Thermosyphon Heated Thermal Store, the Influences of Valve Opening on flow, an Experimental Analysis

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ABSTRACT

This paper outlines initial findings from the design of a Thermal Energy Storage (TES) system whose principal objective is to promote stratification when charged by an intermittent electrical supply. This concept will offer an efficient solution to the heating and provision of domestic hot water within buildings when coupled with a renewable energy source such as wind power.

The principal of operation is to add the energy to the tank through a side arm that creates a thermosyphon and returns the water to the top of the tank at a desired temperature. A system of extraction points will then be employed to prioritise the replenishment of individual tank nodes from top to bottom, thus increasing the useful energy content of the system.

In this paper initial investigations on the control mechanism required to achieve the desired mass flow rate have been carried out experimentally on a 750*litre* tank. The tank was charged under steady input power with different valve opening angles, the results from which show the formation of temperature gradients through the tank's vertical plane.

It is found that the importance of the valve opening lies mainly in permitting large changes in the power inputs to the store. It also allows for small and large temperature rises to be achieved across the side arm, thus enabling nodes to be "topped-up". The requirements to compensate for the changes in driving force are found to be less critical than first anticipated.

Keywords: Intermittent electrical supply, stratification, thermosyphon, charge-cycle.

1. INTRODUCTION

Thermal energy storage (TES) systems have been used in many situations as a buffer between the energy supply system and a building's demand for domestic hot water and space heating, thus allowing smaller power sources to be used to provide the end user with high intermittent bursts of power. In the last few decades, many studies have been carried out on the benefits and the means to achieve stratification within a TES. Stratification is the phenomenon where hot water accumulates in a layer on top of cooler, denser water. As well as benefitting the efficiency of some energy supply equipment by providing cooler return temperatures, this process can be used to increase the usable energy in the system. Most forms of renewable energy, such as solar and wind, are well known for their intermittent patterns which directly impact on the power available from the energy converter.

The use of solar energy for domestic hot water (DHW) and space heating provision is a well understood process where, as mentioned above, stratification plays an important role in increasing the efficiency of the solar collector as well as compensating for the diurnal patterns in energy availability, Hollands (1989).

In most studies, however, the electrical energy is usually considered to be a “back up”, with few restrictions on its quantitative and/or temporal availability. In this research the electrical supply is treated as a principal energy supply but has an intermittent regime in terms of its available power. Thus a system that has the ability to maximize the storage potential of this energy when it is available is desired.

The main principal of operation being tested consists of adding the energy though a side arm as demonstrated in figure 1. This method, referred to as a thermosyphon, was believed to be the easiest way to bring the energy into the tank with minimal infrastructure and disturbance. Furbo (2005) found in side-by-side testing that this mechanism could lead to a large increase in solar collector performance as well as reduced auxiliary energy requirements over conventional systems. In his control mechanism, the upper layers of the tank were supplied with the correct amount of energy at the correct times, bringing the desired volume of water needed by the load to the set point temperature. The system investigated by the authors, in addition to the side arm, would have a number of extraction points that prioritise the areas of the tank needing energy.

The aim of this paper is to evaluate, through theoretical and experimental analyses, the control required in charging a tank using a side arm in the instances where variable temperatures as well as power inputs are encountered.

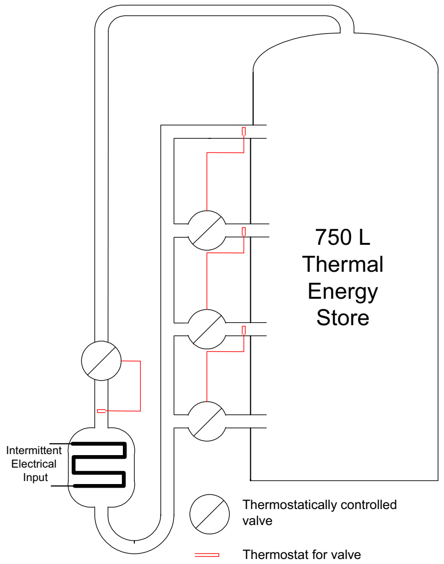

Figure 1: Layout of the TES including control valves (not to scale)

2. THEORETICAL INVESTIGATION

The operation of the system is governed by two fundamental equations. The first determines the desired mass flow rate ($\dot{m}$), Eq. (1), for a given set of operating conditions and at any one point in time.

$$\dot{m} = \frac{\dot{Q}}{cp.\Delta T} \tag{1}$$

Where $\dot{Q}$ is the electrical power input to the heat box and $\Delta T = T_{set} - T_{out}$. T_{set} is the desired set point temperature for the water re-entering the tank after having been heated by the heat box and T_{out} is the temperature of the water flowing out of the tank towards the heat box. cp is the specific heat capacity of the water.

