivering a yearly consumption 15,000 kWh, the estimated average cost savings by implementing StratiFlex™ are 211 €/year. This is a significant reduction of the heating expenses, and will not only benefit the economy of the household, but also environment and future generations. This states the importance of implementing thermal stratification in a heat pump system.

7 Sources

1: M. Haller, et. al., "Components of thermodynamic aspects," in Solar and Heat Pump Systems for Residential Buildings, J.-C. Hadorn (ed.), ch. 3, pp. 51, 1st. ed., Ernst & Sohn, 2015.

2: Jean-Christoph Hardon et. al. (2015), Solar and Heat Pump Systems for Residential Buildings

3: http://www.industrialheatpumps.nl/en/how_it_works/refrigerants/

4: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics