Effects of High Flow Rates on Tank Stratification and Heat Pump Water Heater Performance

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HOT WATER HEAT PUMPS LTD
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Summary

Stratification in hot water cylinders is a natural occurrence which is important in the efficient operation of heat pumps for domestic hot water use. The effects of tank mixing due to the high-water flow rates used in the multi-pass heat pumps leads to a reduction in available hot water for the user and a reduction in the efficiency of the heat pump. This is more so the case when hot water is being used when the heat pump is running. These effects are minimised using a baffle plate and are kept localised at the bottom of the tank, ensuring that there is a reserve of hot water for the user. A Practical Study using an available tank proves that tank mixing is significant even in short time periods and within 8 hours will mix the water until half the tank is at uniform temperature.

Contents

Table of Figures

Introduction

The main advantage of a heat pump for hot water heating is that it provides more water heating capability for a given power input than an electric element. However, this is dependent on several factors. One of these factors is the incoming water temperature should be as cold as possible. Because of this, it is important that the water in the hot water cylinder is stratified so that the hottest part of the tank is at the top to provide the household with hot water and the coldest part is at the bottom.

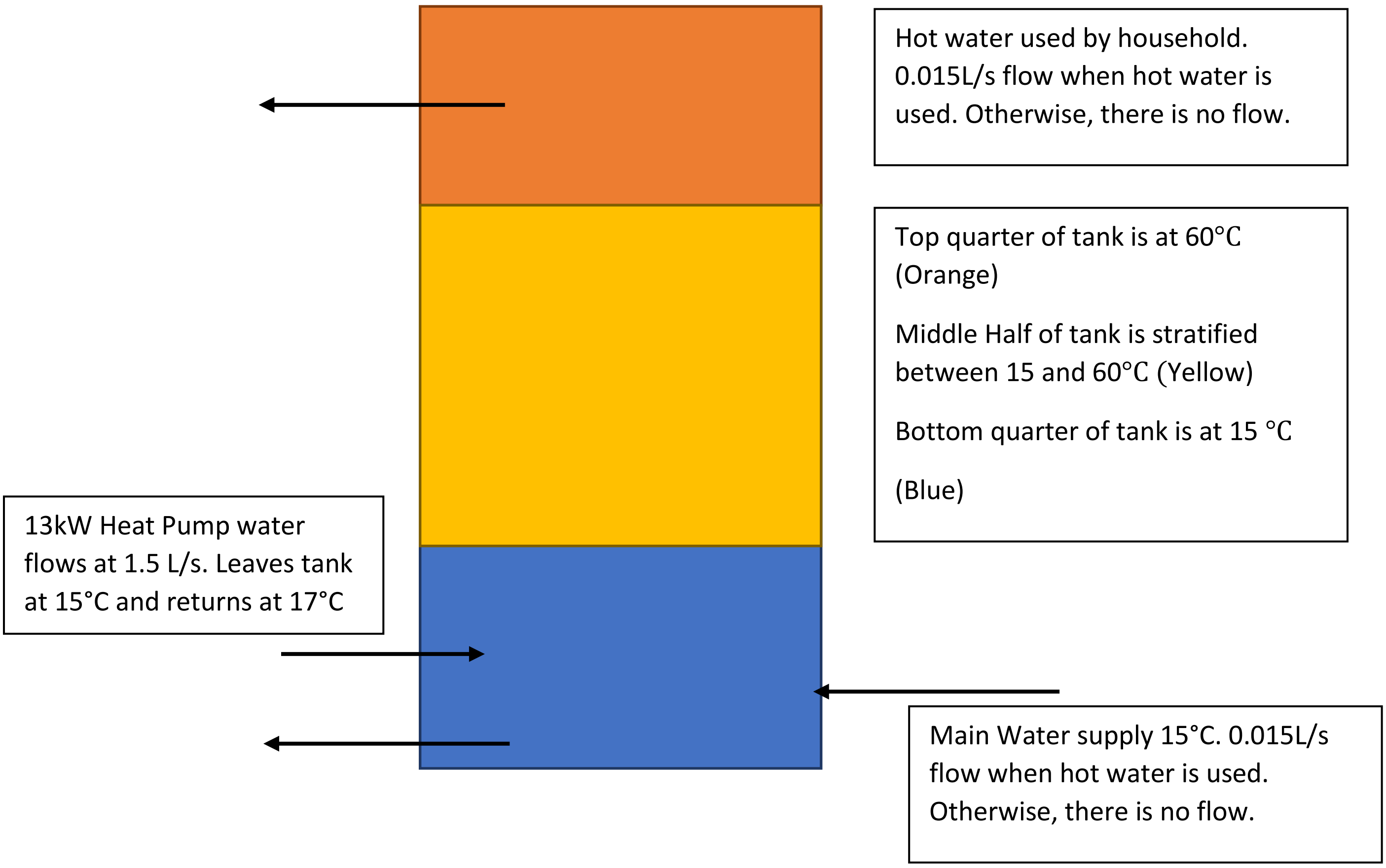
For some multi-pass heat pumps, the water temperature is only raised by 2°C when going through the heat pump. This means that any 60°C water taken out of the tank will not be replaced until the bottom of the tank reaches 58°C. Any mixing that occurs in the cylinder will have the effect of transferring heat from the top to the bottom of the cylinder and vice versa, reducing the amount of 60°Cwater available to the user and increasing the temperature at the bottom of the tank.

Both theoretical and practical analysis was carried out. While it was impractical to use the exact tank for the practical study, the results are in line with the theoretical study.

1. Parameters for Analysis

Two scenarios are analysed for determining the effects that a lack of a baffle plate has on multi-pass heat pump systems. They are based on the heat pump running when there is no hot water being used by the household and when there is around 0.9L/min being used. This is because in the latter case, there will also be a flow of cold 15°C water entering the tank from the mains.

1.1 Tank Stratification and water flows

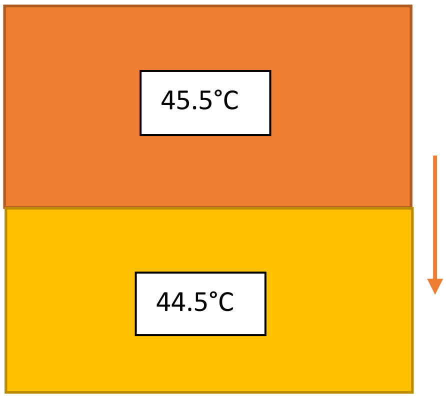


The tank parameters for the theoretical study are as follows:

- Tank Model name: EC300L
- Actual Capacity (L): 292L.
- Stratified Tank Section capacity: 146L, half the total tank capacity
- Tank Diameter (575mm. Tank was wrapped in 50mm insulation making the actual water tank 475mm in diameter)
- Tank Height: 1650mm
- Water to Heat Pump Port: 100m from bottom of tank
- Water Supply from Heat Pump Port: 240mm from bottom of tank
- Port Sizing: 32mm

The stratified section of the tank is assumed to have a linear temperature distribution. It is divided into segments of 3.25L where the temperature difference between the top and bottom of the segment is 1°C. The 60°C and 15°C segments have a volume of 73.1L each which is a quarter of the total volume of the tank and have uniform temperature within the segments.

When there is no water flowing, either due to the heat pump running or hot water being drawn off, there will be heat losses through the insulation. As this will happen regardless of the use of a baffle plate, these have been ignored for this analysis. Because the warmer water is on top of the colder water, there will be no convective heat transfer. What will also happen is conductive heat transfer between the segments due to conduction as shown below:



$$\dot{Q}_{conduction} = \frac{-kA(T_2 - T_1)}{L}$$

T2 = 45.5°C

T1=44.5°C

k = 0.6364 W/sq.m.°C

A= 0.177 sq.m

L=0.0183m the length of each segment

The rate of heat transfer is small, around 0.00619kW.

For finding out the temperature at a particular point in the stratified section of the tank, the following equation is used:

$$T(°C) = 54.55°C/m * (Y(m)) + 15$$

Y is the distance from the bottom of the stratified section of the tank. This begins at 412.5mm from the bottom of the tank. The height of the stratified section is 825mm. The +15 signifies that the bottom of the stratified section is at 15 °C and t54.55 is the temperature gradient.

1.2 Tank Assumptions Summary

- Heat Losses through insulation ignored.
- No convection heat transfer between segments
- Stratified section is 146 L
- Stratified section has a linear temperature distribution with the section divided into segments of 3.25L with a difference of 1 °C between each segment
- 60 °C section of tank is 73.1 L, same for 15 °C section

2. Case 1: No hot water drawn off for use

When the heat pump is running, 1.5L is taken from the tank at 15°C, 100mm from the bottom of the tank and returned at 17°C into the 15°C segment at 240mm from the bottom of the tank through a 32mm diameter pipe. Because of the flow rate, this stream will hit the back of the cylinder and divert into several streams. The velocity of the entering stream is found as follows:

$$Flow\ Area = 0.25 * \pi(\frac{32mm}{1000})^2 = 0.0008042\mathrm{m}^2$$

$$Velocity\ of\ stream = \frac{(FlowRate)}{Flow\ Area} = \frac{(1.5\frac{L}{s}/1000\frac{m^3}{L})}{0.0008042m^2} = 1.865\frac{m}{s}$$

For simplicity, it is assumed that these streams divert into four equal flows. For accuracy, from this point on, we will work based on mass rather than volume. The total mass flow rate is 1.498kg/s. We also assume that there is no water resistance against the water flow to simplify the analysis. This puts the total kinetic energy rate of the stream at 2.605J/s.

$$\dot{E}_{Total\ Stream} = 0.5 * 1.498\frac{kg}{s} * (1.865\frac{m}{s})^2 = 2.605\frac{J}{s}$$

$$\dot{E}_{per\ stream} = \frac{2.605}{4} = 0.651\frac{J}{s}$$

Three of the flows will mix with the 15°C water at the bottom of the tank. This will raise the temperature of the water in this segment.

The fourth stream will continue up until it loses momentum. The flow rate of this stream is 0.3745kg/s and it moves with an initial velocity of 1.8651 m/s based on the initial energy within the flow, the same velocity that the total flow enters the tank. For analysis, we will base it on a mass of 0.3745kg of water:

$$Inital\ Velocity\ in\ upward\ stream = \sqrt{\left(\frac{0.651\frac{J}{s} * 2}{0.3745\frac{kg}{s}}\right)} = 1.865\frac{\mathrm{m}}{\mathrm{s}}$$

$$Momentum\ of\ upward\ stream = 0.3745kg * 1.865\frac{m}{s} = \frac{0.6985kgm}{s}$$

The maximum height that this mass of water will reach is based on the final velocity being equal to zero. The total force acting on the stream is gravity minus the force due to momentum of the mass. For this purpose, a positive value indicates the force is towards the bottom of the tank

$$Force_{due\ to\ momentum\ of\ water} = \left(0.6985kg\frac{m}{s} * 1s\right) = 0.6985N$$

$$\sum F = \left(0.3745kg * 9.81\frac{m}{s^2}\right)_{Gravity} - (0.6985kg\frac{m}{s} * 1s)_{momentum} = 2.975N$$

$$Acceleration = \frac{2.975N}{0.3745\frac{kg}{s}} = 7.94\frac{m}{s}$$

This results in the mass of water having a deceleration of 7.94m/s^2. The distance from the water inlet in the vertical direction that the water stream reaches is found from the following equation:

$$Distance\ from\ tank\ inlet\ (m) = \left(1.8651\frac{m}{s}\right)^2 / \left(2 * \left(7.94\frac{m}{s^2}\right)\right) = 0.219m$$

This means that the 17°C water stops flowing up at 459mm from the bottom of the tank. At this point, the tank is at 17.5°C. However, this flow will have moved water above it meaning that water at 17.5°C will have been pushed up 0.219m. This is repeated until the mass is stopped by the top of the tank, which will then displace water back down.

For simplification, it will be assumed that the temperature of the water entering a segment will be the average of the water temperatures encountered in the 11 segments prior to (as this is the number of segments passed through when moving 0.219m). This means that the 60°C segment (73.1L, 71.88kg in mass) of the tank will receive 0.3745kg of water at an average temperature of 54°C. This will displace the total mass of 60°C water from the segment into the bottom segments. The resulting drop in water temperature is found from an energy balance equation:

$$Q_{60}(kJ) = 71.88kg * 4.18\frac{kJ}{kg°C} * 60°C = 18027kJ$$

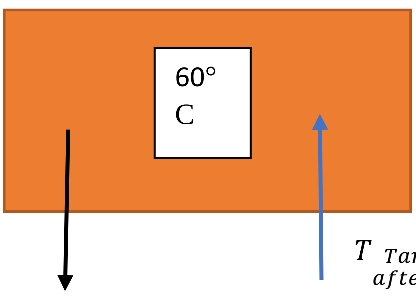
$$Q_{entering} = 0.3745kg * 4.18\frac{kJ}{kg°C} * (54)°C = 84.532kJ$$

$$Q_{leaving} = (0.3745)kg * 4.18\frac{kJ}{kg°C} * 60°C = 93.92kJ$$

$$Q_{60\ after\ mixing} = 18027 + 84.532 - 93.92 = 18017.61kJ$$

$$T_{new} = \frac{18017.61kJ}{71.88kg * 4.18\frac{kJ}{kg°C}} = 59.96°C$$

This is after one second of flow. The segment is losing 9.39kJ per second at this point based on the difference in energy. After 1 minute, the new average temperature would be 58.12°C if the water from the heat pump and the resultant flows into the segment retained the same water temperatures. Over time, under the same assumptions, the final water temperature throughout the tank would be 37.1°C.



Blue Arrow represents energy entering segment (+84.532kJ)

Black arrow represents energy leaving segment. (-93.92kJ)

$$T_{\substack{Tank\ Total \\ after\ mixing}} = \frac{45310kJ}{292kg * 4.18\frac{kJ}{kg°C}} = 37.1°C$$

The actual tank temperature and temperature of the 60°C segment would be higher. This is because the mixing of the tank would mean water entering the 60°C segment would be warmer. At the same time, the final water temperature of the tank would be higher because the incoming water from the heat pump is being heated. However, the end result would still be that the upper segments of the tank reduce in temperature while the lower segments increase until they are at a uniform temperature below the required 60°C which the heat pump will then need to work at a lower COP to bring back up to temperature.

