WEB VERSION

PROJECT REPORT 1:

Efficiency Testing of MicroHeat Continuous Flow Electric Water Heater

Test Conducted By

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for
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Dr Biddyut Paul

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1. INTRODUCTION

1.1 BACKGROUND

MicroHeat Technologies Pty Ltd is an Australian private company focusing on research and development of applications using advanced fluid heating technology. In this context, MicroHeat has developed a Continuous Flow Electric Water Heater (CFEWH) using the MicroHeat PCT patent-protected technology. This development, which has now been commercialised, seeks to achieve energy optimisation and thereby reduce significantly both energy and water consumption in the supply of hot water.

A distinctive feature of the MicroHeat technology is that the water heating process is facilitated by directly energising water via electrodes in the water stream. The technology platform incorporates a microprocessor based control / feedback loop that aims to optimise the energy required to deliver the required output temperature at the desired flow rate. The outlet temperature is controlled to within +/- 1°C at any flow rate or water inlet temperature. The MicroHeat CFEWH is produced in two models with differing maximum flow rates, Series 1 and Series 2. Both models have the same overall dimensions: H245mm x W210mm x D125mm.

This joint research project with Centre for Design and School of Aerospace Mechanical and Manufacturing Engineering (SAMME) at RMIT University in collaboration with industry partner MicroHeat Pty Ltd. SAMME is responsible for experimental performance analysis and validation of the system, and energy modeling of the system using TRNSYS software, incorporating performance characteristics from validation stage, using a ‘whole systems’ approach. The RMIT Centre for Design is responsible for Life Cycle Analysis (LCA) and looking at complete life cycle impacts of the MicroHeat system in the modeled scenarios from the validation stage. This experimental part of the project reported in this document has been conducted by Dr Biddyut Paul of SAMME, RMIT University with the help of Brett Hernadi, IanTaig and Mark Lewis from MicroHeat Pty Ltd.

1.2 OBJECTIVES OF THIS PROJECT

The objectives of this experimental component of the project conducted by RMIT SAMME are to:

- conduct experimental steady flow and dynamic tests on the performance of a Series 1 and Series 2 CFEWH units under a wide range of inlet water conditions
- use the data obtained to evaluate the performance of the system
- provide a report on this performance test to MicroHeat and Centre for Design
- use the performance data for energy modeling in TRNSYS.

1.3 METHODOLOGY

The methodology that has been followed throughout to achieve the experimental objectives is presented below:

- design and construction of experimental setup for testing the heater units in different inlet conditions
- calibration of all the measuring instruments
- conducting experiments on performance tests of Series 1 and Series 2 units, trouble shooting and data collection
- analysis of the results on performance tests and report writing.

1.4 SCOPE OF THIS PROJECT

The main focus of this part of the project is to investigate experimentally the performance of a Continuous Flow Electric Water Heater unit under different inlet conditions. The operational principle of the CFEWH is based on the electrical conductivity of the water. The water is energized using inert electrodes positioned in the water stream. It incorporates a microprocessor based control / feedback loop that delivers absolute outlet temperature control at any flow rate or water input temperature accurate to (+/- 1.0 deg C). Performance was tested for both Series 1 and Series 2 units for steady-flow and ramp-up flow under a range of inlet conditions.

1.5 OUTCOMES

The following outcomes were expected from the experimental tests to validate the MicroHeat's claim:

- experimental steady-flow performance evaluation of a Series 1 and Series 2 unit in a wide range of inlet water conditions
- experimental ramp-up flow performance evaluation of a Series 1 and Series 2 unit in a wide range of inlet water conditions
- standby energy consumption evaluation for both premium cover and standard cover Series 1 and Series 2 unit.
- performance evaluation data to use in the energy modeling in TRNSYS software.

2. EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF THE CONTINUOUS FLOW ELECTRIC WATER HEATER (CFEWH)

2.1 INTRODUCTION

This chapter describes details of the experimental set up, calibration of all measuring instruments, the experimental procedure followed, and data acquisition used to test the performance of the continuous flow electric water heater (CFEWH). Experiments were conducted at the MicroHeat laboratory located at Port Melbourne, Victoria. MicroHeat has developed two types of heater unit: a Series 1 and Series 2 unit. Performance tests were conducted for both Series 1 and Series 2 units for steady flow, stand by and ramp up flow for a range of inlet conditions.

2.2 OVERALL EXPERIMENTAL SETUP

A schematic diagram of the overall experimental set up is shown in Figure 1.

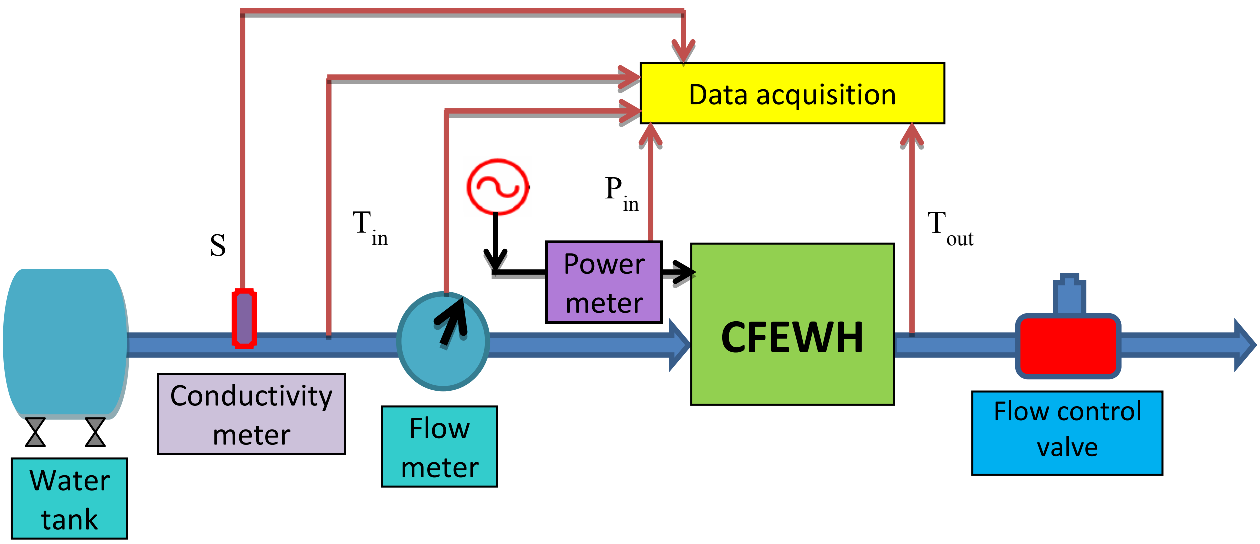

Fig. 1: Schematic diagram of overall experimental set up.

The experimental rig consisted of the following pieces of equipment:

- a conductivity meter, TPS AQUA-CPA (121135/1/K1), to measure the conductivity of water (accuracy ±0.2% of full scale range),
- two temperature sensors RTD PT100 for measuring inlet and outlet water temperature (accuracy ±0.3°C),
- a flow sensor, Gems FT-110 Series – TurboFlow sensor (part number 173934-C, flow measuring range 1-15 L/min with accuracy of ±3% of the reading), for measuring the water flow rate, and
- a Hioki 3169-21 clamp on power HiTESTER for measuring and logging the data for power measurements (accuracy for voltage and current measurement ±0.2% of reading).

A data acquisition system Brain Child VR18 paperless recorder was used to log the data for all measurements. For the ramp-up flow test, a T-type thermocouple tip was used to measure the outlet water temperature as the response time for RTD is higher than thermocouple. The testing apparatus and results are based on the system having no included cold water mixing valve, tempering valve or flow mixing valve at the outlet position. All results are based on the hot water temperature as delivered at the outlet of the CFEWH unit.

2.3 CALIBRATION OF DIFFERENT MEASURING INSTRUMENTS

2.3.1 Calibration of flow sensor

All the equipment was calibrated before conducting the performance test experiments. The flow sensor was calibrated for a wide range of flow rates using a calibrated graduated cylinder, transparent polymethylpentene (PMP), Capacity 2000 mL, and a stop watch. Calibration data and results are shown in Table 1.

Test No	Reading No	Measured Water Vol (mL)	Time Taken (Sec)	Calculated Flow Rate (L/min)	Calculated Flow Rate with Error (L/min)	Test Rig Flow Sensor Reading (L/min)	Average Test Rig Flow Sensor Reading (L/min)	Difference between Average Flow Sensor Reading and Calculated Flow Rate	Average Correction Factor
1	1	985	37.41	1.58	1.58±0.02	1.71-1.76	1.74	0.16	0.15
	2	1150	44.01	1.57	1.57±0.02	1.69-1.74	1.72	0.15	
	3	978	37.13	1.58	1.58±0.02	1.70-1.75	1.73	0.15	
2	1	1813	36.91	2.95	2.95±0.04	3.16-3.20	3.18	0.23	0.23
	2	1818	37.06	2.94	2.94±0.04	3.15-3.20	3.18	0.24	
	3	1818	36.95	2.95	2.95±0.04	3.15-3.20	3.18	0.23	
3	1	1818	27.31	3.99	3.99±0.07	4.20-4.25	4.23	0.24	0.25
	2	1820	27.43	3.98	3.98±0.07	4.21-4.24	4.23	0.25	
	3	1830	27.7	3.96	3.96±0.07	4.20-4.24	4.22	0.26	
4	1	1720	14.80	6.97	6.97±0.24	6.99 - 7.16	7.08	0.11	0.08
	2	1715	14.43	7.13	7.13±0.24	7.12 - 7.27	7.20	0.07	
	3	1775	14.83	7.18	7.18±0.24	7.16 - 7.32	7.24	0.06	
5	1	1440	7.43	11.63	11.63±0.76	11.52 - 11.57	11.55	-0.08	-
	2	1420	7.36	11.58	11.58±0.76	11.68 - 11.73	11.71	0.13	
	3	1638	8.38	11.73	11.73±0.76	11.66 - 11.72	11.69	-0.04	

Table 1: Flow sensor calibration results.

From this table it can be seen that the test rig flow sensor systematically gave higher readings of flow rate, except at the highest flow rate of 11.6 L/min. So, it was necessary to apply a large correction factor to adjust the flow meter readings so that they compared with the results calculated during an independent calibration test. For example, when the actual calculated flow rate was 1.58±0.02 L/min, the flow sensor was giving reading in the range between 1.70 and 1.75 L/min. So, the average correction factor –0.15 was applied for the flow sensor reading range between 1.5 and 2 L/min. similarly the correction factors –0.23, –0.25 and –0.08 was applied for the flow sensor reading range 3 and 3.5 L/min, 4 and 4.5 L/min, and 7 and 7.2 L/min.

The estimated standard deviation associated with the output estimate or measurement result *y*, termed combined standard uncertainty $u_c(y)$ is the positive square root of the combined variance $u_c^2(y)$, is determined from the estimated standard deviation associated with each input estimate x_i, termed uncertainty and denoted by $u(x_i)$. The combined standard uncertainty is given by (BSI 1995):

$$u_c^2(y) = \sum_{i=1}^{N} \left[\frac{\partial f}{\partial x_i} \right]^2 u^2(x_i) . \tag{1}$$

In most cases a measurand *Y* is not measured directly, but is determined from *N* other quantities $X_1, X_2, \ldots, X_N$ through a functional relationship *f*:

$$Y = f(X_1, X_2, ..., X_N) \quad (2)$$

The combined error in calculating water flow rate is mainly coming from uncertainty in measuring the volume of water and uncertainty in measuring time. So, when calculated flow rate is 1.58 L/min in the above table, the error is ±0.02 L/min. Error analysis for different calculated flow rates was done by using the equations above and shown in the table 1 and the detail analysis is given in the Appendix A.

2.3.2 Calibration of temperature sensor

Inlet and outlet RTD temperature sensors in the test rig were calibrated using a T-type thermocouple and another RTD probe connected to a Center 309 Dataloger Digital Thermometer. The RTD sensor considered as reference sensor as it offers very good accuracy, stability and repeatability. RTD probe and thermocouple probe were placed approximately 20 mm below the outlet flow control valve. Three minutes time was given the system to become stable before taking any reading.

Flow Rate (L/min)	Reference Sensors at Outlet		Test Rig Sensors		Difference with Respect to Reference RTD (^{0}C)
	T-type (^{0}C)	RTD (^{0}C)	Inlet RTD (^{0}C)	Outlet RTD (^{0}C)	
10	18.4	18.5	18.6	18.8	+0.3
5.8	34.6	34.6	18.6	34.8	+0.2
5.8	39.4	39.4	18.6	39.7	+0.3
4.8	44.2	44.2	18.6	44.4	+0.2
3.9	47.6	47.6	18.6	47.8	+0.2

Table 2: Temperature sensors calibration results.

The outlet RTD temperature sensor on the test rig always read +0.2-0.3°C higher than the reference outlet sensors. This was because the reference sensors were placed approximately 20 mm below the outlet flow control valve; whereas the test rig outlet temperature probe was located before the outlet flow control valve. No correction factor was applied for temperature measurement.

2.3.3 Calibration of power meter

A Hioki 3169-21 clamp on power HiTESTER was hired from TR Techrentals, a professional test equipment rental provider, for measuring and logging the data for power measurements. This power analyser comes with factory calibration and accuracy for voltage and current measurement is ±0.2% of reading, as mentioned before.

2.3.4 Calibration of conductivity meter

A brand-new calibrated TPS AQUA-CPA (121135/1/K1) conductivity meter was used for all measurements.

2.4 METHOD SYSTEM OPERATION AND DATA ACQUISITION

2.4.1 Experimental procedure

The required apparatus to conduct the experiment and overall experimental setup is shown in Figure 1. Water was supplied from the 200 litre capacity water tank, and connected to the heater unit. The water conductivity sensor, inlet water temperature sensor and flow sensor are connected before the inlet of the heater unit, and the outlet water temperature sensor was connected after the outlet of the heater unit. The input temperature sensor was located approximately 500 mm from the input temperature sensor inside the heater unit. The input flow rate sensor was approximately 250 mm away from the flow rate sensor inside the heater unit. The output temperature sensor is approximately 600 mm from the output temperature sensor inside the unit. All the sensors were connected to the Brain Child VR18 data acquisition system and the data logger was set to log the data every second. The Hioki 3169-21 power analyser was connected to the power terminal of the heater unit to log the data of average power consumption in every second. This power logger has an internal memory to log the data on power measurement.

Three personnel Brett Hernadi, Ian Taig and Mark Lewis from MicroHeat have assisted in setting up the whole system and conducting the experimental procedure. After finalising the experimental set up, tests were conducted from 5th June 2012 to 08 June 2012. Measurements were made for both Series 1 and Series 2 units for steady-flow and ramp-up flow for a range of inlet water temperatures, flow rates and water conductivities.

2.4.2 Steady-flow tests for Series 1 unit

Steady-flow tests with the Series 1 unit were conducted for two inlet water temperatures: tank ambient and 25°C to simulate winter and summer ambient water temperature. Tests were conducted for three flow rates: 1.5, 3 and 4 L/min; and three different water conductivities: 100, 300 and 700 μS. The duration of each test was five minutes and the system was run for three minutes for each test to become the test condition stable before taking any reading. There were in total 18 tests conducted for the Series 1 unit under steady-flow conditions and the parameters for all the tests are tabulated in Table 3.

	Input Test Condition (Steady Flow, Series 1 Unit)				
Test No	**Input Temp (°C)**	**Flow Rate (L/min)**	**Water Conductivity (uS)**	**Time (min)**	**Set Output Temp. in Heater Unit (°C)**
1	Tank Ambient	1.5	100	5	45
2	Tank Ambient	3	100	5	45
3	Tank Ambient	4	100	5	45
4	25	1.5	100	5	45
5	25	3	100	5	45
6	25	4	100	5	45
7	Tank Ambient	1.5	300	5	45
8	Tank Ambient	3	300	5	45
9	Tank Ambient	4	300	5	45
10	25	1.5	300	5	45
11	25	3	300	5	45
12	25	4	300	5	45
13	Tank Ambient	1.5	700	5	45
14	Tank Ambient	3	700	5	45
15	Tank Ambient	4	700	5	45
16	25	1.5	700	5	45
17	25	3	700	5	45
18	25	4	700	5	45

Table 3: Input test conditions for the steady-flow tests of Series 1 unit.

For all the tests, the output temperature was set to be 45°C. A photograph of the overall experimental set up for the Series 1 unit tests is shown in Figure 2.

Fig. 2: Overall experimental set up for the tests of the Series 1 unit.

A sample set of data recorded for a Series 1 test is shown in Table 4. In the data table, 'TMPIN' is the inlet water temperature (°C), 'TMPOUT' is the outlet water temperature (°C), 'FLOWRT' is the flow rate of water (L/min), 'CONDUC' is the conductivity of water at inlet (μS) and 'P_AVE' is the actual average power consumption (W).

MicroHeat CFEWH Test Data

Test Conducted at MicroHeat Lab
Test Date: 05/06/12
Steady Flow Test 1
Series 1 Unit

Overall Inlet test Conditions:
Water flow rate (FLOWRT): 1.5 L/min
Inlet water temp (TMPIN): Tank ambient °C
Water conductivity (CONDUC): 100 µS

Definition of each term in experimental data	
TMPIN	Inlet water temperature
TMPOUT	Outlet water temperature
FLOWRT	Flow rate of water
CONDUC	Conductivity of water at inlet
P_AVE	Actual average power consumption

Total Duration of Test	300	sec
	5	min

Data for Test 1

Date	Time	TMPIN	TMPOUT	FLOWRT	CONDUC	P_AVE
		Average	Average	Instant	Instant	
		°C	°C	L/MIN	uS	W
05/06/2012	16:05:00	17.3	45.4	1.75	101	2939.0
05/06/2012	16:05:01	17.3	45.4	1.7	101	3231.0
05/06/2012	16:05:02	17.3	45.4	1.73	101.1	3069.0
05/06/2012	16:05:03	17.3	45.4	1.72	101.2	3159.0
05/06/2012	16:05:04	17.3	45.4	1.72	101.2	3021.0
05/06/2012	16:05:05	17.3	45.3	1.78	101.1	2996.0
05/06/2012	16:05:06	17.3	45.3	1.73	101.2	3061.0
05/06/2012	16:05:07	17.3	45.3	1.74	101.1	3068.0
05/06/2012	16:05:08	17.3	45.2	1.76	101	3125.0
05/06/2012	16:05:09	17.3	45.2	1.75	101.2	3134.0
05/06/2012	16:05:10	17.3	45.1	1.73	101.1	3000.0
05/06/2012	16:05:11	17.3	45.1	1.75	101.3	3000.0
05/06/2012	16:05:12	17.3	45.1	1.73	101.3	3065.0
05/06/2012	16:05:13	17.3	45	1.73	101.1	3024.0
05/06/2012	16:05:14	17.3	45	1.72	101.1	3056.0
05/06/2012	16:05:15	17.3	45	1.72	101.1	3054.0
05/06/2012	16:05:16	17.3	45	1.73	101.1	3110.0
05/06/2012	16:05:17	17.3	45	1.73	101.3	3117.0
05/06/2012	16:05:18	17.3	45	1.74	101.2	3154.0
05/06/2012	16:05:19	17.3	44.9	1.73	101.1	3150.0
05/06/2012	16:05:20	17.3	45	1.72	101.3	3113.0
05/06/2012	16:05:21	17.4	45	1.71	101.3	3128.0

Table 4: Sample test data for steady-flow test 1 with Series 1 unit.

