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Tuesday, 05 August 2025

Re: UEA KE+ ShowerPowerBooster Ltd "Analysis and verification of the efficacy of a novel low-cost thermal energy storage system" - FINAL REPORT

Dear Alan,

Find below the material related to the above-mentioned Subject.

For any additional information, please do not hesitate to contact me.

Yours sincerely,

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Admissions Director (Engineering)
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Project Background

1 Overview

To practically achieve full decarbonisation in the energy transition, there is a need for affordable energy storage solutions to balance demand with supply from intermittent renewable energy sources and so replace fossil fuels. One accessible method of energy storage is to store surplus supply as heat, which can then be used in domestic or municipal heating and hot water applications. It has recently been recognised that hot water cylinders are a core feature of many existing decarbonisation strategies and can be used for thermal energy storage [*No Place Like Home: Cylinder Batteries – Tapping into the Potential of Hot Water Storage*, Hot Water Association (2022). Available at [6177D216E375E.pdf](6177D216E375E.pdf)].

ShowerPowerBooster Ltd have patented a technology (
Figure 1) to use existing hot water systems for thermal energy storage with minimal modification. This allows replacement of 100% of the heat load from gas with 100% renewable energy. This can be applied in individual homes, hotels, public buildings, and factories, with a particular focus on replacing gas boilers or improving the efficiency of Heat Pumps (HP). The principal advantages of this technology is the rapid and low-cost upgrade of any existing heating system, without needing to replace the hot water system.

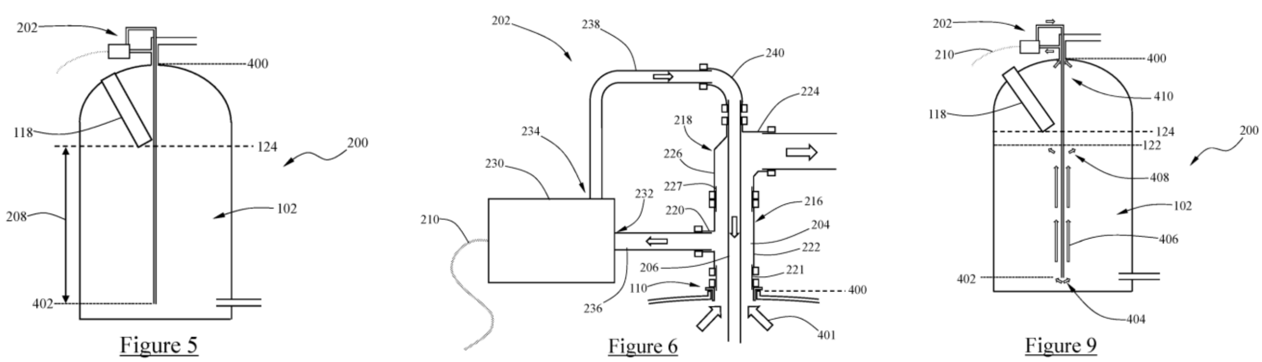


Figure 1: Extracted figures from Patent GB2623198

ShowerPowerBooster Ltd is currently selling a commercialised product, however, two hurdles are blocking both capital investment from stakeholders and unlocking further innovation funds: (1) Independent validation of the technology, (2) optimisation of the design and operation parameters. To address both, academic expertise is required from UEA EMP engineers (SL, JP, DB) to develop computational fluid dynamics (CFD) simulations of the device in operation in a domestic setting. These simulations will be used to:

- Elucidate the efficacy of device operation and address the current uncertainty about how thermal stratification (thermocline) can be maintained in the hot water cylinder while also acting as a heat store.
- Understand the range of valid operational parameters (with a view to optimising these parameters), to minimise the need for auxiliary fossil-fuelled boilers.

Successful development via this KE+ project will realise the following benefits:

<u>Market Application</u>
This technology addresses the pressing need for residential heat storage solutions that work across the full spectrum of UK households. It is equally effective for properties with combi boilers (80% of the market) and those with conventional heating systems, offering a clear path to mass-market deployment. The system enables complete flexibility in heating load management, supporting the transition to a renewable-powered grid while reducing energy costs for consumers.

Benefits To Customers

Storage of low-cost off-peak energy or surplus renewable energy at the flick of a switch.
Replacing up to 100% of gas use in a home without replacing the water tank.
Shift reliance on fossil fuels to surplus renewable electricity at a lower cost compared to heat pumps.

Benefits To The UK Government

Achieving grid balance without building more gas power stations or major upgrades to the UK National Grid but simply repurposing existing water tanks.

Enabling Mass-Market Thermal Storage for Grid Flexibility

This is a fundamental advance in thermal storage efficiency that addresses a critical challenge in grid decarbonisation. By enabling practical, cost-effective residential heat storage at scale, this technology opens new possibilities for grid balancing and renewable energy integration, creating a clear pathway to widespread adoption.

Technical Innovation

At the core of this opportunity is a patented approach to thermal stratification control. The technology maintains separation between stored and incoming water, significantly improving storage efficiency and enabling practical deployment at scale.

2 Business-Academic Partnership

ShowerPowerBooster Ltd has recognised the critical need for a robust business-academic partnership to drive innovation and ensure the successful implementation of their product. This collaboration is essential to leverage the specific skills, expertise, knowledge, and capabilities found at UEA EMP Engineering department to achieve the techno-economic competitiveness for ShowerPowerBooster thermal energy storage innovation. To fully realise value from the innovation, ShowerPowerBooster requires specific skills in computational fluid dynamics, numerical fluid dynamics modelling and optimisation. This expertise is crucial to evaluate the feasibility of the innovative solution.

The device's operational efficiency is critically dependent on the precise modulation of the pump flow rates. Insufficient flow rates may cause the immersion heater thermostat to disengage the heater, while excessively high flow rates risk compromising the tank's thermal stratification (i.e. disruption of the thermocline). Although preliminary theoretical analyses suggest predictable tank behaviour, comprehensive hydraulic modelling is essential to accurately characterise the heating dynamics. This modelling effort is also necessary to rigorously address and refute the unfounded assertions made by certain critics and their allegedly independent experts regarding the device's capacity to maintain stratification.

The expertise in numerical and experimental fluid dynamics and heat transfer available at UEA Engineering Thermofluids Lab (SL, JP) is essential to validate the performance and reliability of the proposed innovation, ensuring they meet the demanding and diverse requirements. Additionally, energy system modelling supported by experimental data is crucial for optimising the future integration of ShowerPowerBooster tech into different energy systems (with or without heat pumps), maximising renewable energy surplus exploitation, overall demand/supply matching, and system efficiency. All these skills, expertise, knowledge, and capability will be provided by SL/JP and the KE Associates (DB).

Funding plays a pivotal role in accelerating and enabling ShowerPowerBooster goals. The UEA KE+ 2025 R2 funds will facilitate access to state-of-the-art numerical and experimental facilities, and specialised academic professionals. The financial support will speed up the innovative device optimisation and independent proof of concept, allowing a comprehensive numerical analysis and techno-economic feasibility, ultimately expediting the access to further government funding and consequent access to market. Furthermore, the academic PI (SL) and Co-I (JP) bring a wealth of knowledge in understanding energy systems, contributing to the optimisation of ShowerPowerBooster solution to further cost-effectiveness.

Considering a long-term post-project vision, we have carefully investigated options to sustain the collaboration forward. The UEA KE+ 2025 R2 project is a short-term first stage feasibility study to facilitate further collaboration including:

i. *Medium-term*: development of a medium-scale state-of-the-art demonstrator (at UEA hosted in ThermoFluids lab or Productivity East) to scale up ShowerPowerBooster enhanced technology from KE+ outcomes and prove the concept.
ii. *Long-term*: application for a follow-on InnovateUK KTP and/or InnovateUK Energy Catalyst Early Stage (Round 11) funding to enable a project to scale up further to residential or industry scale.

The successful acquisition of funding is therefore pivotal in securing the foundation for sustained collaboration between UEA EMP Engineering and ShowerPowerBooster. The funding will not only drive the current project forward but will also create a route for future initiatives. The vision is to guarantee ShowerPowerBooster ongoing access to academic resources, state-of-the-art facilities, and expertise, fostering a collaborative environment for additional innovation. Moreover, the project will create venues for alternative collaboration including student internships, BEng/MEng students' projects, and collaborative workshops with UEA EMP Engineering academics and Productivity East (PE), further solidifying the partnership.

In conclusion, the complementary skills, expertise, and resources from both sides create a synergy that not only accelerates the current initiative but also lays the groundwork for sustained collaboration.

3 Project Outcomes

Outcome 1: Technical feasibility and operating parameters

A demonstration of the efficacy of the device, including a detailed analysis of the fluid flow and thermal energy transport within a typical domestic hot water cylinder. Advancing on this, a range of operating parameters in which the device remains effective will be identified.

Outcome 2: Peer-reviewed publication

To support further development of the technology, a peer-reviewed publication will be produced to establish an independent verification and proof of concept.