The other three flows will mix with the bottom 15°C segment (73.1L, 73.03kg in mass) as well as the water from the segments above pushed down by circulation.

$$Q_{15} = 73.03kg * 4.18\frac{kJ}{kg.°C} * 15°C = 4579kJ$$

$$Q_{17stream} = 1.1235kg * 4.18\frac{kJ}{kg°C} * 17°C = 79.83kJ$$

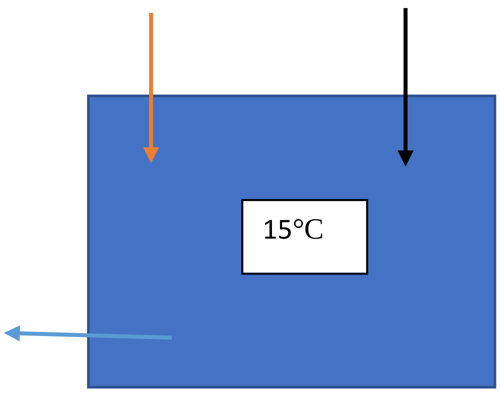
$$Q_{15toHP} = 1.498kg * 4.18\frac{kJ}{kg°C} * 15°C = 93.92kJ$$

$$Q_{above\ segments} = 0.3745kg * 4.18\frac{kJ}{kg°C} * 20.5°C = 32.09kJ$$

$$Q_{Total} = 4579 + 79.83 + 32.09 - 93.92 = 4597kJ$$

$$T_{new} = \frac{4597}{73.03 * 4.18} = 15.06°C$$

There is a much larger change because of the 17°C streams from hitting the back of the cylinder. It is for this reason that the water returning from the heat pump is delivered to the bottom of the tank as delivering it to the top of the tank would have a negative effect on the hot water already stored in the top segment of the tank. Between the stratified segments, the change in energy is varied (for the 45.5°C segment, there is a loss of 2 J and for the 25.5°C segment, this is 7 J. This is only due to the mixing of the tank directly and does not take conduction between the segments into consideration. What is happening is heat transfer from the warmer segments to the colder incoming flows.



Black Arrow represents 17°C Stream (+79.83kJ)

Blue Arrow represents stream to HP (-93.92kJ)

Orange Arrow represents stream from upper segments (+32.09kJ)

3. Case 2: Hot water being drawn off

In this case, 0.0147kg/s of water is being drawn off from the top of the cylinder to be used while the same amount is coming in from the main water supply. For the top segment of the tank, this means that the mass of 60℃ water in the tank is decreasing. The 17℃ stream will be taken higher up in the tank due to help from the pressure difference. Further turbulence is also encouraged in all segments due to the pressure difference between the top and bottom of the tank. This means that after 1 minute, the top segment would now contain 70.998kg of water and 221.2kJ of energy will have left the segment. This leads to the average temperature of the segment dropping to 58.1℃ in 1 minute, a small increase on what was happening when no water was being drawn off.

At the bottom of the tank, the change is minimal due to the entering water being at the same water temperature as the segment.

4. Case 3: Baffle plate installed

Custom cylinders that have a baffle plate fitted a third of the way up the cylinder (at the 550mm mark). This corresponds to the temperature in the stratified region of 22.5°C. The baffle covers a section of the surface area of the tank. In the above situation, the stream of water does not stop at the top of the cylinder as previously but instead stops at the baffle. This means that only a small amount of water mixes with the section of the tank above the baffle and keeps the mixing to the bottom of the tank. To simplify, it is assumed that no mass transfer of water happens beyond the baffle plate.

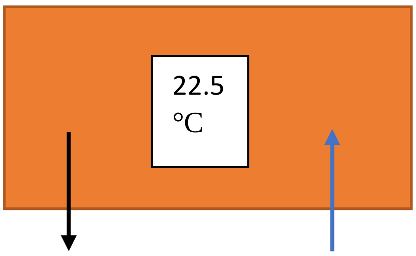
$$Q_{22.5}(kJ) = 3.24kg * 4.18\frac{kJ}{kg°C} * 22.5°C = 304.722kJ$$

$$Q_{entering} = 0.3745kg * 4.18\frac{kJ}{kg°C} * 18.0625°C = 28.28kJ$$

$$Q_{leaving} = (0.3745)kg * 4.18\frac{kJ}{kg°C} * 22.5°C = 35.22kJ$$

$$Q_{22.5\ after\ mixing} = 304.722 + 28.28 - 35.22 = 297.782kJ$$

$$T_{new} = \frac{297.782kJ}{3.24kg * 4.18\frac{kJ}{kg°C}} = 21.98°C$$



Blue Arrow represents energy entering segment (+28.28kJ)

Black arrow represents energy leaving segment. (-35.22kJ)

Not all the displaced water will flow back down to the bottom of the tank in practice. Some will move up the tank into the warmer segments but this will be a much smaller mass of water, hence it will not have as much of a cooling effect and will not reach the same height that the water would without the baffle plate.

The heat loss for the 22.5°C segment is less than the heat loss from the 60°C segment when there was no baffle plate (6.94kJ every second vs. 9.39kJ every second) as there is a smaller temperature difference. In the case of water being drawn off, there will be the added mass loss but that is to be expected. For this reason, this case is not analysed.