The second equation looks at the driving force in the system. This force is dependent on temperature and must therefore be summed, for all layers on the vertical axis within the tank that have different temperature, as found by Eq. (2);

$$P = \sum \Delta\rho.h.g \tag{2}$$

Were $\Delta\rho$ is the density difference between the horizontal layers on the vertical axis of the side arm and its equivalent layer on the tank. h is the height of the layer and g is gravity. The derived units are *Pa*.

To maintain the desired set point temperature, the friction loss around the loop encountered by the water travelling at flow $\dot{m}$ must equal that of the driving force created by the density difference between the tank and side arm.

As the system must be able to cope with a wide range of input powers, leading to large variations in $\dot{m}$, it is not possible to depend solely on the friction found in the pipes and bends. A valve or throttling device must therefore be employed to provide the correct friction at any one point in time, thus maintaining the set point temperature at the outlet of the heat box.

The valve selection was made according to manufacturer's datasheets. Valves are characterized by the friction factor, *kv*, which corresponds to the volume of water that passes through the valve when a pressure drop of 1 *bar* occurs across it. A percentage of the "kv-factor" is then given for various valve opening angles. Due to the very low flow rates and pressure drops encountered in this system, the data was extrapolated to obtain the desired openings under different states of charge. Initial experimentation revealed that this data, once extrapolated and added to the friction losses in the pipes, heat box and tank, was too inaccurate to provide satisfactory levels of control as too many errors in the assumption made accumulated though the calculations. An experimental approach was therefore adopted to evaluate the performance.

3. EXPERIMENTAL INVESTIGATION

Experimental Rig

The experimental rig is made up of a 750*litre* tank made of stainless steel with a wall thickness of 2*mm*. The domes are of a heavier gauge (6*mm*). This was necessary in order to provide the required strength at the bottom for support. The dimensions of this vessel are given in Figure 2. The pipe-work connecting the tank to the heat box has an internal diameter of 37*mm* and is made of polypropylene in order to withstand the heat. All connections on this pipe work are listed in Table 1, along with the valve and heating element details. The heat box was constructed of *2mm* stainless steel and of dimensions shown in figure 2.

Power input was changed by lowering the input voltage to the heating element using a transformer; due to the voltage fluctuations on the grid, the power was found to be variable. From the measurement the fluctuations were *+3%* and *–3%* of the mean measured power for the experimental run. The accuracy of the voltage and current transducers was found to be quite poor only once the experiments were over. Calibration exercises were undertaken and corrections to the recorded data were made accordingly.

The tank was divided into forty controlled volumes. The volumes are made up of ten horizontal layers, each dived into equal quarters. The thermocouples were held in place at the correct height by using four glass fibre tubes as shown in Figure 2. When assembled, the tips of the thermocouple were within a maximum of 5mm from their desired location on the vertical axis. The thermocouples and data logging equipment were calibrated prior to assembly and found to be within 1 degree of a calibrated thermometer.

The tank was insulated using glass wool with a minimum thickness of *100mm*. The pipes and heat box were not insulated.

2.1 Experimental procedures

The tank was allowed to settle for 40 minutes after being mixed using a pump to achieve a uniform temperature throughout. In some experiments, however, some residual heat from the heat box, that had not been mixed, created a top layer a couple of degrees higher than the rest of the tank. The data was gathered at a rate of 1 sample every 5 seconds for temperature, RMS voltage and current.

2.2 Results

Experimental runs were carried out with five valve openings and two distinctive power inputs; all of which were held constant for the duration of the experiment. Plots of temperature over time were created using the measurements. Figures 3, 4 and 5 show the results from valve openings of 15%, 20% and 50%. The input power to these runs was approximately 4.7 kW; further detail of the power input is listed in the caption. The following graphs, Fig, 6, 7 and 8 show the results from three individual three-hour runs. These performed with a combination of two valve openings and two input powers.