2.4.3 Ramp-up tests for Series 1 unit

2.4.3.1 Gradual increase and decrease of flow rate (test 1)

The dynamic response of the Series 1 heater unit was tested by gradual step change of the flow rate from 0 L/min to the maximum allowable limit of the heater capacity and then back to 0 L/min. The time interval of each step change of flow rate was between 30 and 50 seconds. The output temperature was set to be 45°C. Tests were conducted for two input temperatures: tank ambient and 25°C; and for three different water conductivities: 100, 300 and 700 μS. The purpose of these tests was to measure the time taken by the heater to reach the desired output temperature, and also to see the effect of variation in the flow rate on the delivered output temperature for different water of different conductivity (that is, levels of dissolved salts). The gradual ramp-up flow test is defined as ramp-up test 1. Six tests in total were conducted for the ramp-up flow condition, labeled as from 1.1 to 1.6, and all the test parameters are tabulated in Table 5.

	Input Test Condition (Ramp up Flow, Series 1 Unit)			
Test No	Input Temp (°C)	Flow Rate (L/min)	Water Conductivity (uS)	Set Output Temp. in Heater Unit (°C)
1.1	Tank Ambient	0-4.5 / 4.5-1.5	100	45
1.2	25	0-4.3 / 4.3-0	100	45
1.3	Tank Ambient	0-3.7 / 3.7-0	300	45
1.4	25	0-3.7	300	45
1.5	Tank Ambient	0-4.5 / 4.5-2.3	700	45
1.6	25	0-4 /4- 1.5	700	45

Table 5: Input test conditions for ramp-up flow test 1 with the Series 1 unit.

For the ramp-up test the output temperature of the water was recorded using a T-type thermocouple as the response time of RTD sensor is much lower than the thermocouple. A sample set of data recorded for this test is shown in Table 6. In this table ‘AI15’ is the outlet water temperature recorded by the thermocouple sensor (°C), and rest of the terms are the same as those defined in the previous section.

MicroHeat CFEWH Test data

Test Conducted at MicroHeat Lab
Test Date: 06/06/12
Ramp up Flow Test 1.1
Series 1 Unit

Overall Inlet test Conditions:
Water flow Rate: 0-4.5 L/min; 4.5-1.5 L/Min

Inlet water Temp: Tank ambient ^{0}C
Water conductivity: 100 µS

Definition of each term in experimental data	
TMPIN	Inlet water temperature (RTD Sensor)
TMPOUT	Outlet water temperature (RTD Sensor)
AI15	Outlet water temperature (Thermocouple Sensor)
FLOWRT	Flow rate of water
CONDUC	Conductivity of water at inlet
P_AVE	Actual average power consumption

Data for Test 1.1

Date	Time	TMPIN	TMPOUT	AI15	FLOWRT	CONDUC	P_AVE
		Average	Average	Instant	Instant	Instant	
		°C	°C	°C	L/MIN	uS	W
06/06/2012	15:17:30	17	16.9	17.1	0	104.8	0.0
06/06/2012	15:17:31	17	16.9	17.1	0	104.8	0.0
06/06/2012	15:17:32	17	16.9	17.1	0	104.8	0.0
06/06/2012	15:17:33	17	16.9	17.1	0	104.8	0.0
06/06/2012	15:17:34	17	16.9	17.1	0	104.8	0.0
06/06/2012	15:17:35	17	16.9	17	0	104.6	1844.0
06/06/2012	15:17:36	17	16.9	17	2.04	104.8	3038.0
06/06/2012	15:17:37	17	16.9	17.4	2.06	104.7	3227.0
06/06/2012	15:17:38	17	16.9	17.4	2.02	105.2	3298.0
06/06/2012	15:17:39	17	16.9	17.3	2	105.4	3350.0
06/06/2012	15:17:40	17	17	17.4	1.99	105.4	3362.0
06/06/2012	15:17:41	17	17	18.2	2.04	105.4	3384.0
06/06/2012	15:17:42	17	17	19	1.99	105.4	3555.0
06/06/2012	15:17:43	17	17.2	20.5	1.99	105.3	3517.0
06/06/2012	15:17:44	17	17.4	22.4	2	105.4	3564.0
06/06/2012	15:17:45	17	17.7	24.2	2.02	105.4	3475.0
06/06/2012	15:17:46	17	18.3	25.8	2.02	105.4	3501.0
06/06/2012	15:17:47	17	18.9	27.6	2.02	105.4	3518.0
06/06/2012	15:17:48	17	19.8	29.4	2.01	105.3	3532.0
06/06/2012	15:17:49	17	20.8	31.1	2	105.2	3542.0
06/06/2012	15:17:50	17	21.8	32.6	2.03	105.3	3551.0
06/06/2012	15:17:51	17	23	34.1	2.05	105.3	3560.0
06/06/2012	15:17:52	17.1	24.2	35.2	2.02	105.4	3506.0
06/06/2012	15:17:53	17	25.5	36.3	2.02	105.2	3516.0
06/06/2012	15:17:54	17	26.7	37.2	2.03	105.3	3456.0
06/06/2012	15:17:55	17	27.9	37.9	2.04	105.3	3457.0
06/06/2012	15:17:56	17.1	29.1	38.6	2.02	105.2	3524.0
06/06/2012	15:17:57	17	30.3	39.2	2	105.1	3530.0
06/06/2012	15:17:58	17	31.3	39.7	2.07	105	3468.0
06/06/2012	15:17:59	17	32.3	40	2	105.1	3506.0
06/06/2012	15:18:00	17	33.2	40.4	2.05	105.1	3505.0
06/06/2012	15:18:01	17	34	40.7	2.01	105.1	3501.0
06/06/2012	15:18:02	17	34.8	40.9	2.02	105	3372.0
06/06/2012	15:18:03	17	35.4	41.1	2.01	105	3465.0
06/06/2012	15:18:04	17	36.1	41.3	2.02	104.9	5563.0

Table 6: Sample test data for the ramp-up flow test 1.1 with Series 1 unit.

2.4.3.2 Rapid increase of flow rate (test 2)

A ramp-up test for the Series 1 unit was also conducted by a rapid increase of the flow rate from zero up to the maximum allowable limit of the heater capacity in one step. This ramp-up flow test is defined as ramp-up test 2. Six tests of this kind were conducted (labeled as from 2.1 to 2.6), according to the parameters in Table 7. A sample set of data recorded for this test is shown in Table 8.

	Input Test Condition (Ramp up Flow, Series 1 Unit)			
Test No	**Input Temp (^oC)**	**Flow Rate (L/min)**	**Water Conductivity (uS)**	**Set Output Temp. in Heater Unit (^oC)**
2.1	Tank Ambient	0-3.7	100	45
2.2	25	0-5.8	100	45
2.3	Tank Ambient	0-3.8	300	45
2.4	25	0-5.5	300	45
2.5	Tank Ambient	0-4.3	700	45
2.6	25	0-5	700	45

Table 7: Input test conditions for the ramp-up flow test 2 with the Series 1 unit.

MicroHeat CFEWH Test Data

Test Conducted at MicroHeat Lab
Test Date: 06/06/12
Ramp up Flow Test 2.1
Series 1 Unit

Overall Inlet test Conditions:
Water flow Rate: 0-3.7 L/min (Straight)
Inlet water Temp: Tank ambient ^{0}C
Water conductivity: 100 µS

Definition of each term in experimental data	
TMPIN	Inlet water temperature (RTD Sensor)
TMPOUT	Outlet water temperature (RTD Sensor)
AI15	Outlet water temperature (Thermocouple Sensor)
FLOWRT	Flow rate of water
CONDUC	Conductivity of water at inlet
P_AVE	Actual average power consumption

Test Data 2.1

Date	Time	TMPIN	TMPOUT	AI15	FLOWRT	CONDUC	P_AVE
		Average	Average	Instant	Instant	Instant	
		°C	°C	°C	L/MIN	uS	W
06/06/2012	15:28:18	16.6	16.9	17	0	104.5	0.0
06/06/2012	15:28:19	16.6	16.9	17	0	104.3	0.0
06/06/2012	15:28:20	16.6	16.9	17	0	104.4	0.0
06/06/2012	15:28:21	16.6	16.9	17	0	104.3	0.0
06/06/2012	15:28:22	16.6	16.9	17	0	104.5	78.0
06/06/2012	15:28:23	16.6	16.9	17	0	104.4	3368.0
06/06/2012	15:28:24	16.6	16.9	17.2	3.94	104.4	6370.0
06/06/2012	15:28:25	16.6	16.9	17.1	3.92	104.3	7109.0
06/06/2012	15:28:26	16.6	16.9	17	3.91	104.3	7444.0
06/06/2012	15:28:27	16.6	16.9	18	3.86	104.3	7439.0
06/06/2012	15:28:28	16.6	16.9	19.1	3.93	104.4	7669.0
06/06/2012	15:28:29	16.6	17.1	23.1	3.92	104.3	7543.0
06/06/2012	15:28:30	16.5	17.5	27	3.93	104.2	7633.0
06/06/2012	15:28:31	16.5	18.3	31	3.95	104.3	7630.0
06/06/2012	15:28:32	16.5	19.6	34.9	3.96	104.3	7452.0
06/06/2012	15:28:33	16.5	21.2	37.7	3.94	104.2	7364.0
06/06/2012	15:28:34	16.5	23.2	39.9	3.94	104.3	7424.0
06/06/2012	15:28:35	16.5	25.3	41.3	3.93	104.2	7367.0
06/06/2012	15:28:36	16.5	27.5	42.1	3.94	104.4	7313.0
06/06/2012	15:28:37	16.5	29.6	42.7	3.9	104.3	7374.0
06/06/2012	15:28:38	16.5	31.5	42.9	3.95	104.3	7393.0
06/06/2012	15:28:39	16.5	33.2	43.2	3.93	104.2	7403.0
06/06/2012	15:28:40	16.5	35.2	43.3	3.95	104.2	7421.0
06/06/2012	15:28:41	16.5	35.9	43.3	3.95	104.2	7337.0
06/06/2012	15:28:42	16.5	37	43.5	3.9	104.1	7510.0
06/06/2012	15:28:43	16.5	37.9	43.7	3.93	104.2	7472.0
06/06/2012	15:28:44	16.5	38.7	43.9	3.92	104.1	7321.0
06/06/2012	15:28:45	16.5	39.3	44	3.93	104.1	7361.0
06/06/2012	15:28:46	16.5	39.8	44.2	3.96	104	7354.0
06/06/2012	15:28:47	16.5	40.3	44.4	3.94	104.1	7369.0

Table 8: Sample test data for ramp-up flow test 2.1 with the Series 1 unit.