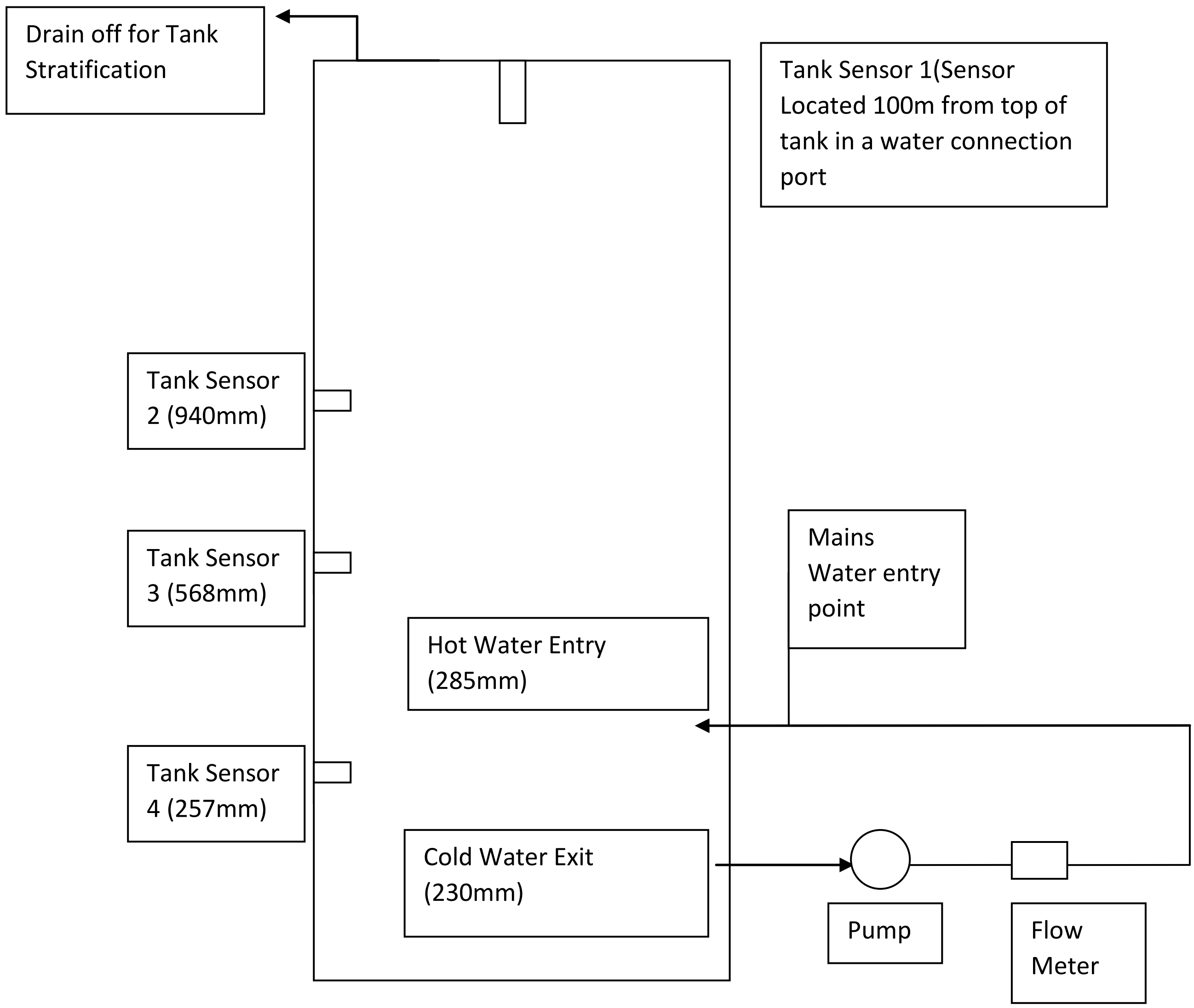
For the bottom segment of the tank, there is no change in the effects as the incoming stream without the baffle plate has the same average temperature. Therefore, the main purpose of the baffle is to reduce mixing to a small segment of the tank and minimise losses in the top two thirds of the tank.

Standard Hot water cylinders and those for solar systems do not have a baffle plate because they do not have the high flow rates that recirculation heat pumps do when operating. This means that there is minimal mixing occurring in the tank.

5. Practical Test Results

5.1 Test Setup

To further illustrate the effects, a test was conducted on a 500L Hot Water Cylinder which did not have a baffle plate installed. The location of the tank sensors and water connections are shown below. Listed measurements are distance from the bottom of the tank. Tank Height was 1692mm. The tank was encased in 50mm insulation. The tank was kept at a pressure of approximately 110 kPa for testing. Tank pressure was read from the tank drain off line at the top of the tank.



Normally the Mains Water Entry point would be between the Cold Water Exit and the pump but the availability of a tee on the supply side near the hot water entry, time constraints and the minimal distance between the ports meant that the mains water was added on the supply side. As there was no heating of the water in the circuit and the circuit left and returned from the same zone in the tank, this was suitable for the tests.

Tank Sensors 3 and 4 were located 200mm within the internal tank. Tank Sensor 2 was located 290mm within the internal tank. All sensors were coated in thermal paste before being placed in the sensor pockets. Tank Sensor 1 was 50mm within the internal tank from the top.

Before heating the tank, the tank sensor temperature readings were noted to account for any error between sensors. They are noted as follows:

Tank Sensor 1	Tank Sensor 2	Tank Sensor 3	Tank Sensor 4
18.3	18.3	17.7	17.7

The data is adjusted to bring Tank sensors 3 and 4 in line with Tank Sensors 1 and 2. From this point onwards, the adjusted values for Tank Sensors 3 and 4 will be shown.