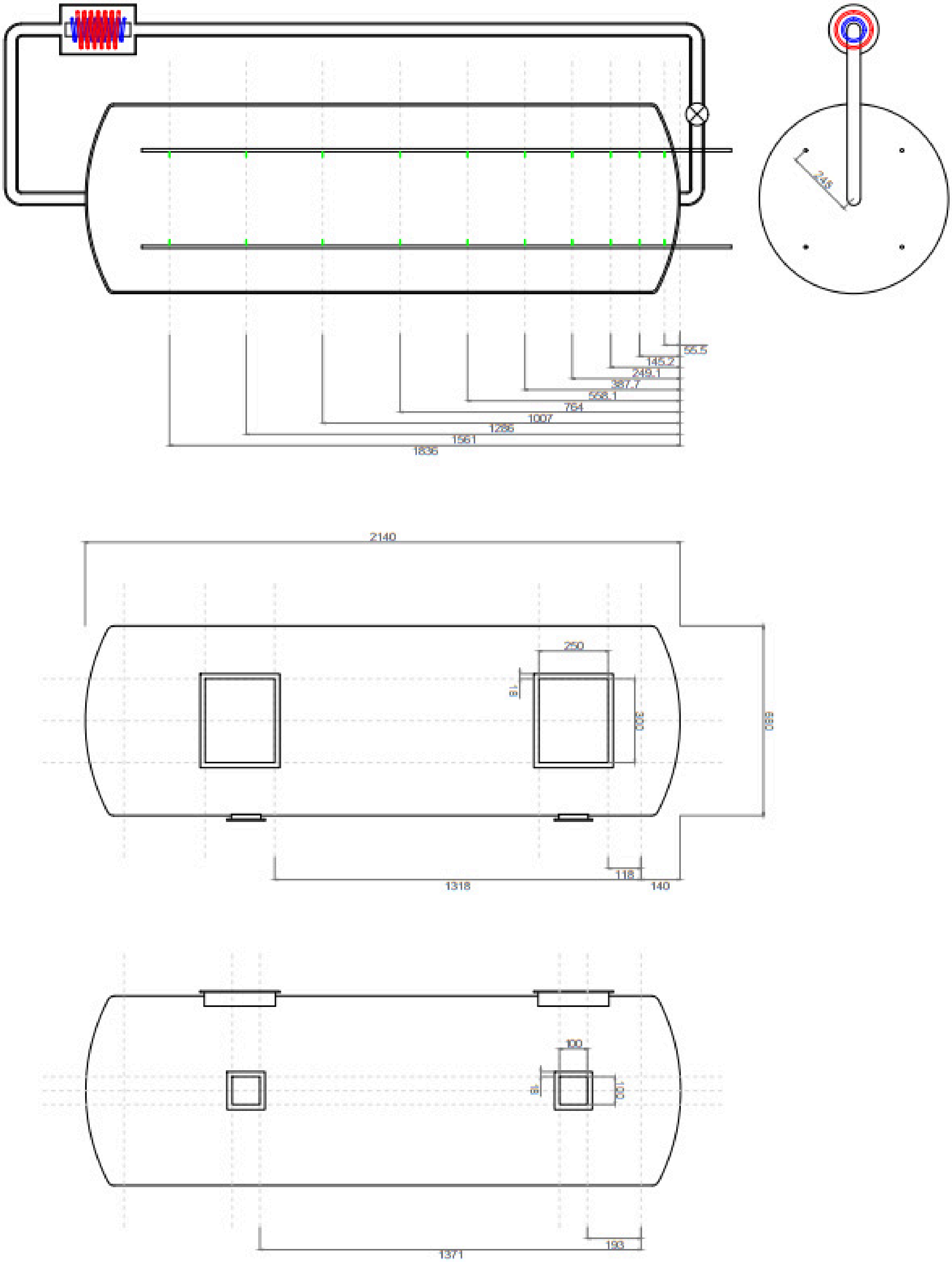

Figure 2: Experimental rig, general layout and dimensions.

Ball Valve	DN 40, PN 20
Ball Valve Actuator	Nenutec NABM 1.1-10
Pipes	37mm ID, 47mm OD, POLYPROPENE
Fittings	1 ½” BSP threaded • 2 × Straight couplings • 2 × 90° bends (top), • 2 × tees with blanks (bottom bends).
Insulation	Glass Wool, 100 mm thickness
Heating element	2 × 2440mm, 8mm OD, coiled to specified diameter. 13500 W/m^2 at 3.5 kW input

Table 1: Experimental specification.

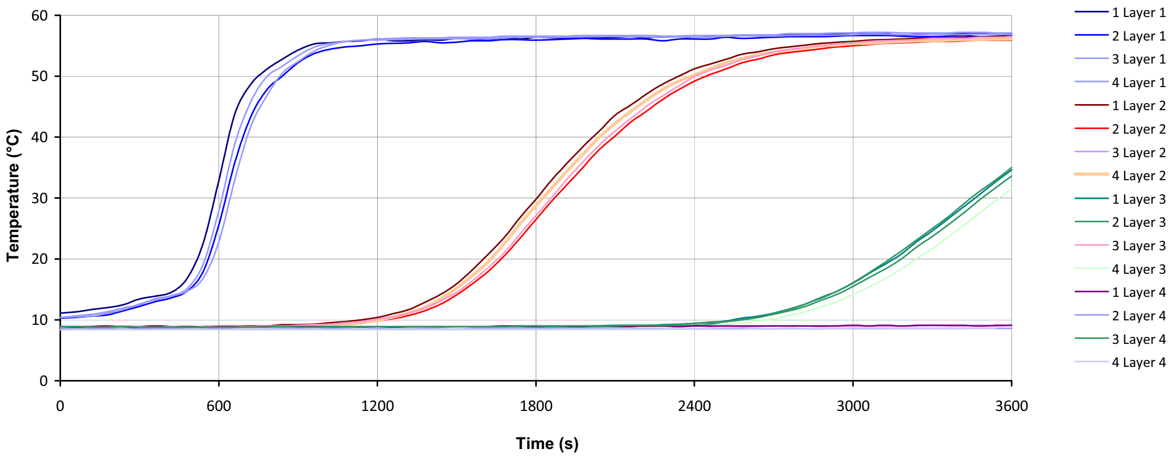

Figure 3: 4.9 kW mean electrical input, 15% valve opening.