2.4.4 Standby energy consumption test for Series 1 unit (Premium Cover & Standard cover unit)

MicroHeat has developed two types of heater unit: one a premium unit with an exterior cover that includes the temperature setting and flow rate display panel; and the second the standard unit without the display panel. Both the units were tested for standby energy consumption (Figure 3). For this test both the units were left switched on without operating the unit and the power consumption was recorded every thirty seconds. Sample sets of data for both the tests are shown in Tables 9 and 10.

Premium Unit

Standard Unit

Fig. 3: Standby energy consumption test for premium and standard Series 1 unit.

MicroHeat CFEWH Test Data		
Test Conducted at MicroHeat Lab		
Test Date: 06/06/12 - 07/07/12		
Standby Energy Consumption Test		
Series 1 Premium Unit with Temperature Setting and Flow Rate Display Panel		
Overall Inlet test Conditions:		
The CFEWH unit connected to the main power supply only		
Test Result:		
Energy consumption rate of single phase premium unit with temperature setting and flow rate display panel is 0.94 W		

Test Data		
DATE	TIME	P_AVE[W]_1
06/06/2012	15:59:07	0.000
06/06/2012	15:59:37	0.950
06/06/2012	16:00:07	0.950
06/06/2012	16:00:37	0.950
06/06/2012	16:01:07	0.950
06/06/2012	16:01:37	0.950
06/06/2012	16:02:07	0.950
06/06/2012	16:02:37	0.950
06/06/2012	16:03:07	0.950
06/06/2012	16:03:37	0.950
06/06/2012	16:04:07	0.950
06/06/2012	16:04:37	0.950
06/06/2012	16:05:07	0.950
06/06/2012	16:05:37	0.950
06/06/2012	16:06:07	0.950
06/06/2012	16:06:37	0.950
06/06/2012	16:07:07	0.950
06/06/2012	16:07:37	0.950
06/06/2012	16:08:07	0.950
06/06/2012	16:08:37	0.950
06/06/2012	16:09:07	0.950
06/06/2012	16:09:37	0.950
06/06/2012	16:10:07	0.950
06/06/2012	16:10:37	0.950
06/06/2012	16:11:07	0.950
06/06/2012	16:11:37	0.950
06/06/2012	16:12:07	0.950
06/06/2012	16:12:37	0.950
06/06/2012	16:13:07	0.950
06/06/2012	16:13:37	0.950
06/06/2012	16:14:07	0.950
06/06/2012	16:14:37	0.950
06/06/2012	16:15:07	0.950

Table 9: Sample test data for standby energy consumption for the Series 1 unit with premium cover.

MicroHeat CFEWH Test Data		
Test Conducted at MicroHeat Lab		
Test Date: 07/07/12		
Standby Energy Consumption Test		
Series 1 Standard Unit without Temperature Setting and Flow Rate Display Panel		
Overall Inlet test Conditions:		
The CFEWH unit connected to the main power supply only		
Test Result:		
Energy consumption rate of single phase premium unit without temperature setting and flow rate display panel is 0.61 W		
Test Data		
DATE	TIME	P_AVE[W]_1
07/06/2012	08:44:07	0.600
07/06/2012	08:44:37	0.600
07/06/2012	08:45:07	0.610
07/06/2012	08:45:37	0.610
07/06/2012	08:46:07	0.610
07/06/2012	08:46:37	0.600
07/06/2012	08:47:07	0.600
07/06/2012	08:47:37	0.600
07/06/2012	08:48:07	0.590
07/06/2012	08:48:37	0.590
07/06/2012	08:49:07	0.590
07/06/2012	08:49:37	0.590
07/06/2012	08:50:07	0.590
07/06/2012	08:50:37	0.590
07/06/2012	08:51:07	0.590
07/06/2012	08:51:37	0.590
07/06/2012	08:52:07	0.590
07/06/2012	08:52:37	0.600
07/06/2012	08:53:07	0.600
07/06/2012	08:53:37	0.590
07/06/2012	08:54:07	0.590
07/06/2012	08:54:37	0.590
07/06/2012	08:55:07	0.590
07/06/2012	08:55:37	0.600
07/06/2012	08:56:07	0.600
07/06/2012	08:56:37	0.600
07/06/2012	08:57:07	0.600
07/06/2012	08:57:37	0.600
07/06/2012	08:58:07	0.600
07/06/2012	08:58:37	0.600
07/06/2012	08:59:07	0.600
07/06/2012	08:59:37	0.600
07/06/2012	09:00:07	0.610

Table 10: Sample test data for standby energy consumption for the Series 1 unit with standard cover.

2.4.5 Steady-flow test for Series 2 unit

Steady-flow tests with Series 2 unit were conducted for two inlet water temperatures: tank ambient and 25°C. Tests were conducted for three flow rates: 4, 7 and 12 L/min; and two different water conductivities: 100 and 600 µS. In total 9 tests were conducted for the Series 2 unit in steady flow condition, and all the test parameters are tabulated in Table 11.

	Input Test Condition (Steady Flow, Series 2 Unit)				
Test No	**Input Temp (°C)**	**Flow Rate (L/min)**	**Water Conductivity (uS)**	**Time (min)**	**Set Output Temp. in Heater Unit (°C)**
1	Tank Ambient	4	100	5	45
2	Tank Ambient	7	100	5	45
3	Tank Ambient	12	100	5	45
4	Tank Ambient	12	100	5	50
5	25	4	100	5	45
6	25	7	100	5	45
7	Tank Ambient	4	600	3	45
8	Tank Ambient	7	600	160 Sec	45
9	Tank Ambient	12	600	3	45

Table 11: Input test conditions for the steady flow tests of the Series 2 unit.

For all the tests, output temperatures were set to be 45°C, except in test 4 in which it was 50°C. The photograph of overall experimental set up for the Series 2 unit is shown in Figure 4.

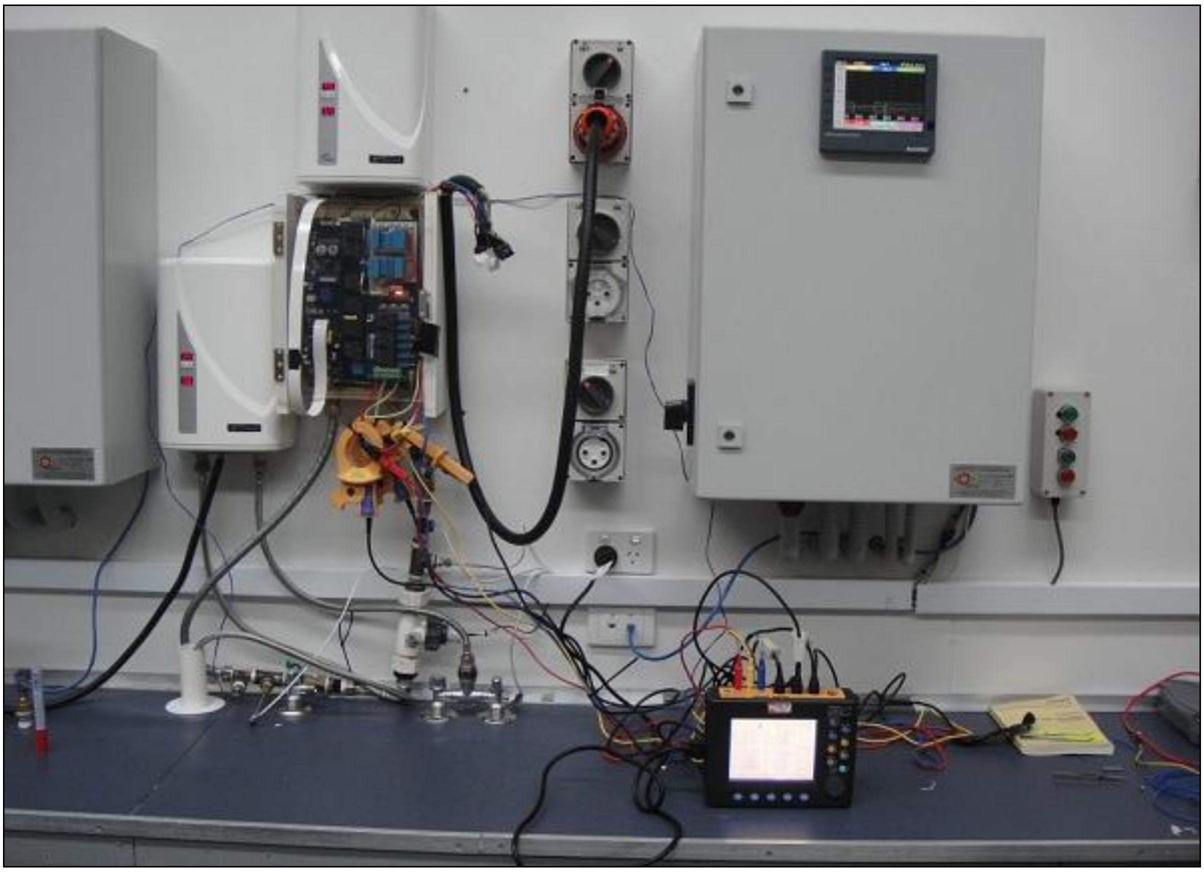

Fig. 4: Overall experimental set up for Series 2 unit.