Impact

The UK Hot Water Association (HWA) recognise that domestic hot water cylinders are a vital component of zero and low-carbon heating solutions [*No Place Like Home: Cylinder Batteries – Tapping into the Potential of Hot Water Storage*, Hot Water Association (2022). Available at 6177D216E375E.pdf]. However, many emerging innovations using the hot water cylinder as a smart thermal storage device require replacement and refitting of current systems (costing approximately £1,400 each). The ShowerPowerBooster device aims to enable existing hot water cylinders to be used as thermal storage devices, without replacement of the cylinder, requiring instead a novel device to be inserted into the pre-existing system at minimal expenditure.

If the innovation development is successful, this represents a rapid-to-implement and low-cost solution to domestic thermal energy storage, implementable in some 9 million existing hot water cylinders used domestically. This represents a commercial benefit to ShowerPowerBooster Ltd. It has been estimated that the company will achieve around 1% of the potential 9 million customers a year, i.e. 90,000 customers. Th estimated profit is based on £100 each unit shared 50/50 with a manufacturer, leading to £50 x 90,000 = £4.5 million figure. This figure is assuming ShowerPowerBooster do not sell in EU.

The key environmental benefit of this technology is a facile route to decarbonisation of hot water heating (contributes towards UK 2050 targets). At a local scale, this is through enabling excess energy storage from renewable sources as thermal energy. At a national scale, this technology aids in grid balancing activities. Principal social benefits are that the technology enables a broad range of customers to participate in decarbonisation activities, due to the low cost and ease of implementation in existing hot water systems.

Post-project actions

This project aims to support access to further funding to move this innovation to higher TRL levels (6-9), which will require successful demonstration in operational environments.

The scope of the innovation may then be expanded from domestic heat storage to industrial and municipal environments.

4 Project Plan

The project plan (Figure 2) spanned **three stages** (S), transitioning from **Steady state efficacy and operating parameters** (S1) to **Modulated-pump efficacy and operating parameters** (S2) and finally, **Efficacy and operating parameters under demand** (S3). The allocated weeks (W) per task (T) ensure a well-paced execution of each stage, fostering a successful outcome for the project.

Resource and responsibility allocation for each stage:

- System design parameters and technical support: AW
- Project management and technical support: SL, JP
- Experimental validation: SL, DB
- Computational study and analysis: DB, using ANSYS
- Reporting: DB, SL, JP

S1: Steady state efficacy and operating parameters [W1-4]

S1.1: Model setup and validation [W1-2]

Establish experimentally validated ANSYS Fluent model for steady state operation.

S1.2: Demonstration of system efficacy [W3]

Use ANSYS Fluent model to demonstrate system efficacy under steady pumping conditions.

S1.3: Operating parameter survey [W3-4]

Determine the range of pump flow and water temperatures that enable successful device operation without disrupting thermocline.

S2: Modulated-pump efficacy and operating parameters [W5-8]

S2.1: Model setup [W5]

Update model to allow dynamic, modulated pumping scenarios.

S2.2: Demonstration of system efficacy [W6]

Demonstrate system performance under dynamic/modulated pumping

S2.3: Operating parameter survey [W6-8]

Describe the range of appropriate pumping profiles (magnitude and duration)

S3: Efficacy and operating parameters under demand [W9-12]

S3.1: Model setup [W9-10]

Update model to allow for the input/output of hot/cold water during pumping.

S3.2: Demonstration of system efficacy [W11]

Demonstrate device performance under demand conditions.

S3.3: Operating parameter survey [W11-12]

Describe the range of pumping profiles and system demands that maintain device performance.

Stages (S)	Week	1	2	3	4	5	6	7	8	9	10	11	12
S1: Steady state efficacy and operating parameters	**1-4**												
S1.1 Model setup and validation	1-2												
S1.2 Demonstration of system efficacy	3												
S1.3 Operating parameter survey	3-4												
S2: Modulated-pump efficacy and operating parameters	**5-8**												
S2.1 Model setup	5												
S2.2 Demonstration of system efficacy	6												
S2.3 Operating parameter survey	6-8												
S3: Efficacy and operating parameters under demand	**9-12**												
S3.1 Model setup	9-10												
S3.2 Demonstration of system efficacy	11												
S3.3 Operating parameter survey	11-12												

Figure 2: Project Plan

5 Budget

Brief Description	Amount £ (inc. VAT)	Description of Costs
Consumables	**£8,915.8**	ANSYS CFD Enterprise Commercial License (Q-346214)
	£2,000.00	Consumables (incl. raw materials, sensors, auxiliaries) for bespoke experimental test rig for thermal energy storage unit cycling for CFD validation.
KE Associate(s)	**£9,065.74**	**Name: Mr David Balaam** Grade/Spine point: G6, pt 22 FTE/hours: 100%FTE Duration (inc. dates): 3 months
UEA Academic Supervisor(s)	**£673.70**	**Name: Dr Stefano Landini** FTE/hours: 5%FTE Duration (inc. dates): 3 months
	£759.79	**Name: Dr Jack Panter** FTE/hours: 5%FTE Duration (inc. dates): 3 months
Total Project Costs	**£21,415.03**	
Partner cash contribution	**£5,353.76**	
TOTAL UEA Grant KE+ Fund	**£16,061.27**	

Project Report

Abstract

Under normal operating conditions, typical immersion heaters that are installed within domestic hot water cylinders can only effectively heat the top-most water in the cylinder to the desired temperature, typically ~ 65°C. This places a reliance on external water heating devices to provide thermal energy to the rest of the system. Nearly 80% of the external devices in the UK are powered by fossil fuels [1], thus contributing to carbon emissions. Furthermore, thermal losses between the external device and the cylinder reduce efficiency.

THE DEVICE is a pump that can be retrofitted to the 22mm outlet common to the majority of currently installed cylinders in domestic applications. THE DEVICE extracts hot water through this outlet from the normal reserve at the top of the cylinder and pumps it via a plastic pipe inserted back through the 22mm outlet into the cold-water reserve near the bottom of the cylinder. THE DEVICE is designed to be retrofitted to an existing cylinder without draining it or adding additional connectors to its structure.

For it to work effectively it is imperative that, during normal operation, THE DEVICE does not destroy the naturally occurring thermocline layer that forms between the hot and cold-water reserves inside the cylinder. Doing so would homogenise the water temperature throughout the cylinder and prevent hot water from being supplied to other components of a domestic hot-water system until the whole cylinder had reached the desired temperature.

This project outcomes demonstrates that during normal operation of a correctly installed THE DEVICE, the thermocline remains intact at lower flow rates, and that moderate flow rates cause disruption across the thermocline layer lowering the temperature of the hot water reserve. Evidence also shows that whilst pipe length is a factor in the stability of the thermocline layer, it is the flow rate through the 22mm outlet that is the primary cause of disruption.

1 Model development

The simulation model was developed using Ansys Fluent 2024 R2 to investigate both thermal and viscous fluid interactions within a typical cylinder with THE DEVICE installed at the top. The normal operating scenario is that THE DEVICE extracts water from the 22mm outlet at the top of the cylinder and pumps it via an internal 10mm outside diameter pipe inserted back through this outlet. The pipe extends from the top near the bottom of the cylinder. This section provides a detailed explanation of the model, and the subsequent meshing and simulation-solving parameters and settings.

1.1 Assumptions

Several assumptions have been made to reduce the computational workload of the simulation:

- Fluid flow within the system was assumed turbulent and incompressible.
- The temperature of the fluid within the model does not exceed the limits of the equations used to model its properties ($5^{\circ}C < T_{water} < 95^{\circ}C$, taken from Water Thermodynamic Properties [3]).
- The fluid is assumed to be Newtonian, allowing the use of the classical continuity, momentum, and energy equations.
- The immersion heater element was modelled as a constant volumetric heat source of dimensions taken from a typical commercially available product.
- Energy losses to the surrounding environment throughout the whole system (including external components not included in the model geometry) are assumed to be negligible.

1.2 Governing equations

The numerical model is developed for a three-dimensional grid, and therefore the continuity, momentum, and energy equations are solved in three dimensions. The governing equations implemented in the CFD software (expressed below in vector notation) are based on this assumption:

Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \tag{1}$$

where ∇ is the gradient operator, ρ is the density of the water [kg/m^3], and **v** is the velocity vector [m/s] in Cartesian coordinates.

Momentum

$$\rho\left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{v}\right) = -\nabla P + \rho \boldsymbol{g} \tag{2}$$

where P is the pressure field [Pa] and $\boldsymbol{g}$ is the gravitational acceleration vector [m/s^2]. Note that the gravitational force is zero along the x- and z-axes.

Energy

$$\rho\left(\frac{\partial \epsilon}{\partial t} + (\boldsymbol{v} \cdot \boldsymbol{\nabla})\epsilon\right) = -\nabla \cdot \boldsymbol{q} \tag{3}$$

$$\boldsymbol{q} = -k\, \nabla T \tag{4}$$

where ϵ is the specific internal energy [J/kg], k is thermal conductivity [W/mK, and T is the thermodynamic temperature [K]. The term $\boldsymbol{q}$ is the heat flux vector [W/m^2]. Note that the density, thermal conductivity, and specific heat properties of water in the fluid domain are functions of temperature.

Turbulence

The turbulent flow is modelled using Menter's k-ω SST model [2]. It was chosen for its combination of the good numerical properties of the standard k-ω model near the wall boundaries and those of the k-ε model further away from the boundaries.