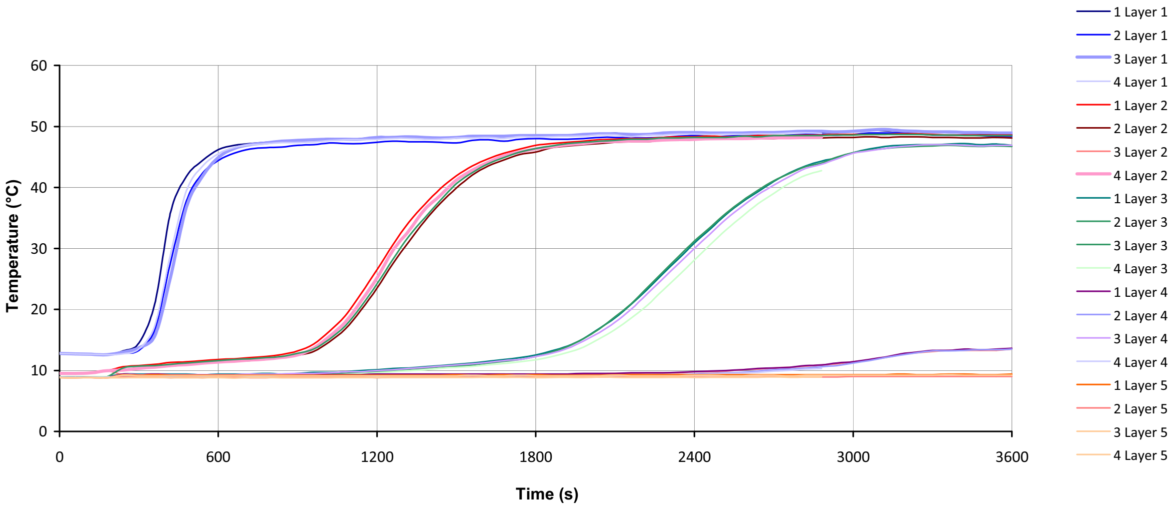

Figure 4: 4.75 kW mean electrical input, 20% valve opening.

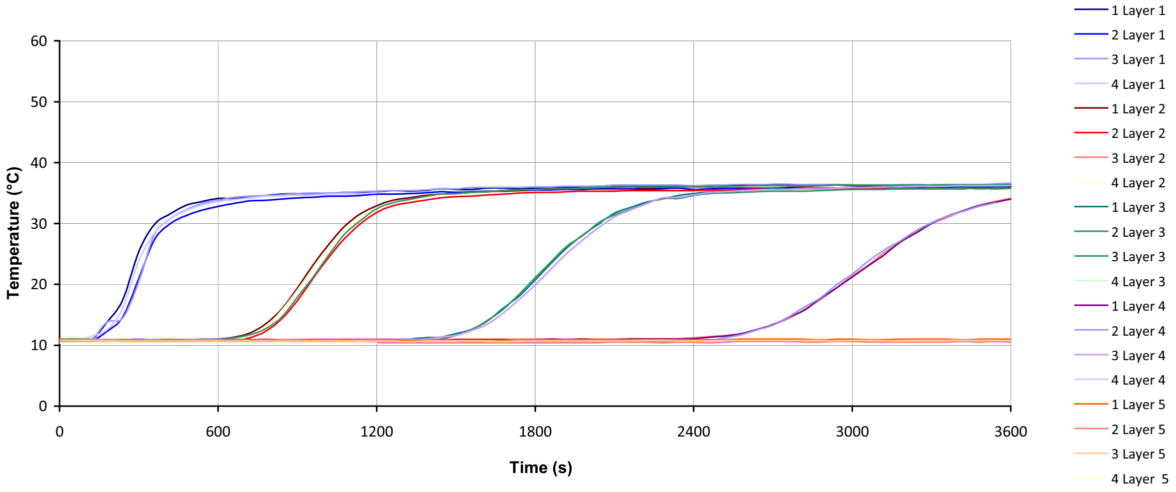

Figure 5: 4.88 kW mean electrical input, 50% valve opening.