A sample set of data recorded for this test is shown in Table 12. In the data table 'TMPIN' is the inlet water temperature recorded by RTD sensor (°C), 'AI15' is the outlet water temperature recorded by the thermocouple sensor (°C), 'TMPOUT' is the outlet water temperature (°C) recorded by RTD sensor, 'FLOWRT' is the flow rate of water (L/min), 'CONDUC' is the conductivity of water at inlet (µS), and 'P_AVE[W]_1' is the actual average power consumption (W).

MicroHeat CFEWH Test Data

Test Conducted at MicroHeat Lab

Test Date: 07/06/12

Steady Flow Test 1

Series 2 Unit

Overall Inlet test Conditions:

Water flow rate (FLOWRT): 4 L/min

Inlet water temp (TMPIN): Tank ambient °C

Water conductivity (CONDUC): 100 µS

Definition of each term in experimental data	
AI15	Outlet water temperature (Thermocouple Sensor)
TMPIN	Inlet water temperature (RTD Sensor)
TMPOUT	Outlet water temperature (RTD Sensor)
FLOWRT	Flow rate of water
CONDUC	Conductivity of water at inlet
P_AVE[W]_1	Actual average power consumption

Total Duration of Test		300	sec
		5	min

Data for Test 1

Date	Time	AI15	TMPIN	TMPOUT	FLOWRT	CONDUC	P_AVE [W]_1
		Instant	Average	Average	Instant	Instant	
		°C	°C	°C	L/MIN	uS	W
07/06/2012	17:02:00	44.5	17.1	44.4	4.3	114.1	8024.0
07/06/2012	17:02:01	44.6	17.1	44.4	4.32	114.3	8036.0
07/06/2012	17:02:02	44.5	17.1	44.5	4.3	114.2	8013.0
07/06/2012	17:02:03	44.6	17.1	44.5	4.31	114.1	7952.0
07/06/2012	17:02:04	44.5	17.1	44.5	4.29	114.3	7983.0
07/06/2012	17:02:05	44.5	17.1	44.5	4.24	114.1	8025.0
07/06/2012	17:02:06	44.5	17.1	44.6	4.23	114.2	8077.0
07/06/2012	17:02:07	44.6	17.1	44.6	4.27	114.2	7952.0
07/06/2012	17:02:08	44.5	17.1	44.6	4.25	114.2	7946.0
07/06/2012	17:02:09	44.7	17.1	44.6	4.24	114.3	7962.0
07/06/2012	17:02:10	44.8	17.1	44.6	4.22	114.4	7971.0
07/06/2012	17:02:11	44.8	17.2	44.7	4.24	114.4	7955.0
07/06/2012	17:02:12	44.8	17.2	44.7	4.22	114.4	7951.0
07/06/2012	17:02:13	44.8	17.2	44.7	4.26	114.3	8065.0
07/06/2012	17:02:14	44.7	17.2	44.7	4.23	114.2	8017.0
07/06/2012	17:02:15	44.7	17.2	44.8	4.24	114.5	7976.0
07/06/2012	17:02:16	44.7	17.2	44.8	4.23	114.4	7966.0
07/06/2012	17:02:17	44.8	17.2	44.8	4.22	114.4	7968.0
07/06/2012	17:02:18	44.8	17.2	44.8	4.25	114.4	7961.0
07/06/2012	17:02:19	44.8	17.2	44.8	4.24	114.4	7983.0
07/06/2012	17:02:20	44.8	17.2	44.8	4.22	114.4	7972.0
07/06/2012	17:02:21	44.8	17.2	44.9	4.25	114.4	7971.0
07/06/2012	17:02:22	44.8	17.2	44.9	4.24	114.4	7963.0
07/06/2012	17:02:23	44.8	17.2	44.9	4.22	114.4	7972.0
07/06/2012	17:02:24	44.8	17.2	44.9	4.24	114.4	7977.0
07/06/2012	17:02:25	44.8	17.2	44.9	4.23	114.4	7985.0
07/06/2012	17:02:26	44.8	17.2	44.9	4.23	114.4	7991.0
07/06/2012	17:02:27	44.9	17.2	44.9	4.22	114.4	8002.0

Table 12: Sample test data for steady-flow test 1 with the Series 2 unit.

2.4.6 Ramp-up test for Series 2 unit

2.4.6.1 Gradual increase and decrease of flow rate (test 1)

The dynamic response of the Series 2 heater was tested by gradually varying the flow rate from the minimum (4.5 L/min) to the maximum allowable limit (12 L/min) of the heater capacity and then back to the minimum limit. The output temperature was set to be 45°C. Tests were conducted for two input temperatures: tank ambient and 25 ^{0}C; and for two different water conductivities: 100 and 600 μS. Four tests in total were conducted under the ramp-up flow condition, labeled as from 1.1 to 1.4, and all the test parameters are tabulated in Table 13. A sample set of data recorded for this test is shown in Table 14.

	Input Test Condition (Ramp up Flow, Series 2 Unit)			
Test No	Input Temp (^{o}C)	Flow Rate (L/min)	Water Conductivity (uS)	Set Output Temp. in Heater Unit (^{o}C)
1.1	Tank Ambient	4.5-8.3 / 8.3-4.5	100	45
1.2	25	5.2-9.8 / 9.8-3.7	100	45
1.3	Tank Ambient	4.8-11.8 / 11.8-4.7	100	45
1.4	Tank Ambient	4-11.5 / 11.5-3	600	45

Table 13: Input test conditions for the ramp-up flow test 1 with the Series 2 unit.

MicroHeat CFEWH Test Data

Test Conducted at MicroHeat Lab
Test Date: 08/06/12
Ramp-up Flow Test 1.2
Series 2 Unit

Overall Inlet test Conditions:

Water flow Rate: 5.2-9.8 L/min; 9.8-3.7 L/Min

Inlet water Temp: 25 ^{0}C

Water conductivity: 100 µS

Definition of each term in experimental data	
TMPIN	Inlet water temperature (RTD Sensor)
TMPOUT	Outlet water temperature (RTD Sensor)
AI15	Outlet water temperature (Thermocouple Sensor)
FLOWRT	Flow rate of water
CONDUC	Conductivity of water at inlet
P_AVE	Actual average power consumption

Test Data 1.2

Date	Time	TMPIN	TMPOUT	AI15	FLOWRT	CONDUC	P_AVE
		Average	Average	Instant	Instant	Instant	
		°C	°C	°C	L/MIN	uS	W
08/06/2012	14:48:44	24.8	25.2	25.3	2.81	96.2	5133.0
08/06/2012	14:48:45	24.7	25.2	25.3	5.33	96.9	6837.0
08/06/2012	14:48:46	24.6	25.2	25.1	5.36	102.2	7227.0
08/06/2012	14:48:47	24.6	25.3	26.1	5.29	100.6	7461.0
08/06/2012	14:48:48	24.6	25.3	28.8	5.32	100	7606.0
08/06/2012	14:48:49	24.6	25.6	32.1	5.37	99.3	7680.0
08/06/2012	14:48:50	24.5	26.1	35.2	5.33	98.7	7762.0
08/06/2012	14:48:51	24.5	27.1	37.9	5.35	98.6	7761.0
08/06/2012	14:48:52	24.5	28.3	40	5.34	98.5	7767.0
08/06/2012	14:48:53	24.5	29.8	41.4	5.33	98.4	7729.0
08/06/2012	14:48:54	24.6	31.3	42.4	5.33	98.2	7764.0
08/06/2012	14:48:55	24.6	32.9	43.1	5.33	98.3	7766.0
08/06/2012	14:48:56	24.6	34.4	43.6	5.26	98.1	7779.0
08/06/2012	14:48:57	24.6	35.7	43.9	5.35	98.1	7784.0
08/06/2012	14:48:58	24.6	37	44.2	5.22	98.2	7815.0
08/06/2012	14:48:59	24.7	38.1	44.4	5.34	98.1	7815.0
08/06/2012	14:49:00	24.6	39	44.6	5.27	97.9	7802.0
08/06/2012	14:49:01	24.6	39.8	44.8	5.32	97.6	7780.0
08/06/2012	14:49:02	24.6	40.5	44.9	5.3	97.6	7808.0
08/06/2012	14:49:03	24.6	41.1	45.1	5.3	97.6	7792.0
08/06/2012	14:49:04	24.6	41.7	45.2	5.29	97.4	7786.0
08/06/2012	14:49:05	24.6	42.1	45.2	5.35	97.5	7762.0
08/06/2012	14:49:06	24.6	42.5	45.3	5.32	97.3	7767.0
08/06/2012	14:49:07	24.6	42.8	45.4	5.29	97.3	7756.0
08/06/2012	14:49:08	24.6	43.1	45.4	5.33	97.2	7737.0
08/06/2012	14:49:09	24.6	43.4	45.4	5.35	97.1	7723.0
08/06/2012	14:49:10	24.6	43.6	45.4	5.31	97	7688.0
08/06/2012	14:49:11	24.6	43.8	45.5	5.17	96.9	7778.0
08/06/2012	14:49:12	24.6	43.9	45.5	5.35	96.9	7718.0

Table 14: Sample test data for ramp up flow test 1.2 with the Series 2 unit.