1.3 Geometry model

The three-dimensional geometry was modelled in Ansys Design Modeller (Figure 3), including the definition of key boundary names for later use in Ansys Fluent. The geometry is asymmetrical in all three axes due to the positioning of the immersion heater element, inlets, and outlets. The body of the modelled cylinder is based on the dimensions of a copper cylinder manufactured by Newark Cylinders. Its dimensions are given as 0.45 metres in diameter and 1.5m tall. The top is an oblate hemispheroid of a height 0.5 × the cylinder radius. Where the cylinder side meets the base is rounded with a radius of 25mm. A circular pressure inlet of diameter 0.022m is located on the side of the cylinder 0.05m above the base. An annular mass-flow outlet, outside diameter 0.022m and inside diameter of 0.01m, is located at the highest point of the cylinder. Both protrude from the body of the cylinder by 0.01m. The model incorporates the internal component of THE DEVICE, comprising a straight, solid-walled, rigid, cylindrical pipe of diameter 0.01m and length 1.46m, extending vertically from the centre of the annular outlet. At the top of the pipe is a mass-flow inlet Ansys Design Modeller reports the combined volume of the cylinder and of the pipe as 0.23170m^3 (231.7 litres).

The 22mm outlet, 10mm inlet, and pipe component are centred on the central vertical axis, and the central axis of the pipe is oriented normal to the z-plane. The immersion heater element is modelled on the commercially available *Tesla Incoloy Immersion Heater Element 27"* with a nominal power rating of 3kW. Made of Incoloy 800 (a commercial alloy of nickel and chromium), it serves as an electrically powered resistive heating element and is typical of immersion heaters in domestic applications. It is inserted into the cylinder near the top, placing the element at an angle of 5° from vertical. The heating element is U-shaped, ≈ 0.635m from cap to tip. The straight sections are separated by 0.045m and the body is 0.008m in diameter. The source model also includes a separate temperature probe although this is not included in the model. To simplify the model, the 'cap' of the immersion heater is modelled as a contiguous part of the cylinder wall. The heating element has a volume of 6.47×10^{-5} m^3 and surface area of 0.0323 m^2. Water is extracted from the cylinder solely via the 22mm outlet and inserted via the 10mm inlet. The mass-flow rate of this outlet and inlet are matched in simulations where only the operation of THE DEVICE is being modelled. In simulations featuring a discrepancy between water exiting via the 22mm outlet and entering via the 10mm inlet additional water is supplied into the system solely via a 22mm inlet on the side of the cylinder, 0.05m (5cm) from its base. This water is supplied at a temperature of 15°*C*. The cylinder model does not include any other inlets or outlets, and water may not enter or exit the cylinder by any other means.

1.4 Boundary conditions

Three distinct domains exist within the model:

- the immersion heater element (solid)
- the pipe (fluid)
- the main body within the cylinder (fluid).

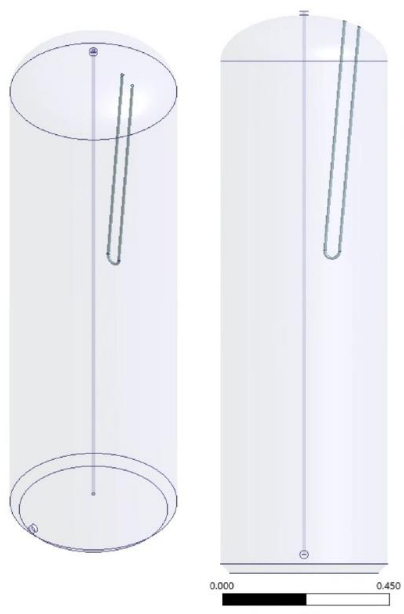


Figure 3: Geometry of the cylinder model in 3-dimensions (left). Contour plots are shown in 2-dimensions on the XY-plane (right)

Each of these domains were subjected to different boundary conditions and initial conditions and acted upon each other in a manner of conjugate heat transfer. The heating element was modelled as a constant volumetric heat source, S_h, and is expressed as:

$$S_h = \frac{\dot{Q}_{element}}{V_{element}} \approx 4.17 \times 10^7 \text{ W/m}^3 \quad (5)$$

where $\dot{Q}_{element}$ = 2,700 W (note: whilst the source of the model is nominally rated at 3.0kW, it was measured experimentally as drawing ≈ 2.7 kW at 230 volts), and $V_{element}$ = 6.47×10^{-5} m^3. The cylinder's fluid domain was configured to have a coupled boundary condition where it contacted the solid domain of the heating element, ensuring thermal energy leaving the heating element was equal to the thermal energy entering the fluid domain.

In simulations where only the operation of THE DEVICE is being modelled the circular 22mm inlet near the base of the cylinder was configured as a wall, as the model assumes a constant mass of water within the cylinder.
The 22mm annular outlet at the top of the cylinder is configured as a mass-flow outlet. The centre of this outlet has a diameter of 10mm and is configured as the mass-flow inlet for the pipe domain. Mass flow rate at the 10mm inlet and the surrounding 22mm outlet, $\dot{m}$, are determined by the following equation:

$$\dot{m} = \dot{V}\frac{\rho}{1000} \tag{6}$$

Where $\dot{V}$ is the volumetric flow rate [L/min or lpm] under investigation and ρ is the density of inflowing water, a function of temperature as measured at the 22mm outlet. This simulates the circulation of the out-flowing water back into the system in a close loop with no external losses. An adiabatic condition is assumed between the outlet and inlet. A 2mm wall with coupled boundary conditions on both sides was configured where the two fluid domains contacted each other along the sides of the pipe domain, enabling heat transfer through the pipe wall to be modelled. An internal boundary condition was configured at the lower end of the pipe domain in order to model the two fluid domains as one contiguous domain at this surface.

1.5 Mesh generation

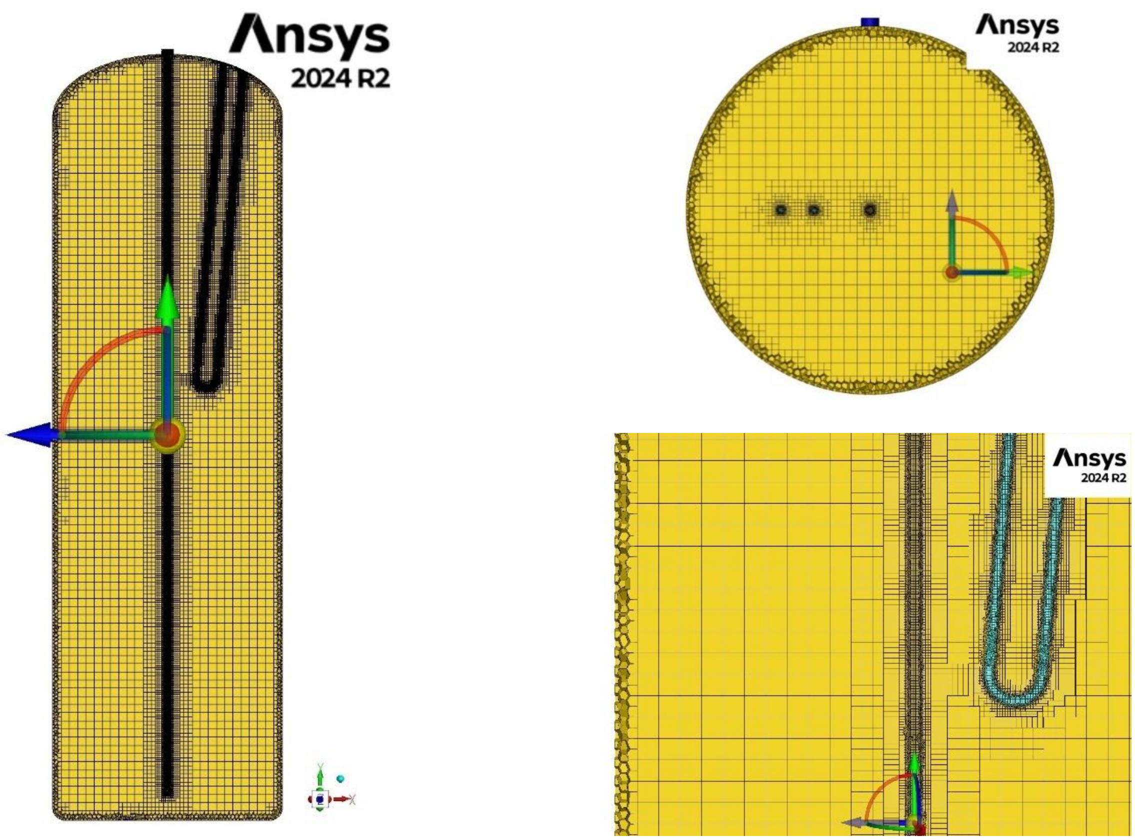


Figure 4: The final poly-hexacore mesh used in the simulation is presented here. It incorporates three meshed domains (two fluids, one solid). This figure shows cross-sectional views parallel to the XY- and XZ-planes (left and centre respectively). The figure on the right shows in more detail the mesh around the pipe and heating element domains within the cylinder body domain. The fluid domains have a combined cell count of ≈887 thousand, a minimal orthogonal quality of 0.50 (after mesh improvement), and a maximum aspect ratio quality index of 14.25. The datum point is at the centre of the base of the longitudinal axis of the cylinder, with the y-component defined parallel to this axis.