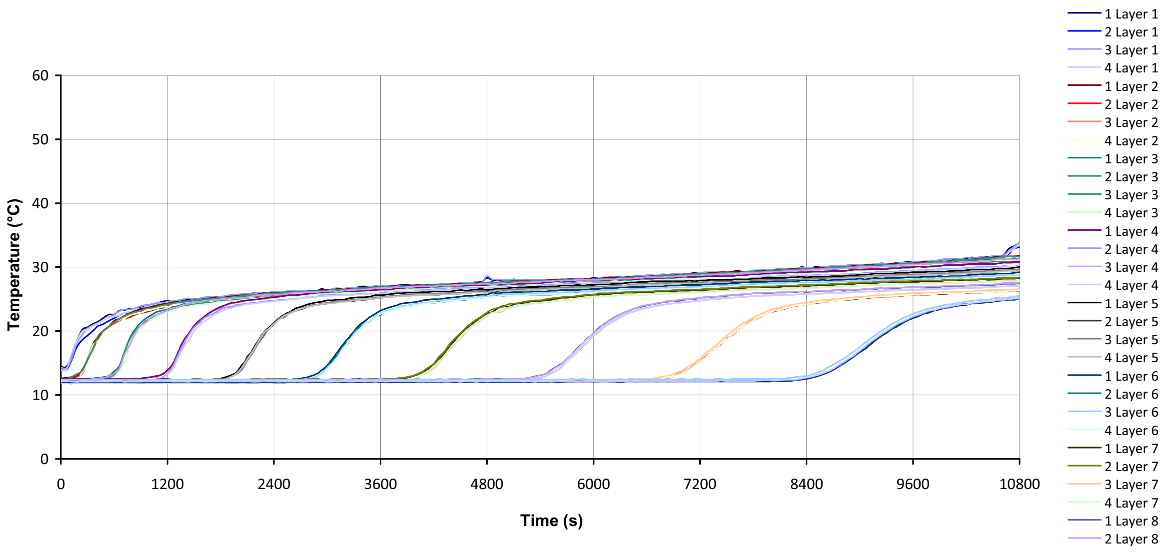

Figure 6: 4.8 kW mean electrical input, 100% valve opening.

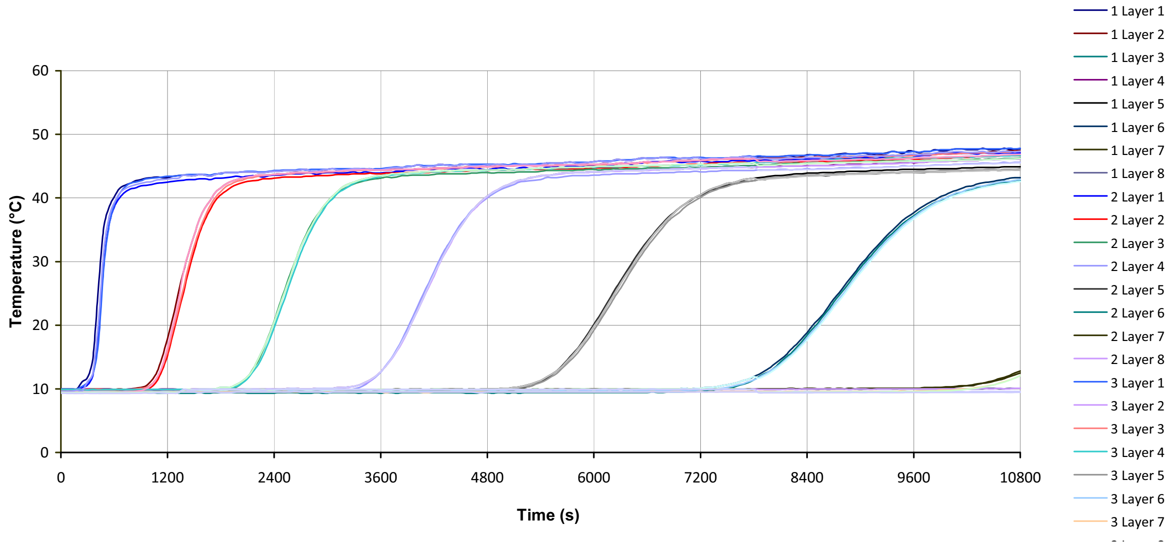

Figure 7: 4.88 kW mean electrical input, 25% valve opening.