2.4.6.2 Rapid increase of flow rate (test 2)

A ramp-up test for the Series 2 unit was also conducted in a one-step increase of the flow rate from zero up to the maximum allowable limit of the heater capacity. For this condition four tests were conducted (labeled as from 2.1 to 2.4), according to the parameters in Table 15. A sample set of data recorded for this test is shown in Table 16.

	Input Test Condition (Ramp up Flow, Series 2 Unit)			
Test No	Input Temp (^oC)	Flow Rate (L/min)	Water Conductivity (uS)	Set Output Temp. in Heater Unit (^oC)
2.1	Tank Ambient	0-8.7	100	45
2.2	25	0-9.2	100	45
2.3	Tank Ambient	0-11.6	100	45
2.4	Tank Ambient	0-11.5	600	45

Table 15: Input test conditions for ramp-up flow test 2 with the Series 2 unit.

MicroHeat CFEWH Test Data

Test Conducted at MicroHeat Lab
Test Date: 08/06/12
Ramp up Flow Test 2.2
Series 2 Unit

Overall Inlet test Conditions:
Water flow Rate: 0-9.2 L/min (Straight)

Inlet water Temp: 25 ^{0}C
Water conductivity: 100 µS

Definition of each term in experimental data	
TMPIN	Inlet water temperature (RTD Sensor)
TMPOUT	Outlet water temperature (RTD Sensor)
AI15	Outlet water temperature (Thermocouple Sensor)
FLOWRT	Flow rate of water
CONDUC	Conductivity of water at inlet
P_AVE	Actual average power consumption

Test Data 2.2

Date	Time	TMPIN	TMPOUT	AI15	FLOWRT	CONDUC	P_AVE
		Average	Average	Instant	Instant	Instant	
		°C	°C	°C	L/MIN	uS	W
08/06/2012	14:58:30	25	25.3	25.5	0	88.5	0.0
08/06/2012	14:58:31	25	25.3	25.5	0	88.3	4.0
08/06/2012	14:58:32	25	25.3	25.5	0	88.3	1282.0
08/06/2012	14:58:33	25	25.3	25	0	88.4	7283.0
08/06/2012	14:58:34	24.9	25.3	25.5	8.19	88.2	10011.0
08/06/2012	14:58:35	24.9	25.3	25.6	9.02	93.1	11682.0
08/06/2012	14:58:36	24.8	25.4	28.6	9.34	90.3	11751.0
08/06/2012	14:58:37	24.7	25.6	32.8	9.28	88.1	12160.0
08/06/2012	14:58:38	24.5	26.3	37.1	9.27	88.5	12165.0
08/06/2012	14:58:39	24.4	27.4	39.6	9.31	89.7	12174.0
08/06/2012	14:58:40	24.4	28.8	40.6	9.31	90.7	12208.0
08/06/2012	14:58:41	24.4	30.5	41.3	9.28	90.9	12188.0
08/06/2012	14:58:42	24.5	32.1	41.8	9.3	90.7	12156.0
08/06/2012	14:58:43	24.6	33.7	42.4	9.3	90.6	12019.0
08/06/2012	14:58:44	24.6	35	42.6	9.34	90.7	11976.0
08/06/2012	14:58:45	24.7	36.2	42.8	9.25	90.9	11984.0
08/06/2012	14:58:46	24.7	37.3	42.9	9.37	90.9	11997.0
08/06/2012	14:58:47	24.7	38.2	42.9	9.26	90.8	12002.0
08/06/2012	14:58:48	24.7	38.9	42.9	9.27	90.9	11965.0
08/06/2012	14:58:49	24.7	39.6	42.9	9.25	90.7	11954.0
08/06/2012	14:58:50	24.7	40.1	43	9.27	90.7	11965.0
08/06/2012	14:58:51	24.8	40.5	43	9.33	90.8	11960.0
08/06/2012	14:58:52	24.8	40.8	43	9.25	90.9	11974.0
08/06/2012	14:58:53	24.8	41.1	43.1	9.32	91.3	11993.0
08/06/2012	14:58:54	24.8	41.4	43.1	9.31	90.9	11945.0
08/06/2012	14:58:55	24.8	41.6	43.1	9.25	90.7	11976.0
08/06/2012	14:58:56	24.8	41.8	43.2	9.32	90.8	11956.0
08/06/2012	14:58:57	24.8	41.9	43.3	9.38	90.6	12020.0
08/06/2012	14:58:58	24.8	42.1	43.2	9.29	90.5	12000.0
08/06/2012	14:58:59	24.9	42.2	43.2	9.28	90.6	12016.0

Table 16: Sample test data for ramp-up flow test 2.2 with the Series 2 unit.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 INTRODUCTION

This chapter presents all the experimental results obtained and estimates of the performance for both the Series 1 and Series 2 CFEWH units.

3.2 RESULTS FOR STEADY-FLOW TESTS OF SERIES 1 UNIT

Using the test data obtained and described in section 2.4.2, the instantaneous energy efficiency at each data point, and the overall average energy efficiency of the heater over the full test period were estimated.

The instantaneous energy efficiency of the water heater was estimated as follows:

$$\eta_{inst} = \frac{P_{th}}{P_{act}} = \frac{\dot{m} C_p \Delta T}{P_{act}}$$

where, P_{th} = Theoretical power required (W), P_{act} = Actual power input (W), η_{inst} = efficiency, $\dot{m}$ = mass flow rate of water (gm/s), C_p = specific heat of water (J/gm^{0}C), ΔT = (T_{out} – T_{in}) = difference between the outlet and inlet water temperatures (°C).

The overall average energy efficiency of the heater for the test period can be expressed as:

$$\eta_{ovall} = \frac{E_{th}}{E_{act}}$$

where, E_{th} = theoretical energy required (Wh) to raise the temperature of water by the measured amounts, and E_{act} = actual energy input (Wh).

A sample set of results for the steady-flow test 1 for the Series 1 unit is shown in Table 17. The overall energy efficiency for test 1 was in this case 99.6%.

MicroHeat CFEWH Analysed Results

Specific Heat of Water	4186	J/kg°C

Note: Correction factor for flow rate:

Flow meter was giving reading higher value than actual flow rate

Flow meter calibrated for different flow ranges

For 1.5 to 2 L/min flow range the factor is 0.15 L/min less

Flow meter Reading	Calibartion Factor	Calibrated Flow rate
L/min	L/min	L/min
1.5	0.15	1.35

Definition of each term in results	
$(T_{in}-T_{out})$	Outlet and Inlet water temperature difference (Delta T)
P_{th}	Theoretical power required to heat up the water
η_{inst}	Instantaneous efficiency of the unit at each data point
E_{act}	Total actual electrical energy consumed to heat up the water
E_{th}	Total theoretical total energy required to heat up the water
$\eta_{ov\,all}$	Overall effciency of the unit in the experiemntal period

Results for Test 1 (Steady Flow Test, Series 1 Unit)

Calibrated Flow Rate	Delta T	Theoretical Power Required	Instantaneous Efficiency	Actual Total Energy Consumed	Theoretical Total Energy Required	Overall Efficiency	Standard deviation of overall effieincy (%points)
	$(T_{in}-T_{out})$	P_{th}	η_{inst}	E_{act}	E_{th}	$\eta_{ov\,all}$	
L/Min	°C	W	%	Wh	Wh	%	
1.6	28.1	3136.7	106.7	256.9	255.9	99.6	2.6
1.55	28.1	3038.7	94.0				
1.58	28.1	3097.5	100.9				
1.57	28.1	3077.9	97.4				
1.57	28.1	3077.9	101.9				
1.63	28	3184.2	106.3				
1.58	28	3086.5	100.8				
1.59	28	3106.0	101.2				
1.61	27.9	3133.8	100.3				
1.6	27.9	3114.4	99.4				
1.58	27.8	3064.4	102.1				
1.6	27.8	3103.2	103.4				
1.58	27.8	3064.4	100.0				
1.58	27.7	3053.4	101.0				
1.57	27.7	3034.1	99.3				
1.57	27.7	3034.1	99.3				
1.58	27.7	3053.4	98.2				
1.58	27.7	3053.4	98.0				
1.59	27.7	3072.7	97.4				
1.58	27.6	3042.4	96.6				
1.57	27.7	3034.1	97.5				
1.56	27.6	3003.9	96.0				

Table 17: Results for steady-flow test 1 with the Series 1 unit.

From the above results table, it is apparent that some of the calculated instantaneous efficiency values came out to be more than 100%, which is in principle impossible. Error analysis for the calculated instantaneous efficiency was done by using the equations described in section 2.3.1 and the detail analysis is given in the Appendix B. The error was estimated to be in the range of ±2%.

The most likely explanation of the anomalous efficiency results is a small systematic error in the instantaneous flow meter readings. It is to be noted that a large correction factor had to be applied to adjust the flow meter readings as mentioned in section 2.3.1, so that they compared with the results calculated during an independent calibration test. There was also some indication of a random error in the flow meter readings.

Moreover, the CFEWH unit determines the amount of power to apply to the water based on the input temperature sensor and input flow rate, which are included in the CFEWH unit. The data recording station records externally to the CFEWH unit the input/output temperature and flow rate. The latter readings were used to calculate the theoretical power needed to raise the temperature of the flowing water. The input temperature sensor recording station was located approximately 500 mm away from the input temperature sensor inside the unit; the input flow-rate sensor recording station was approximately 250 mm away from the flow-rate sensor inside the unit; and the output temperature sensor recording station was approximately 600 mm away from the output temperature sensor inside the unit. So, the combined effect of possible systematic error in the flow meter, random errors across all sensors, and the spatial separations of all the sensors used in the experiment might have affected calculated instantaneous efficiency results.