After creating the geometry model, the simulation mesh was generated in Ansys Fluent (Figure 4) using a poly-hexacore mesh pattern with mesh improvement to reduce the minimum orthogonality of the mesh quality. The mesh sizing parameters shown in Table 1 were used throughout the study.

Table 2 shows the quality parameters of the resultant mesh.

Table 1: Mesh size parameters Table 2 shows the quality parameters of the resultant mesh.

surface (mm)		volume (mm)		cell-count (×1000)			total (×1000)	
min	**max**	**min**	**max**	**cylinder (f)**	**pipe (f)**	**heater (s)**	**fluid**	**all**
0.5	8	0.5	16	791	96	62	887	949

Table 2: Mesh quality parameters

	minimum	average	maximum
orthogonality	0.71095	0.99784	1.00000
skewness	6.3×10^{-7}	0.00216	0.28905
aspect ratio	1.00013	1.33097	14.2502

2 Simulation setup

For highest accuracy, the three-dimensional model was represented in Ansys Fluent with double precision activated.

2.1 Material properties

All fluid domains are composed of liquid water. The solid domain (the immersion heater) is composed of Incoloy 800. The cylinder outer wall boundary is composed of copper, and the central pipe wall boundary is composed of cross-linked polyethylene. The GRANTA MDS Database within Ansys provided the material property values for Incoloy 800 (nickel-allow-Incoloy- 800), copper (copper), and cross-linked polyethylene (plastic-pe-cross-linked). These properties are listed in Table 3. For the solid material, constant values for these parameters are used across all temperatures.

Table 3: Solid material parameters

		Incoloy 800	cross-linked pe	copper
ρ	**(kg/m^3)**	7949.4	1068.1	8978
C_p	**(J/(kg K))**	454.0	1589.5	381
k	**(W/(m K))**	11.639	0.21784	387.6

Whilst the databases included with Ansys provide some useful default values for the properties of liquid water, and although the Boussinesq approximation is more commonly used in simulations that require greater accuracy, both methods suffer from the same shortcoming: the assumption of constant density for all aspects other than buoyancy. This can lead to inaccurate results, therefore, using Pramuditya's approximations [3], a piecewise polynomial formula is used to approximate density, ρ, specific heat capacity, C_p, thermal conductivity, k, and viscosity, μ, as functions of temperature between the temperatures of 278.15 and 368.15 Kelvin ($5^{\circ}C < T_w < 95^{\circ}C$). Below and above this range the values at 278.15 K and 368.15 K are used respectively. The polynomial formula coefficients and constant values are reported in Table 4.

Table 4: Liquid water parameters [3]

	$T_w < 278.15K$	liquid water $278.15K \leq T_w \leq 368.15K$	$T_w > 368.15K$
$\rho(T)$	999.16	$765.33 + 1.8142T - 3.5 \times 10^{-3}T^2$	958.9
$C_p(T)$	4170.9	$2.807 \times 10^4 - 281.7T + 1.25T^2 - 2.48 \times 10^{-3}T^3 + 1.857 \times 10^{-6}T^4$	4147.9
$k(T)$	0.5735	$-0.5752 + 6.397 \times 10^{-3}T - 8.151 \times 10^{-6}T^2$	0.6751
$\mu(T)$	1.481×10^{-3}	$9.67 \times 10^{-2} - 8.207 \times 10^{-4}T + 2.344 \times 10^{-6}T^2 - 2.244 \times 10^{-9}T^3$	2.831×10^{-4}

2.2 Data points

Water temperature within the cylinder model was recorded at the 22mm annular outlet, and at each end of the central pipe. A 2 x 2 x 15 array of 25mm 'sensor' squares was also incorporated to record average temperature at 0.1m intervals up the entire cylinder starting at 0.05m from the base. These temperature points are identified as "tmp+n" where *n* is the distance from the base of the cylinder in centimetres. Temperature was averaged across all four sensors at each height interval and recorded at every time step.

2.3 Convergence criteria

The criteria used to establish convergence are reported in Table 5.

Table 5: Residuals, under-relaxation factors, and solution parameters used in this study

Residuals	Momentum	1e-6
	x-velocity	1e-6
	y-velocity	1e-6
	z-velocity	1e-6
	Energy	1e-6
Under-relaxation factors	Pressure	0.3
	Density	1
	Energy	1
	Momentum	0.5
	Body Forces	1
Solution parameters	Time-step scheme	fixed
	Time step size (s)	$(0.0 \leq t \leq 1.0)$: 0.01
		$(1.0 \leq t \leq 900.0)$: 1.00

3 Results

3.1 Mesh independence

The mesh independence was verified using four meshes of the geometry, with each using a refinement of the previous mesh sizes throughout the model. Mesh sizes can be summarised as ranging from ≈815k (≈752 in the fluid regions) to ≈6,689k (≈6,625 in the fluid regions). Specific parameters and their corresponding sizes are detailed in table 6. Each mesh was tested against the 1.5lpm flow rate with temperature readings taken at the outlet, 1.05m, and 0.05m extracted from the results, these points being the top of the cylinder, just above the rising thermocline, and at the bottom of the central pipe respectively.

Table 6: Mesh size parameters

	surface (mm)		volume (mm)		cell-count (×1000)			total (×1000)	
	min	max	min	max	cylinder (f)	pipe (f)	heater (s)	fluid	all
0.	1.0	16	1.0	32	655	96	63	752	815
1.	0.5	8	0.5	16	791	96	62	887	949
2.	0.25	4	0.25	8	1,600	96	63	1,696	1,759
3.	0.125	2	0.125	4	6,530	96	63	6,625	6,689

Of the mesh sizes listed, 1. was used for the simulations. Select simulations were repeated with cells half and quarter the size (2. and 3. respectively), however, these simulations yielded similar results despite the increased computational burden, thus the smaller cell size is appropriate. Doubling the cell size (0.) did not reduce the cell-count by a significant enough amount to justify the potential for the introduction of inaccuracies in the results. The figures below compare the results of the 1.5lpm continuous flow in scenario 1 from mesh sizes 1, 2, and 3 in Table 6.

3.2 Operating scenarios

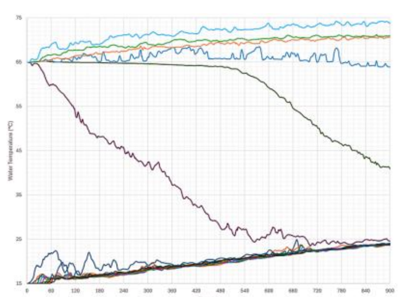
THE DEVICE is designed to run continuously and can pump water at a rate of between 1.5 and 12 litres per minute (lpm), hence, the following scenarios were investigated subject to flow rates of 1.5, 3.0, 4.5, 6.0, 7.5, and 12.0 lpm.

The purpose of the study was to examine the effects of recirculation flowrate on water temperature and thermocline integrity during the continuous operation of THE DEVICE in conjunction with the immersion heater. In all scenarios the heating element is energised throughout.

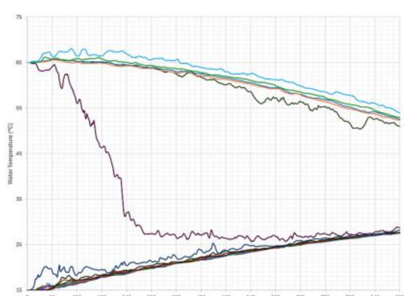
No water was discharged outside of the cylinder, nor was any additional water introduced into the system. The graphs reported in the following sections depict water temperature in the first 15 minutes of simulated time of each scenario for each flow rate.

<u>OS1: Normal operation and installation</u>

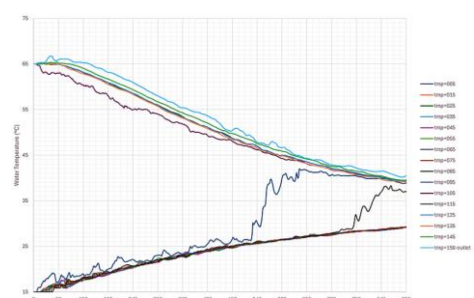
Under normal operating conditions, hot water at the top of the cylinder would be pre-heated to a temperature of 65°C by the immersion heater, which automatically cuts out when water 1.0m from the base of the cylinder reaches this temperature. Cold water is supplied to the cylinder at a temperature of up to 15°C to replenish hot water extracted (via the 22mm outlet at the top of the cylinder) by external usage. In this scenario conditions within the cylinder were initialised at 65°C at or above 1m and 15°C everywhere else (the "normal operation" scenario).