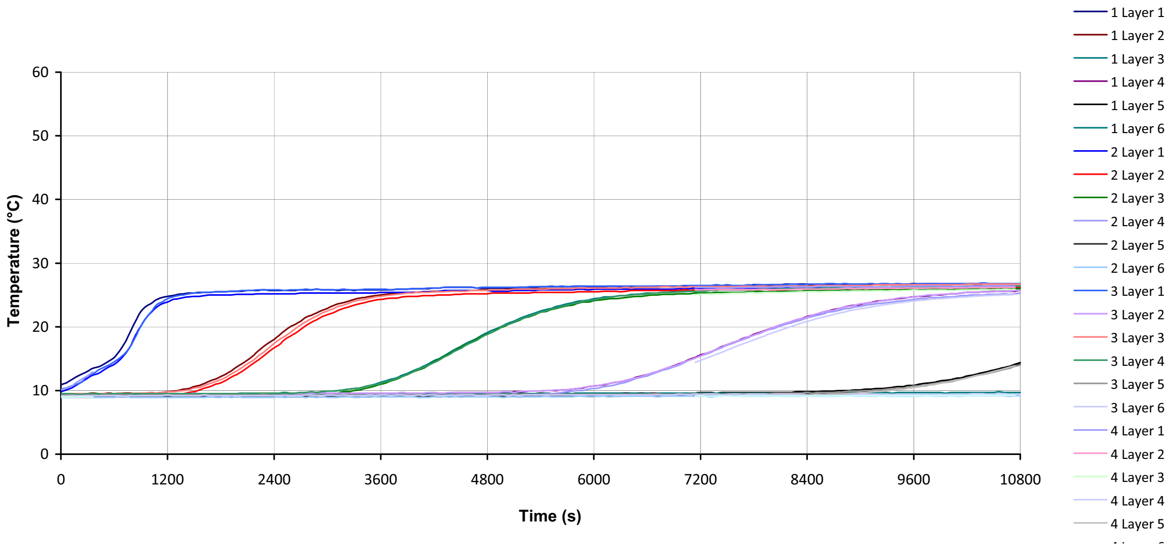

Figure 8: 1.31 kW mean electrical input, 25% valve opening.

4. ANALYSIS and DISCUSSION

The results show that the valve opening has a large influence on the temperature rise across the side arm. A plot of temperature over time, Fig 9, was carried out using the data from Node 1.1 of each of the experiments with high input power. It can be seen that the time taken for the node to get up to a steady temperature is increased for smaller valve openings. The 25% opening, is the exception in this plot, due to a slightly lower $\dot{Q}$ than in the rest of the plots. The temperature at time *1200 seconds* was plotted for the various valve openings in Fig. 10 to reveals the valve operating characteristics

The increased temperature of the water entering the tank, due to the driving force decreasing as the charge progresses, is visible but may not be as large as one could expect. One reason for this is that the experimental length is too short to reflect this clearly, especially in the situations were the valve has a small opening angles, Fig 3, 4 and 7, due to very low $\dot{m}$ and therefore a small section of the tank being heated.

The driving force, eq. (2), was computed for each recording, allowing a plot of pressure vs. ΔT to be made, please refer to Fig 11, 12 and 13. This plot was constructed using the following method. The temperature recordings were used to represent the whole of the controlled volume they are in, therefore no thermo-clines within any particular node were shown. The temperature of the side arm was taken as the temperature of the top node. The graphs produced break down the charge cycle in to a series of events. In all situations the pressure increases with the temperature difference until a steady state is reached, after which, the decreasing driving force leads to a higher temperature entering the top of the tank. In Fig 11, due to the fully open valve the tank fully replenished itself in the *10800 seconds.* Between the period of *8200 to 9780 seconds,* ΔT and P drop before starting a new stabilization cycle at time *9780 seconds*. This drop in ΔT and P is unlikely to be as pronounced in real life as it appears on the graph. This due to the time lag associated with using the upper and lower node temperatures to compute the driving force and the temperature of the side arm.