As mentioned in section 2.4.2, in total 18 tests were conducted for the Series 1 unit in the steady-flow condition, and a summary of all the test results is provided in Table 18.

Summary of Results for Test 1 to 18 (Steady Flow Test, Series 1 Unit)							
Test No	Time (min)	Avearge Flow Rate (L/min)	Average Water Conductivity (uS)	Average Inlet Temp. (°C)	Average Outlet Temp. (°C)	Average Actual Power Consumed (W)	Overall Efficiency (%)
1	5	1.6	101.4	17.5	45.4	3083.2	99.6
2	5	3.0	100.1	16.9	45.0	5867.0	99.7
3	5	4.0	99.7	16.8	45.0	7844.3	99.7
4	5	1.5	91.3	24.7	45.4	2254.4	98.9
5	5	2.9	91.4	24.8	45.3	4239.2	99.0
6	5	3.9	91.7	24.9	45.2	5618.4	99.1
7	5	1.6	337.7	17.0	44.9	3114.0	99.7
8	5	3.0	334.7	16.6	45.1	5924.5	100.0
9	5	4.0	333.5	16.4	44.9	7860.1	100.0
10	5	1.6	320.0	24.9	45.2	2256.4	100.0
11	5	2.9	319.6	24.8	45.2	4210.5	99.6
12	5	3.9	320.6	24.8	45.1	5516.5	99.6
13	5	1.6	710.3	17.4	45.2	3063.1	100.0
14	5	3.0	703.2	16.8	45.1	5910.4	99.9
15	5	4.0	702.1	16.6	44.9	7785.2	100.3
16	5	1.6	681.7	24.8	45.3	2273.5	99.9
17	5	2.9	680.6	24.8	45.3	4198.9	100.0
18	5	4.0	684.7	24.8	45.2	5639.2	99.9

Table 18: Summary of test results for the steady-flow tests of the Series 1 unit.

From this table it was found that measured mean steady-state efficiency of the series 1 unit was 99.7 ±2%. In sum, the measured overall efficiency was very close to 100% irrespective to the input condition of water flow rate, conductivity and inlet temperature.

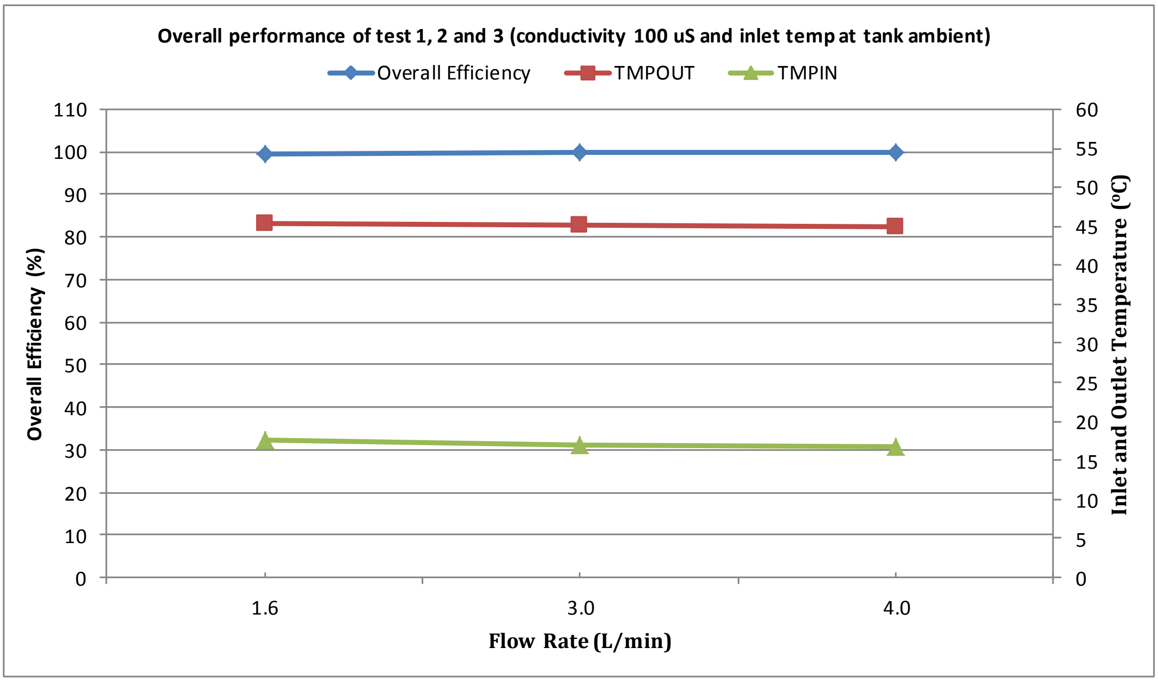

Fig. 5: Overall performance of the Series 1 unit at different water flow rate.

Figure 5 shows the overall efficiency and set output temperature of the Series 1 unit at 1.6, 3 and 4 L/min water flow rates for tests 1, 2 and 3 respectively. The inlet water temperature was tank ambient, that is around 17 ^{0}C with ±0.5°C variation, and conductivity was around 100 µS with ±1 µS variation. From this figure it can be seen that the overall steady-state efficiency was 99.7% which is very close to 100%, and the output temperature was fairly constant at 45°C with ±0.4°C variation.

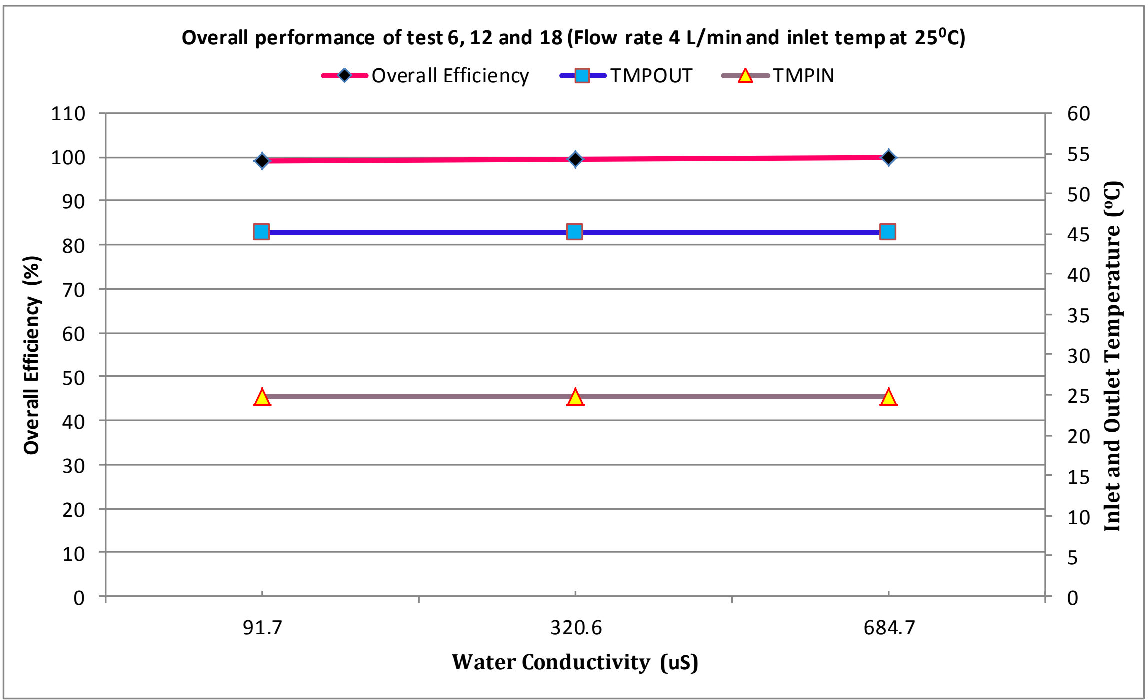

Fig. 6: Overall performance of the Series 1 unit at different water conductivities.

To see the effect of water conductivity on the overall efficiency of the heater, a graph has been plotted for overall efficiency of the Series 1 unit at three average water conductivities: 92, 321 and 685 µS for tests 6, 12 and 18 respectively (Figure 6). For these tests the average inlet water temperature was 25 ^{0}C with ±0.2°C variation, and the flow rate was 4 L/min with ±0.1 L/min variation. From this figure it is also apparent that overall steady-state efficiency was 99.5% which is very close to 100%, and the output temperature was fairly constant at 45°C with ±0.2°C variation.

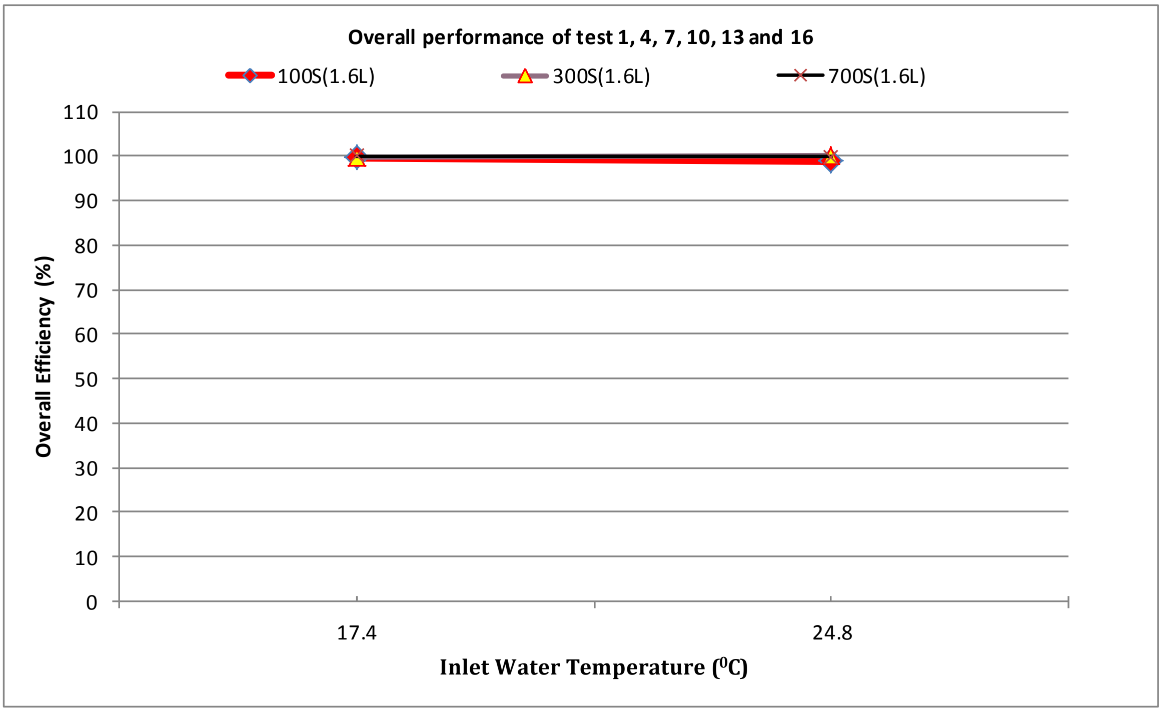

Fig. 7: Overall performance of the Series 1 unit at different inlet water temperatures.