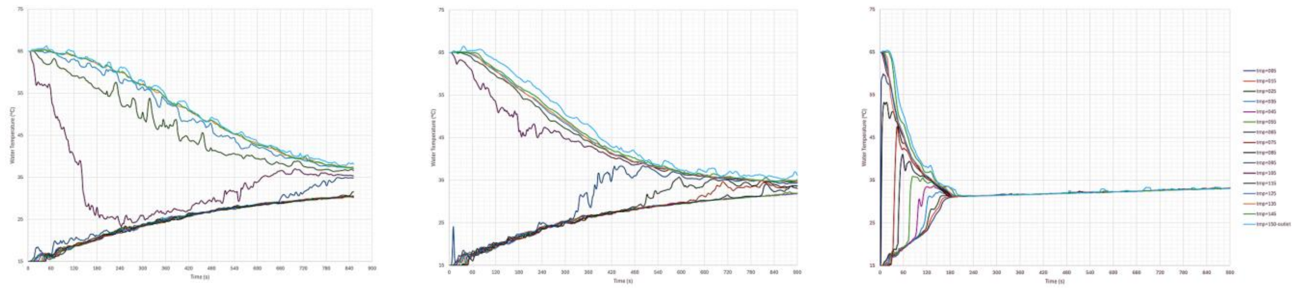
1.5 lpm



3.0 lmp

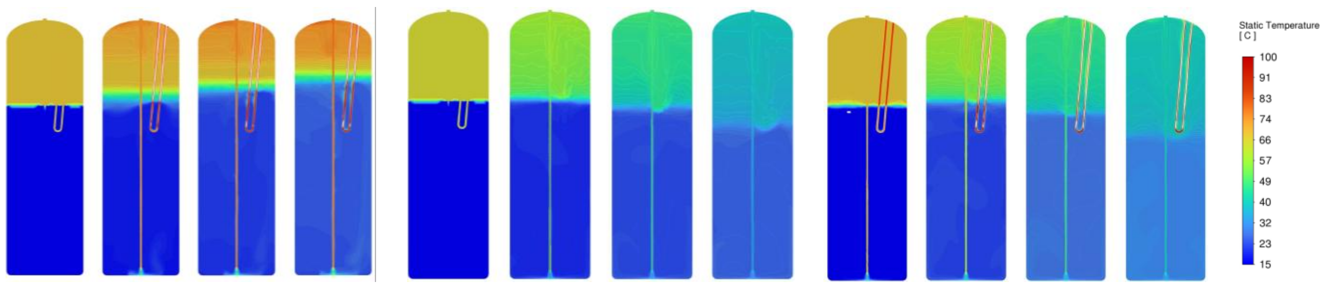


4.5 lpm

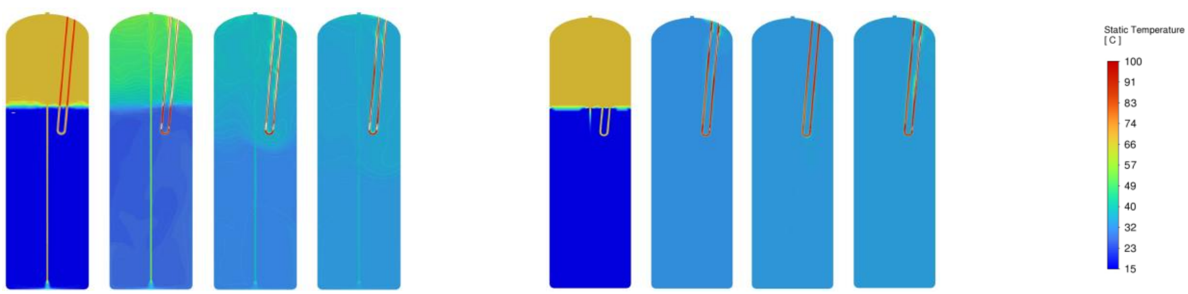


6.0 lpm 7.5 lpm 12.0 lpm

Figure 5: OS1 Water temperature over time. Each line represents a different height within the cylinder.



1.5 lmp 3.0 lmp 4.5 lpm

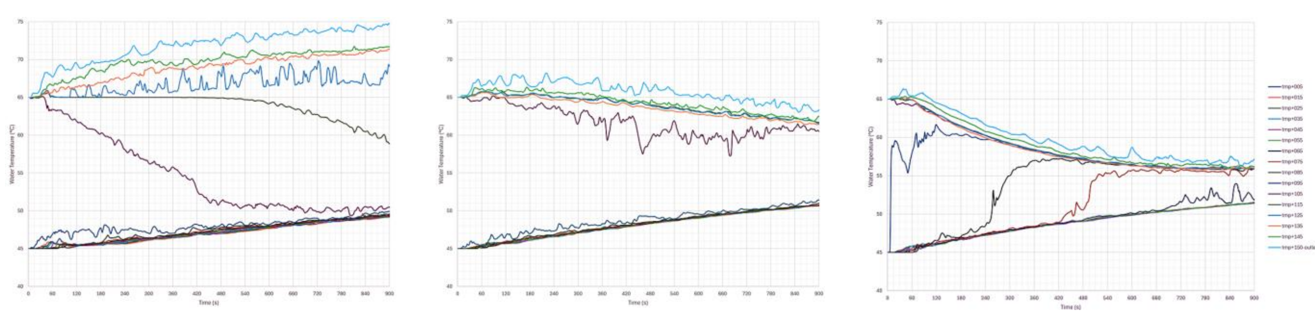


7.5 lmp 12 lmp

Figure 6: OS1 Temperature contours at 0, 300, 600, and 900 seconds (l-r)

<u>OS2: Normal installation, starting from a partially pre-heated state</u>

In normal operation it is anticipated that THE DEVICE may activate at times when the cylinder remains partially heated (either from prior operation or heated from external sources). In this scenario conditions within the cylinder were initialised at 65°C at or above 1m, and 45°C everywhere else (the "pre-heated" scenario).



1.5 lpm 3.0 lmp 4.5 lpm

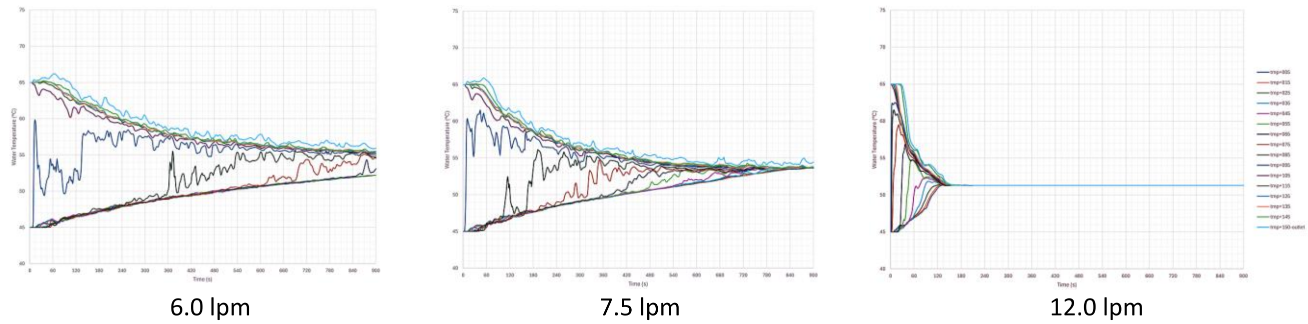


Figure 7: OS2 Water temperature over time. Each line represents a different height within the cylinder.

<u>OS3: Normal operation, short pipe installation</u>

Incorrect installation of THE DEVICE may result in the central pipe being short. The central pipe was modelled with a length of 0.76m, terminating 0.75m from the bottom of the tank ("short pipe" scenario).

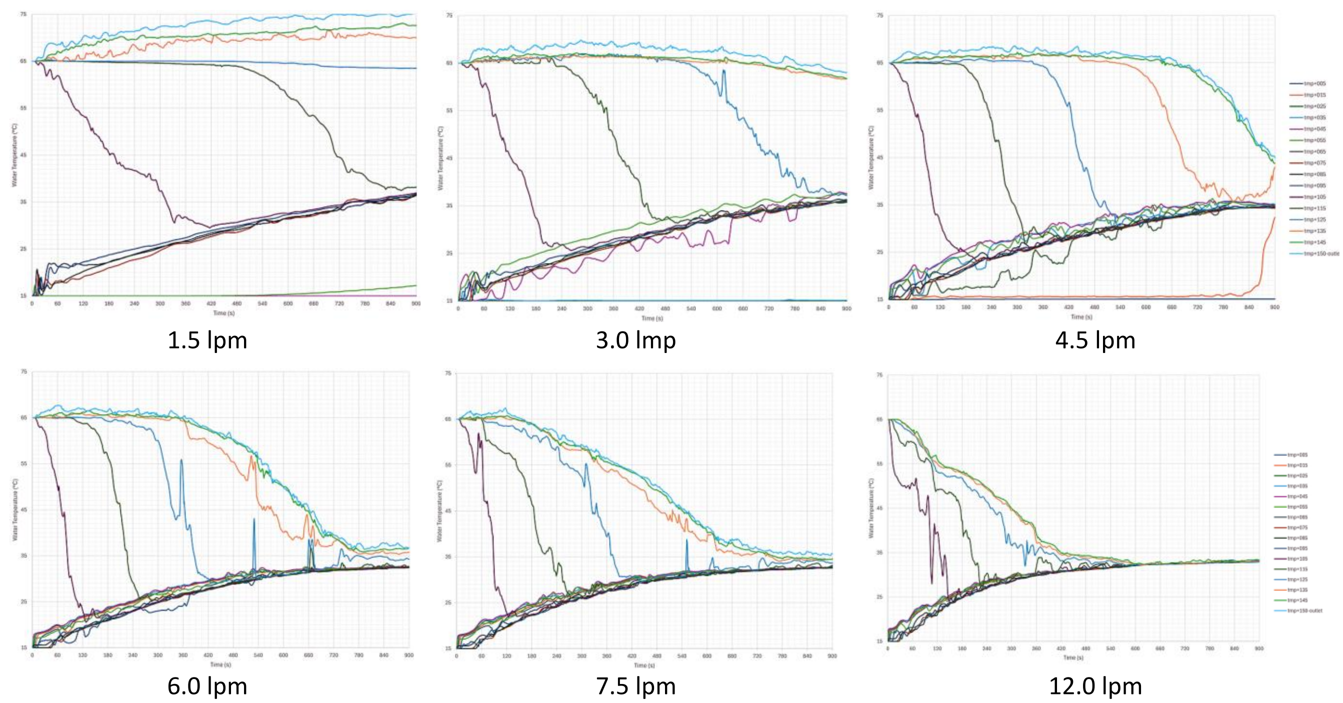


Figure 8: OS3 Water temperature over time. Each line represents a different height within the cylinder.