After heating the tank, the following sensor readings were taken.

Tank Sensor 1	Tank Sensor 2	Tank Sensor 3	Tank Sensor 4
56.4	58.2	57.9	57.6

Water was then drained off until the following tank water temperatures were recorded. Mains water was put into the tank via the Hot Water Entry port.

Tank Sensor 1	Tank Sensor 2	Tank Sensor 3	Tank Sensor 4
57.4	57	26.9	22.2

Water was mixed through a circuit via a circulation pump and flow meter as shown in the previous diagram. This saved the requirement of having a heat pump in operation. The flow rate was between 1.6 and 1.875L/s throughout testing.

Due to time constraints, the initial test was 20 minutes directly after heating and stratification. The tests were resumed the next day and run for a duration of 8 hours.

Data was collected through a Data Logger. There was a 10 second interval between data points within the datasets. Due to timeout issues with the data logger, there are gaps between some datasets of an hour. However, there are no sudden changes within the data based on measured values either side of the gaps.

5.2 Test Results

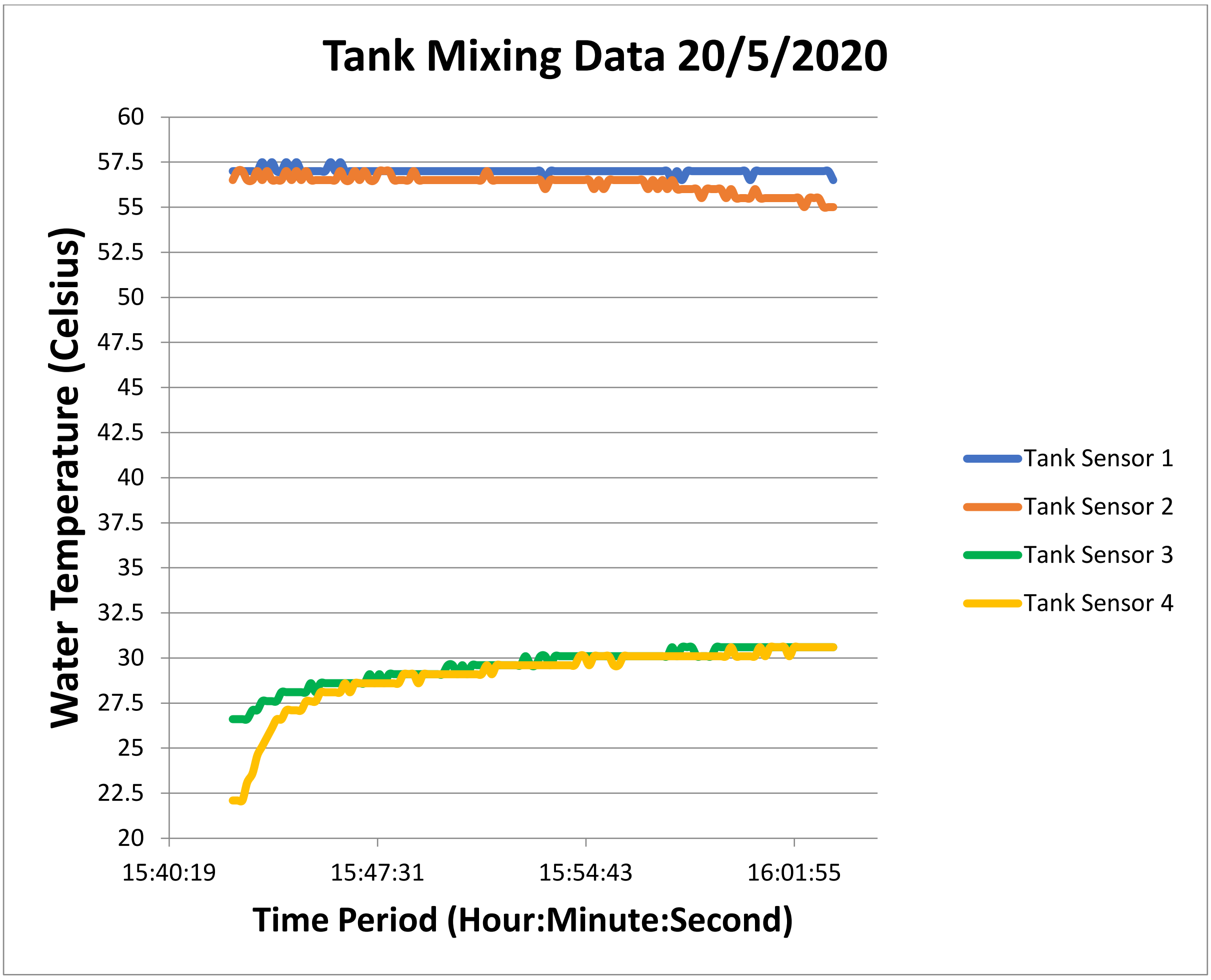


Figure 1: Initial Tank Mixing Data from 20/5/2020

After the tank was stratified, the circulation pump was run for an initial period of 20 minutes. Figure 1 shows the results from this test. The data shows a rapid increase in the temperature at Tank Sensor 4 and a slower increase in temperature for Tank Sensor 3. These two sensors then track together. Within 20 minutes, approximately 62.5L (based on the water below Tank Sensor 4 being at 22.2 degrees Celsius) of water has increased in temperature by 8.4 degrees Celsius due to mixing.