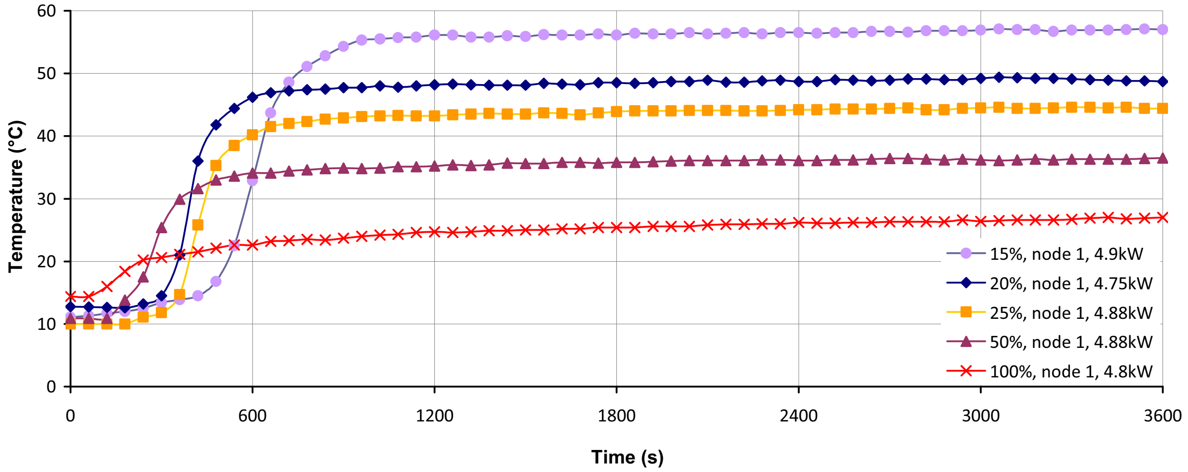

Figure 9: Temperature profile for nodes 1 layer 1

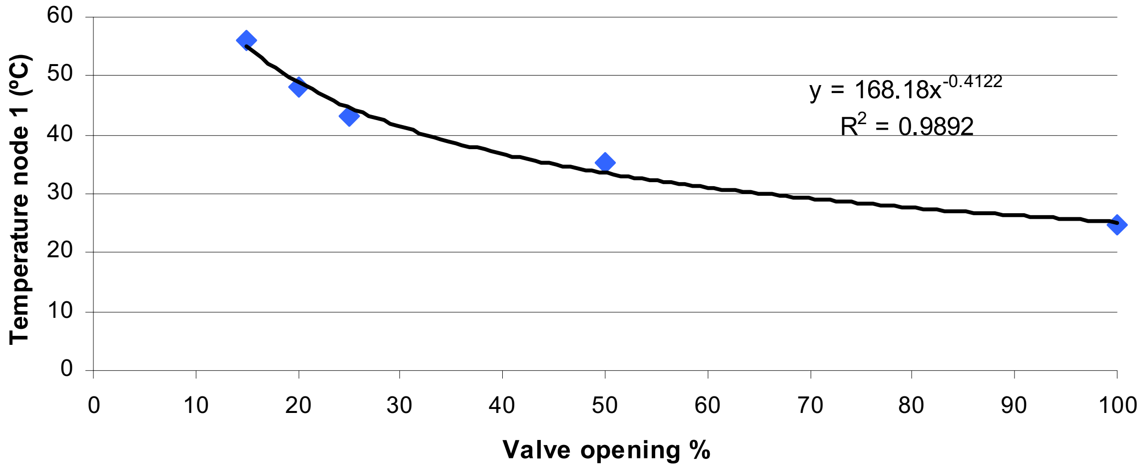

Figure 10: Temperature rise through valve at time 1200 seconds

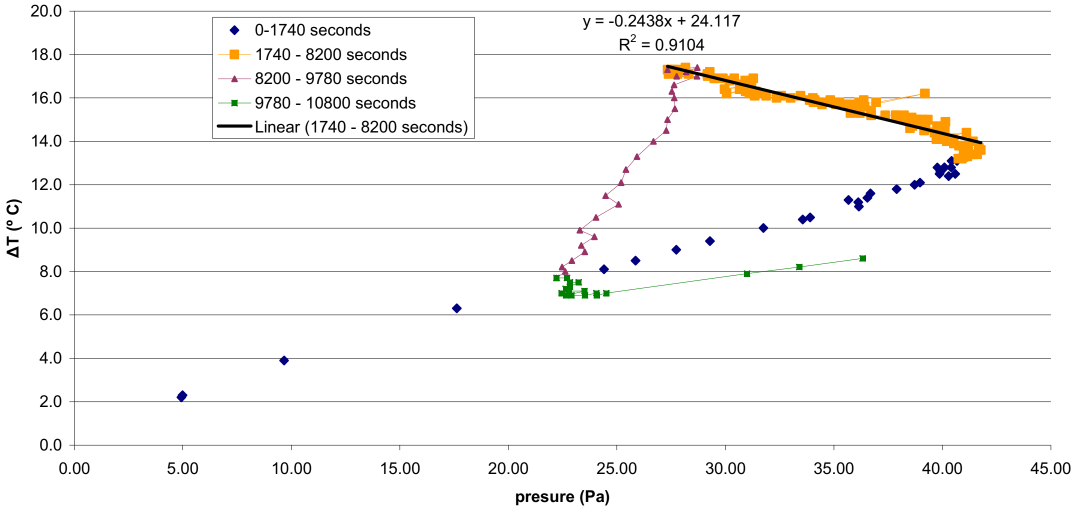

Figure 11: Pressure vs. temperature rise. 4.8 kW, 100% valve opening.