<u>OS4: Normal operation, long pipe installation</u>

Incorrect installation of THE DEVICE may result in the central pipe being too long. The central pipe was modelled as having a length of 1.64m. The outlet was directed radially away from the central pipe (*perpendicular* to the cylinder outer wall) at a height of 0.0005m (0.5mm) from the base of the cylinder and a distance of 0.175m from the central axis ("long pipe" scenario).

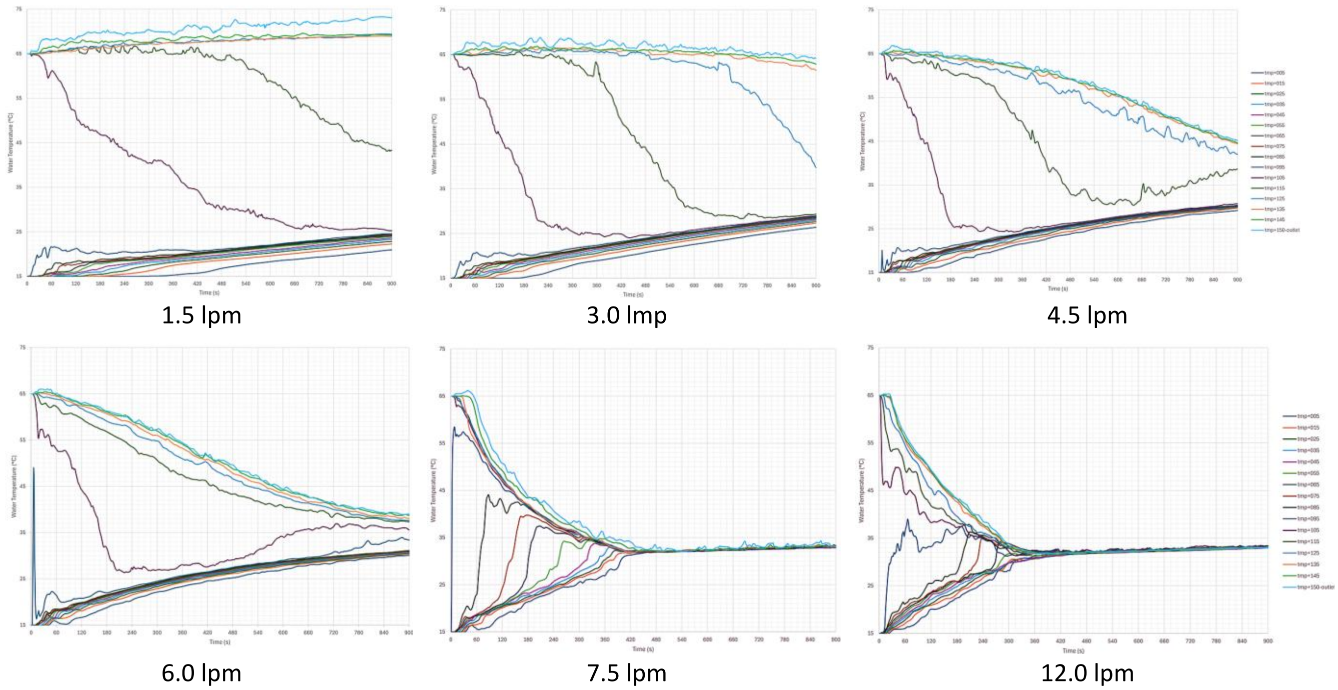


Figure 9: OS4 Water temperature over time. Each line represents a different height within the cylinder.

<u>OS5: Normal operation, extra-long pipe installation</u>

Incorrect installation of THE DEVICE may result in the central pipe being too long (more-so than scenario 4). The central pipe was modelled as having a length of 1.73m. The outlet was directed tangential to the central pipe (*parallel* to the cylinder outer wall) at a height of 0.0005m (0.5mm) from the base of the cylinder and a distance of 0.175m from the central axis (the "extra-long pipe" scenario).

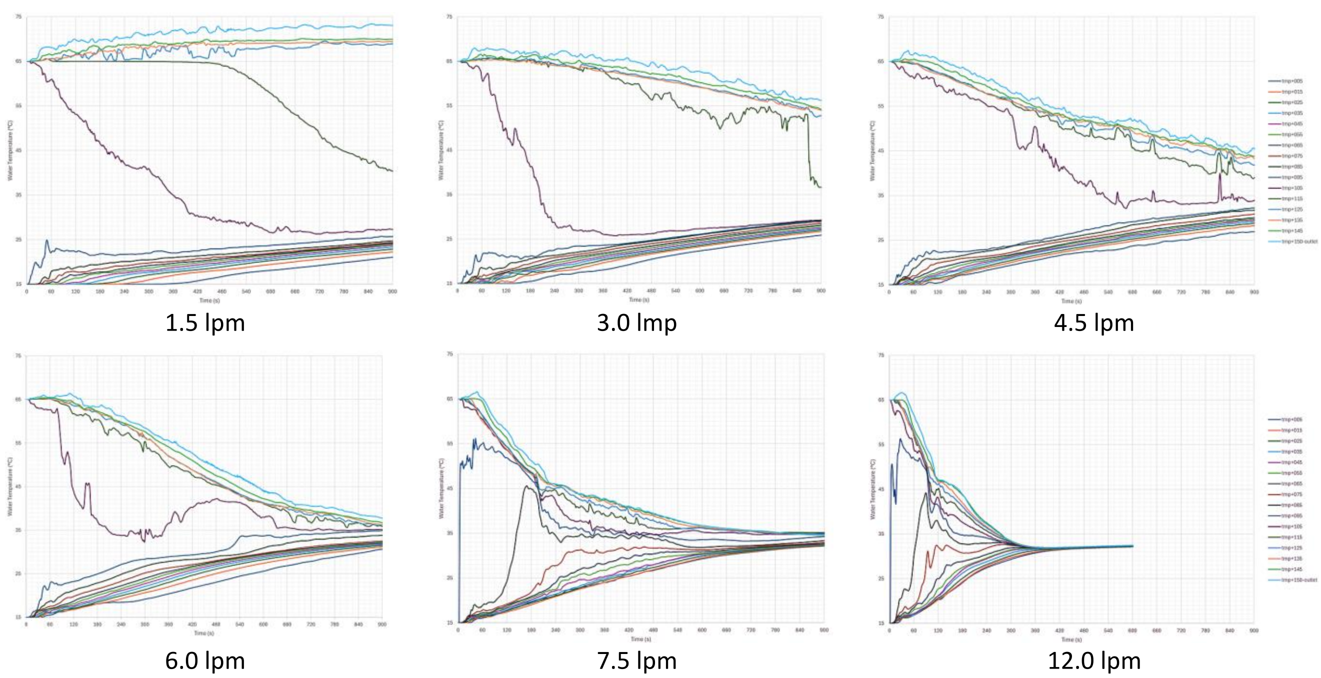
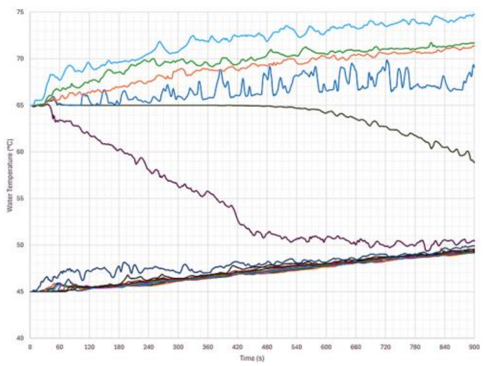


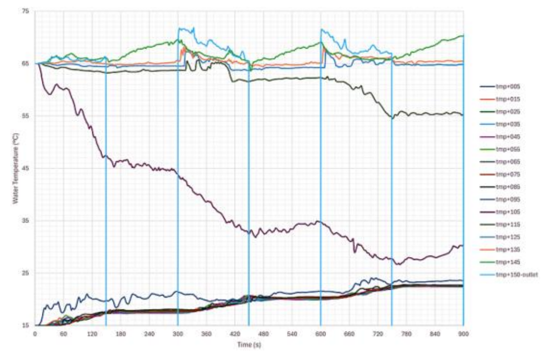
Figure 10: OS5 Water temperature over time. Each line represents a different height within the cylinder.