At the top of the cylinder after this period of time, there is little change in Tank Sensor 1. As this is at the top of the tank, this should be expected. Tank Sensor 2 starts to show a decrease in temperature at around 15:55. This was when water was drained off for approximately a minute to note the effects which are minimal at this stage. Had more water been drawn off for longer, the drop off would have been quicker. This drop of in temperature continues for the rest of the test.

Tank Sensor 1	Tank Sensor 2	Tank Sensor 3	Tank Sensor 4
56.5	55	30.6	30.6

The table above shows the temperatures after the first dataset of tank mixing. The pump was kept running after this dataset for another 20 minutes but the data has not been logged.

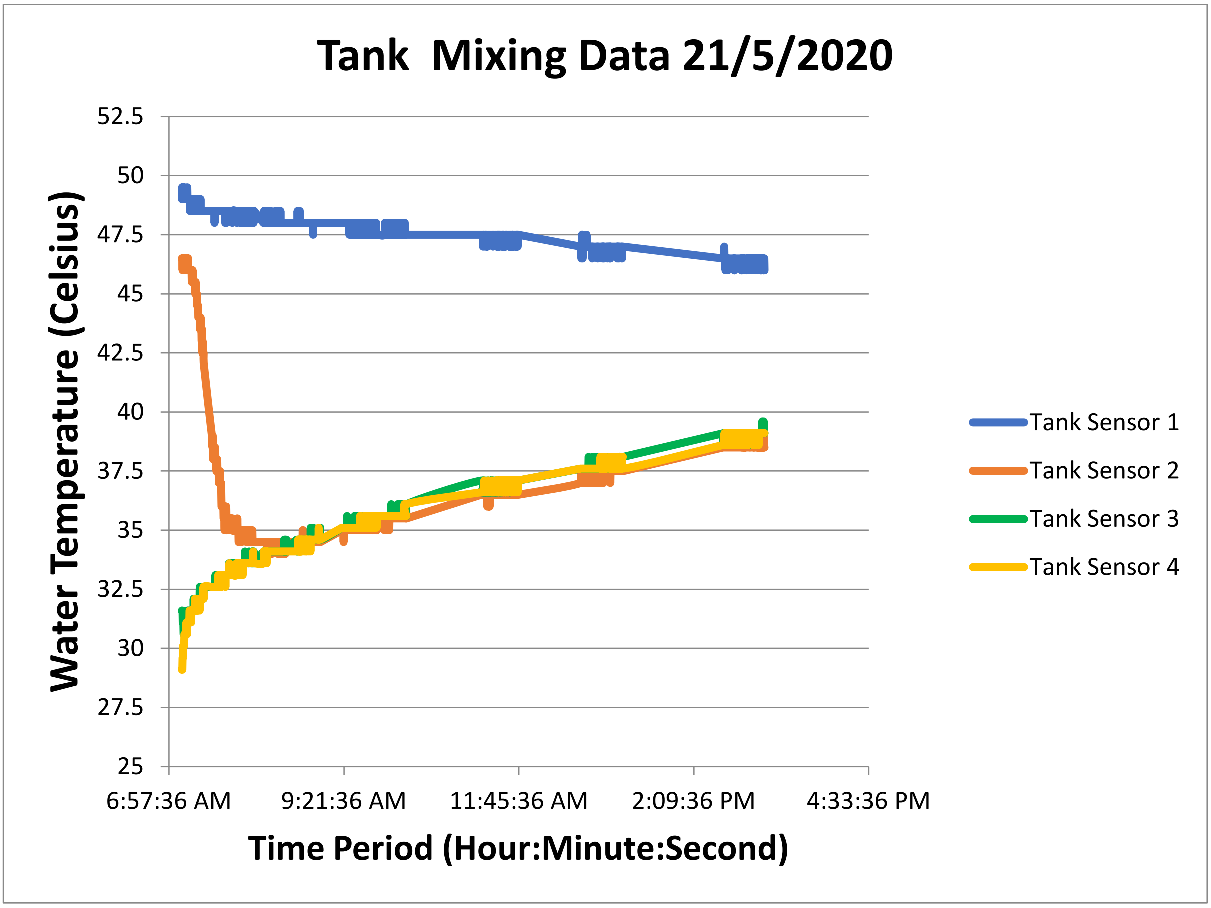


Figure 2: Tank Mixing Data from 21/5/2020 after an overnight period.

Tank Sensor 1	Tank Sensor 2	Tank Sensor 3	Tank Sensor 4
49.0	46.5	31.6	29.1

The second graph shows tank mixing on day 2 with the table showing the starting tank sensor temperatures. The tank has re-stratified overnight and there is a drop in temperature. As mentioned before, there will be some conduction heat transfer and this will likely be the reason that Tank Sensor 4 reads lower than Tank Sensor 3 even though the two sensors had been tracking in the prior graph. When the pump starts running, these sensors track at the same temperature.