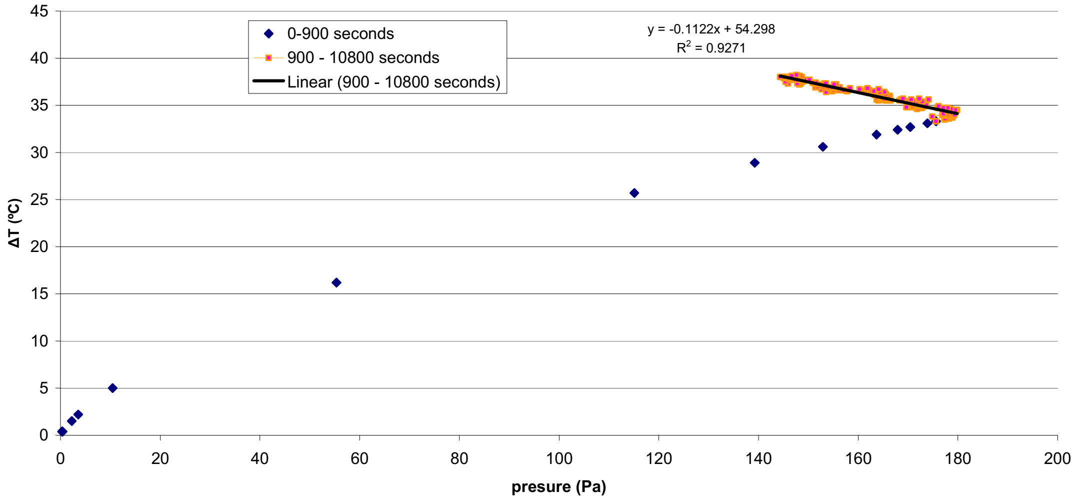

Figure 12: Pressure vs. temperature rise. 4.88 kW, 25% valve opening.

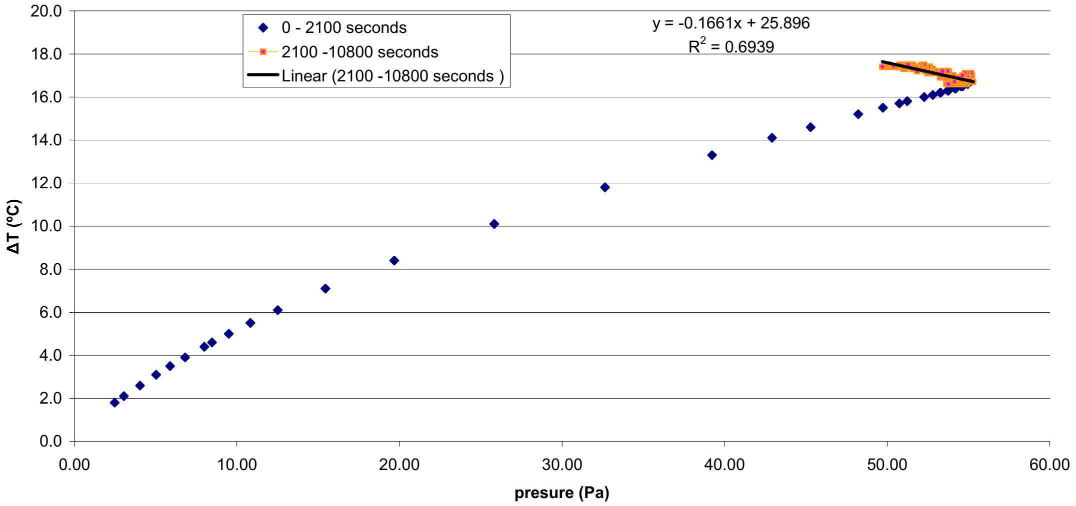

Figure 13: Plot of pressure vs. temperature rise. 1.31 kW, 25% valve opening.

5. CONCLUSIONS

Due to the time lag between the water exiting the side arm and reaching the top thermocouples, it, is difficult to compute accurately the exact temperature in the side arm. It is recommended that a few measurements be made along the length of the riser to facilitate computation as well as providing real data for its operation.

The domes weigh *18 kg* each and have an estimated specific heat capacity of *90 kJ/kg.k* each. This, combined with the thermal mass of the tank walls, can be seen to have an impact on the thermo-cline created within the tank. The first layers to enter the tank are cooled rapidly as they descend. Quantifying this in a plug flow model would help with the estimation of the effectiveness of the system to promote stratification.

Changes in viscosity will influence the flow rate too, as the water heats up the friction encountered at a given mass flow rate will decrease. Experiments with higher initial temperature should be carried out to quantify this.

The results show clearly that the valve adds enough control to permit "topping up" of individual nodes were ΔT of 10 or 20 C are required as well as allowing very small $\dot{m}$ to be controlled when the driving force is at its highest.

Work in the immediate future will try and extract a function that depicts the desired valve opening for a set of operating conditions. The level of stratification achieved will also be quantified.

ACKNOWLEDGEMENTS

This research was carried out with support from the UHI Strategic Development Body, the European Regional Development Fund, Highlands and Islands Enterprise and Comhairle nan Eilean Siar.

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