Two more scenarios were investigated to allow further investigation of processes seen in the above scenarios.

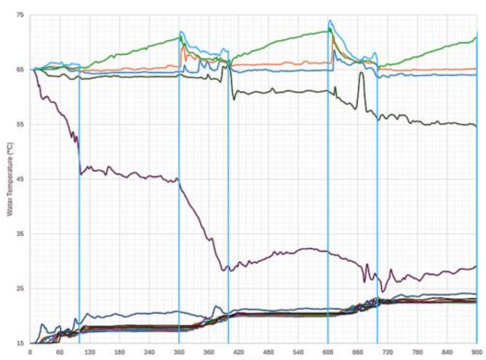
OS6: Periodic flow Non-continuous, cyclical flow was investigated. With all other parameters the same as the Normal Operation scenario, an on-off flow cycle was repeated over a combined cyclical period of 300 seconds using flow rates of 3.0 lpm for 150 seconds, 4.5 lpm for 100 seconds, and 6.0 lpm for 75 seconds. Each flow rate was chosen to maintain an average flowrate of 1.5 lpm over the cyclical period. The results of all three periodic flow rates were then compared to both the continuous flow rate at 1.5 lpm and of their corresponding continuous flow rates.



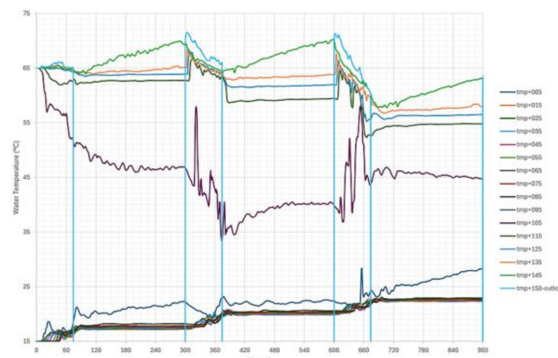
1.5lpm (continuous)



3.0lpm for 150s, followed by 0.0lpm for 150s



4.5lpm for 100s, followed by 0.0lpm for 200s

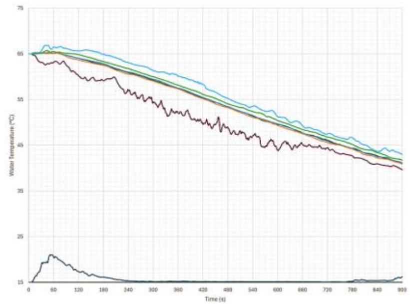


6.0lpm for 75s, followed by 0.0lpm for 225s

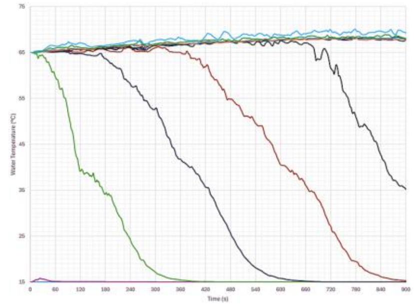
Figure 11: OS6 Water temperature over time. Note that the graph for 1.5lpm continuous flow (Scenario 1) is repeated here for comparison.

OS7: Zero flow In this scenario, a flow rate of 0.0 (zero) lpm through THE DEVICE was modelled. Water was extracted from the 22mm outlet at three different flow rates. These were chosen to correspond to typical usage examples in a domestic setting; a single user with a normal shower (light use at 4.0lpm), multiple users/appliances extracting water simultaneously (heavy use at 8.0lpm), and a single user operating a power shower device (very heavy use at 12.0lpm). A constant volume of water was maintained in the cylinder via the 22mm inlet near the base of the cylinder. Water entering the cylinder via the 22mm inlet was at a temperature of 15°C. Each flow rate was modelled starting from one of three distinct initial conditions for the temperature of the water within the cylinder:

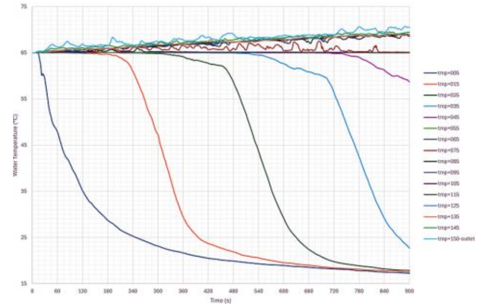
1. top third heated to 65°C, bottom two thirds at 15°C
2. top two thirds heated to 65°C, bottom third at 15°C
3. cylinder fully heated to 65°C



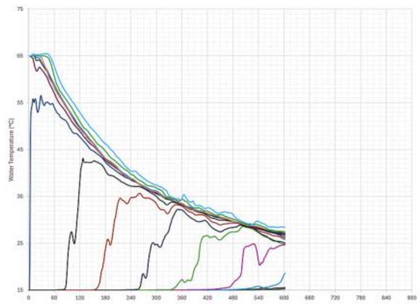
4.0lpm from 1/3 heated state



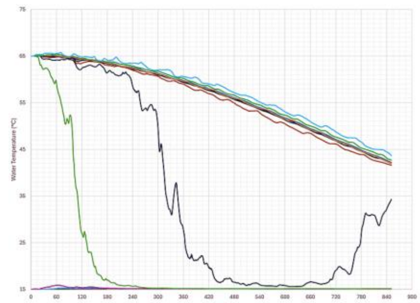
4.0lpm from 2/3 heated state



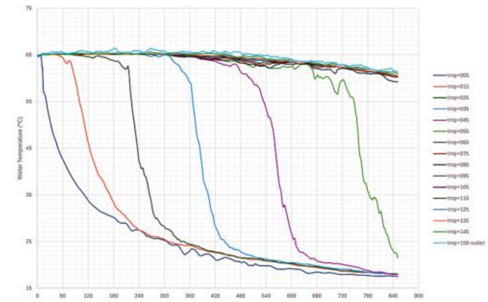
4.0lpm from a fully heated state.



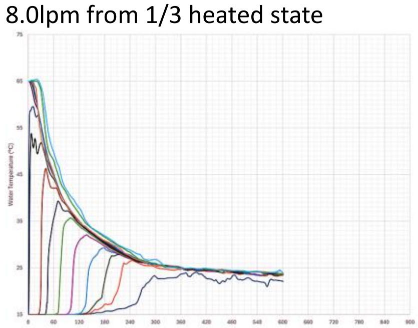
8.0lpm from 1/3 heated state



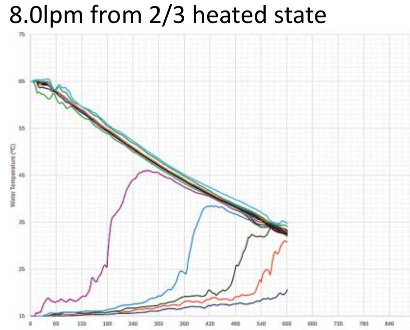
8.0lpm from 2/3 heated state



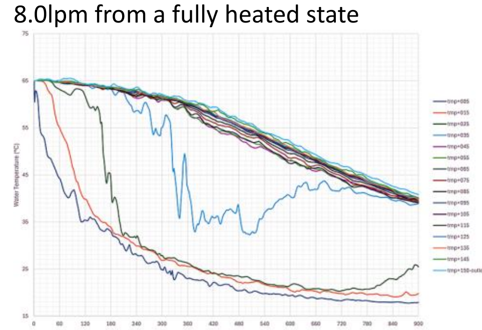
8.0lpm from a fully heated state



12.0lpm from 1/3 heated state



12.0lpm from 2/3 heated state



12.0lpm from a fully heated state

Figure 12: OS7 Water temperature over time. Each line represents a different height within the cylinder

Discussion

Analysis of the data, and a review of animated temperature contour plots (stills provided in fig. [XXX]) revealed three distinct processes occurring within the body of water.

Process 1: turbulent motion above the thermocline

A combination of water draws through the relatively narrow outlet created eddy currents in the region of water above the thermocline. Whilst factors such as cylinder geometry, outlet diameter, central pipe diameter, and convection currents generated from the heating element contributed to the scale and intensity of these currents, the most significant driver for these currents was the flow rate of water being extracted by THE DEVICE.

Consequently, as the hot water was extracted, and the volume of hot water diminished the thermocline layer moved upwards towards the top of the cylinder. When the thermocline layer reached this turbulent motion, cold water from below the thermocline layer was drawn up into the hot water causing it to mix with and cool the hot water. As the size of the eddies was proportional to the volumetric flow rate, higher flow rates caused this mixing to occur much sooner and more rapidly than at lower flow rates. The smaller difference in water temperatures above and below the thermocline layer modelled in scenario

2 contributed to the effects of this process. At the highest flow rates (up to 12.0lpm) this disruption occurred almost immediately.