Although water was added from the mains during testing to keep the tank pressurised, this had little effect on the results.

Tank Sensor 2 had a significant drop in temperature within the first hour until the tank at this point is at a similar temperature to sensors lower down the tank. This could indicate that this sensor location is now well within the mixing zone of the HWC at the start of the test and so reacts more significantly to the pump flow than in the previous day's test where it may have been within the upper tank zone before there was water drawn off.

Throughout the day, the bottom half of the tank continues to increase in temperature as it mixes with the top half of the tank. After 8 hours, the top of the tank has only reduced in temperature by 3 degrees Celsius. However, the bottom half of the tank has increased in the average temperature from 35.73 to around 39 degrees Celsius, meaning a temperature increase of 0.41 degrees per hour.

Tank Sensor 1	Tank Sensor 2	Tank Sensor 3	Tank Sensor 4
46.0	38.5	39.1	39.1

A quick energy calculation will show that there has been heat transfer as a result of tank mixing. This is a rough estimate due to no sensors being placed in the upper third of the tank between Tank Sensors 1 and 2. Due to the use of an existing tank for the test, adding sensor pockets would be ineffective as they would only reach the internal tank surface and not be as effective as sensors that penetrated the internal tank.

$$\triangleq Q_{heat\ lower\ tank} = 280kg * \frac{4.18kJ}{kg.K} * (39 - 35.73)^{\circ}C = 3827.208kJ$$

$$\triangleq Q_{heat\ upper\ tank} = 3827.208kJ$$

$$49^{\circ}C - (\triangleq Q_{heat\ upper\ tank}/(220kg * \frac{4.18kJ}{kg.K})) = 44.83^{\circ}C$$

The result shows that the top half of the tank would be at 44.83 °C average temperature which is lower than the reading on Tank Sensor 1.

With the same flow rate, the mixing effect would happen quicker on smaller tanks such as the EC300L in the theoretical study in Cases 1 and 2. This is because the incoming water would have a greater effect.

This temperature drop would not be as significant with a baffle plate installed as mixing would be minimised at the locations of Tank Sensors 1,2 and 3.

6. Importance of stratification

Without use of the baffle plate, any hot water within the tank is mixed with cooler water at the bottom of the tank. For domestic use, cooling the water at the top of the tank has an immediate effect on the temperature of the hot water leaving the tap. Mixing valves rely on different mass flow rates between the hot and cold-water streams to bring the water down to a set temperature. These will be set based on the temperature of the hot water leaving the cylinder. Should the temperature be less, the mixing valve will need to be adjusted to account for the lower hot water temperature or else the hot water temperature at the tap will be lower than required.

For operation of the heat pump, maximum efficiency occurs when the water entering the heat pump is at the coldest possible temperature. This is because of its effect on the Log Mean Temperature Difference (LMTD) which is a factor in heat output.

$$\dot{Q} = U * A * LMTD$$

$$LMTD = \frac{\triangleq T_1 - \triangleq T_2}{\ln\left(\frac{\triangleq T_1}{\triangleq T_2}\right)}$$

$$\triangleq T_1 = T_{refrigerant\ in} - T_{water\ out}$$

$$\triangleq T_2 = T_{refrigerant\ out} - T_{water\ in}$$

The condenser operates on a counter flow arrangement. This means that the flow of refrigerant is opposite to the flow of the water. Temperature Difference 1 is based on the incoming refrigerant temperature minus the outgoing water temperature while Temperature Difference 2 is based on the outgoing refrigerant temperature minus the incoming water temperature. When the refrigerant is condensing, the incoming and outgoing refrigerant temperature is the same. Any increase in incoming water temperature without a change in the refrigerant parameters results in a lower LMTD as there is a lower temperature difference. Though it does increase the value on the numerator in the LMTD equation, the denominator has a larger increase.

$$\triangleq T_2 \downarrow = T_{refrigerant\ out} - \uparrow T_{water\ in}$$

$$LMTD \downarrow = \frac{(\triangleq T_1 - \triangleq T_2) \uparrow}{\ln\left(\frac{\triangleq T_1}{\triangleq T_{2\downarrow}}\right) \uparrow\uparrow}$$

If the incoming water temperature increases from 15°C to 17°C, to maintain the same LMTD and heat output, the condensing temperature will have to increase by two degrees. This will mean the condensing pressure will have to increase. This requires more work from the compressor as the evaporator is limited by the ambient conditions in how much heat it can absorb. This leads to an increase in input power and a reduction in COP.

$$\frac{\dot{Q}}{P \uparrow} = COP \downarrow$$

7. Conclusions

The effect on stratification due to tank mixing is shown to reduce the amount of 60℃ water available to the user, more evident when there is draw off from the tank while the heat pump is running. It is also shown that tank mixing has a negative effect on the performance of the heat pump. Test results on a larger tank show the same end results, the only difference being the time taken for the tank to fully mix.

Finally, it can be proven that installing a baffle plate on the bottom third of the tank has a positive effect on maintaining stratification within most of the tank while maintaining cold water to supply to the heat pump. This explains the necessity for custom cylinders in the application of multi-pass heat pump water heaters.