This process is further demonstrated in scenario OS7 (zero flow) in which the sole driver for water flow is extraction from the top. In the flow rates that were investigated the level of disruption to the thermocline layer was much more apparent at higher flow rates, with only the lowest flow rate (4.0lpm) demonstrating any preservation of this layer, and even then, only when it started 0.5m from the base of the tank (the 2/3 heated initial state). At 8.0lpm the thermocline began exhibiting disturbance when the thermocline layer rose to ≈ 0.45m from the base, with the hot region of water showing the evidence of mixing and cooling after 8 minutes when initialised in a fully heated state

Process 2: turbulent motion below the thermocline

At the outlet of the central pipe near the base of the cylinder turbulent flow resulted from hot water being rapidly dispersed into the surrounding cold water. As with the turbulent motion at the top of the cylinder (process 1), cylinder geometry was a factor in the scale of these eddies, as was the temperature difference between the hot and cold water, however, the primary determinant was the flow rate being discharged from the end of the central pipe. In scenario OS4, the flow directed directly at the cylinder wall was deflected upwards creating a localised eddy current, and in scenario OS5, the orientation of the outlet of the central generated tangential flow within the cylinder. Neither contributed significantly to the effect of process 1.

Process 3: water heating below the thermocline

The discharge of hot water from the end of the central created a small pocket of heated water at the base of the cylinder of a size determined by the factors effecting process 2. This pocket acted as a secondary heat source at the base of the cylinder, fuelled by hot water fed down the central pipe by THE DEVICE and sourced from the hot water at the top of the tank. At lower flow rates this was the primary source of thermal energy increasing the temperature in the lower region of water. At higher flow rates, this temperature increase in the lower region was caused primarily by turbulent mixing with water from the upper region resulting in a homogenisation of temperature throughout the tank. The material of the central pipe provided a sufficiently insulating barrier for the hot water within that it provided only a negligible heating effect to the cold water that surrounded it.

Preservation of the thermocline

In all scenarios the evidence suggests that, at low flow rates (below 3.0lpm), the thermocline remains intact, with the 'cold' reserve being warmed at the expense of the volume of the 'hot' reserve but without undergoing cooling. At intermediate flow rates (between 3.0 and 7.5lpm), the stability of thermocline demonstrates an increasing sensitivity to other features and parameters within the cylinder (e.g. geometry, or temperature difference between the upper and lower regions of water). In this range distinct thermoclines are evident but are sufficiently disrupted to cause the water in the hot reserve to mix with water from the cold reserve causing the hot reserve to cool.

At higher flow rates (above 7.5lpm) the data suggests that turbulent flow across the interface causes considerable disruption of the thermocline layer resulting in rapid homogenisation of the water temperature throughout the cylinder. In scenario 3 flow was directed vertically down, however, water flowing out of the pipe was not deflected by the cylinder base or walls at flow rates lower flowrates (below 6.0lpm). Allowing the water to exit the pipe more freely protected the stability of the thermocline for longer than was otherwise seen at a given flow rate with a longer pipe.

Secondary thermocline in the scenario featuring the short pipe.

In scenario OS3, where the pipe is shorter than standard, lower flow rates (below 6.0lpm) allowed a second thermocline layer to form between the initial thermocline layer and the base of the cylinder. The exact position of this second thermocline layer depends on the flow rate, with increased flow rates causing this secondary thermocline layer to form closer to the base. Water in this middle thermal stratification is heated in a manner consistent with the other scenarios, however, as the volume of this middle strata is smaller than the total volume of the cylinder below the initial thermocline layer this heating effect is more rapid. Below this second thermocline layer the water temperature remained consistent with unheated water.

Effects of periodic flow

For each of the three periodic flow rates two comparisons should be made. The first comparison is against the continuous flow rate of 1.5lpm. The second is against the corresponding continuous flow rate. At all three periodic flow rates, there is a broad similarity in the rate of heating of the cold-water region, and the preservation of the thermocline layer. All three periodic flow rates exhibited comparable cooling effects to the hot region as was found in their corresponding continuous flow rates. It should therefore be concluded that configuring THE DEVICE for periodic flow adds needless complexity to the setup with no practical advantages over running continuously at a lower flow rate.

Conclusions

THE DEVICE, as a means of storing thermal energy within a domestic hot-water cylinder heated solely by the internal immersion heater, is a viable option provided that the flow rate of extraction from the cylinder remains low enough so as not to disrupt the thermocline layer.

Furthermore, a 210 litre tank storing water at 85°C will store around 17 kWh of thermal energy, which is enough water to provide for 14 hot showers.

Further refinement of the design and operation of THE DEVICE should incorporate a temperature-determined cut-off switch to prevent mixing as the hot water reserve becomes depleted and the thermocline layer rises to a height concurrent with the disruption caused by extracting the hot water. The length of the pipe, whilst being a key factor in the efficacy of THE DEVICE, does not directly have an effect on the stability of the thermocline, however, care must be taken if shortening the pipe to fit within the tank in order to maximise the volume of cold water that is heated.

Future Developments

A test rig including a lab-scale prototype of the DEVICE (Figure 13: Prototype and Test RigFigure 13) has been developed and manufactured to carry on further testing and strengthen the conclusions achieved in this project. This will be commissioned in August 2025 and used to carry on experimental testing to gather data needed to prove further the flexibility of the technology and reinforce the research paper before submission to a peer-reviewed Q1 journal.

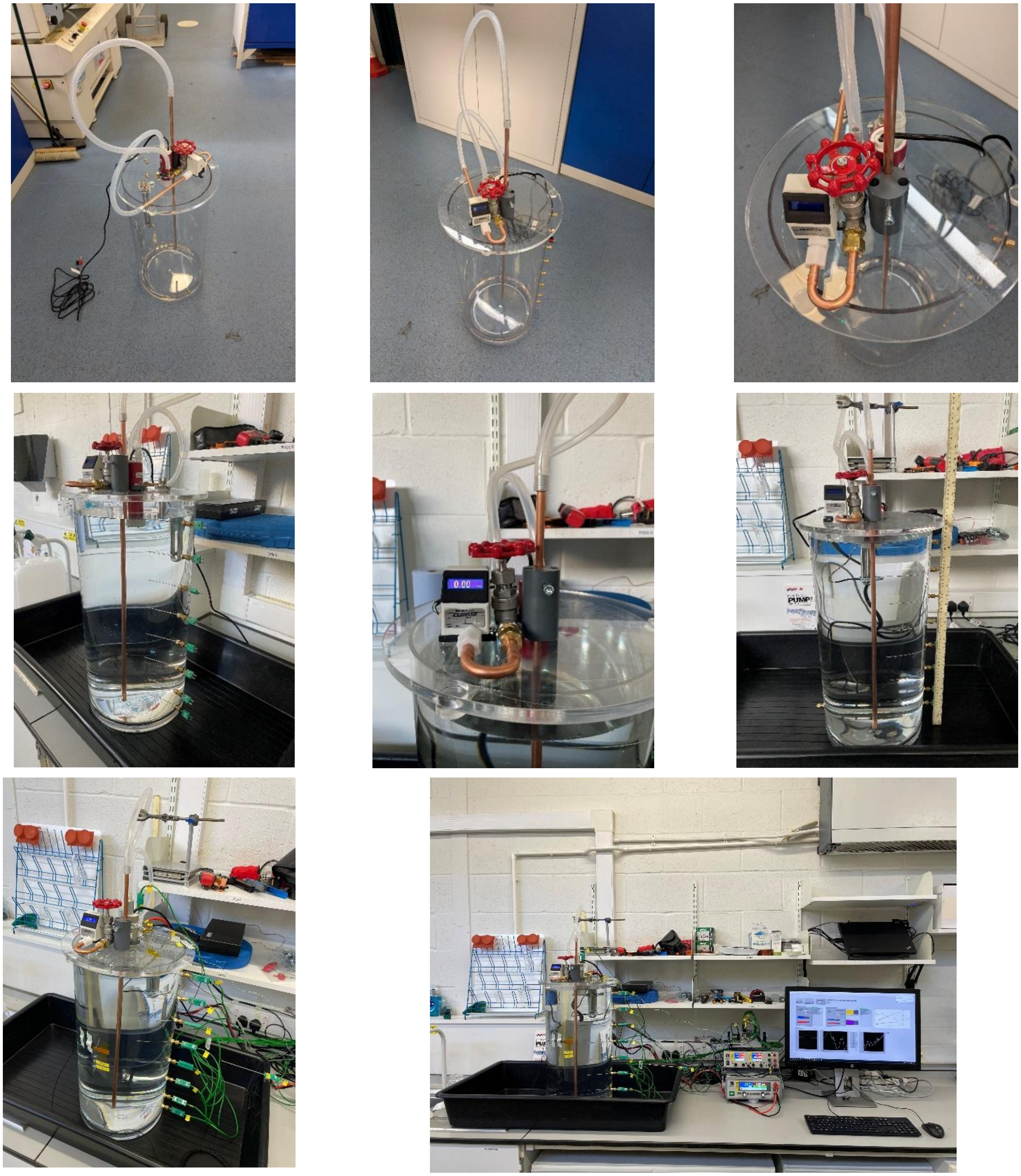


Figure 13: Prototype and Test Rig

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