The effect of inlet water temperature on overall efficiency can be seen from Figure 7. Graphs were plotted for two inlet water temperatures: 17.4 and 24.8°C. For these tests, the water flow rate was 1.6 L/min and the conductivities were 100, 300 and 700 µS. The overall efficiency was found to be 99.7% which is very close to 100% in all the cases irrespective to inlet water temperatures and water conductivities.

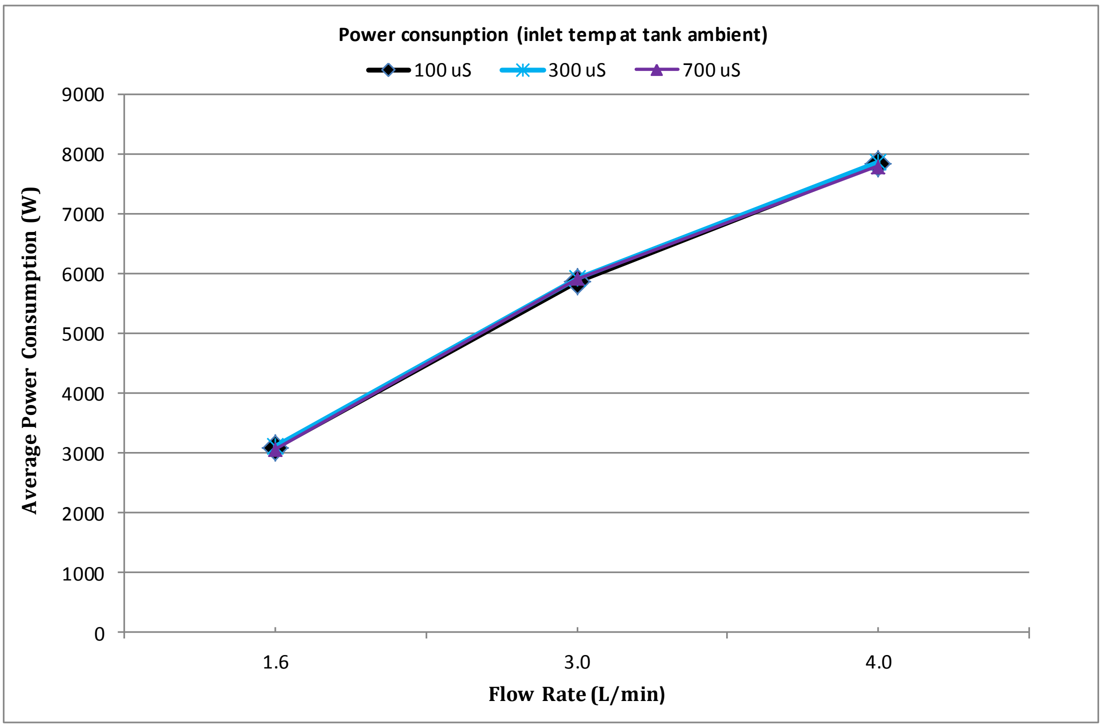

Fig. 8: Average power consumption for the Series 1 unit at different water flow rates.

To see the effect of water flow rate on the power requirement to heat the water, a graph has been plotted for average power consumption for three different flow rates, 1.6, 3 and 4 L/min; and three conductivities of water, 100, 300 and 700 µS (Figure 8). For these tests the average inlet water temperature was tank ambient, which was around 17 ^{0}C with ±0.5°C variation, and average output temperature was 45°C with ±0.5°C variation. It can be seen from the graph that the heater unit draws power according to the flow rate of water. For example, when the flow rate was 1.6 L/min the power consumption was around 3096 W with ±30 W variation, and for the flow rate of 4 L/min power consumption was around 7830 W with ±45 W variation. It is apparent from the graph that the power consumption is same for any particular flow rate of water irrespective of water conductivities.

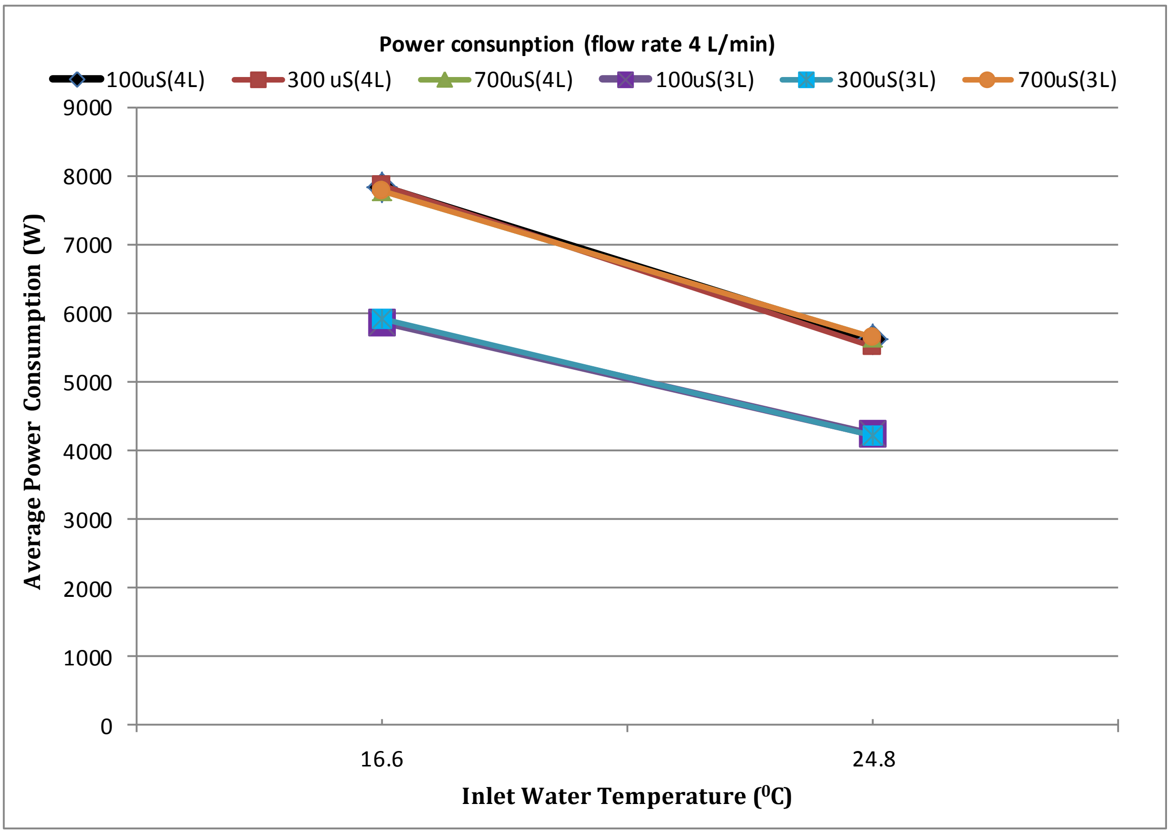

Fig. 9: Average power consumption for the Series 1 unit at different inlet water temperatures.

To see the effect of inlet water temperature on the power required to heat the water, a graph has been plotted for average power consumption for two different average inlet temperatures of water that simulate winter and summer ambient water temperature conditions: namely 17°C and 25°C (Figure 9). For these tests, the water flow rates were 3 L/min and 4 L/min and the three conductivities of water: 100, 300 and 700 µS. It can be seen that there was a significant reduction in power consumption when the inlet water temperature was increased. For example, when the water flow rate was 4 L/min and inlet water temperature was 17°C the average power consumption was around 7830 W with ±45 W variation for 45°C output temperature. For the same flow rate and same output water temperature, when the inlet water temperature was 25°C the average power consumption was reduced to around 5628 W with ±15 W variation. So, as expected there is substantially lower energy consumption in summer by this unit.

3.3 RESULTS FOR RAMP-UP TESTS OF SERIES 1 UNIT

3.3.1 Gradual increase and decrease of flow rate (test 1)

Results obtained from the ramp-up flow test 1.1 for the Series 1 unit with gradual increase and decreases of flow rate are shown in Figure 10. For the Series 1 unit the heater did not start operating until it reached the minimum flow rate of 1.5 L/min. For this test the flow rate was increased in steps from 0 to 1.9, 3.5 and 4.5 L/min, and then stepped down from 4.5 to 2.8 and 1.6 L/min. For this test the average conductivity of water was 100 µS. From Figure 10 it can be seen that from tank ambient temperature 17 ^{0}C to reach the desired set output temperature 45°C, it took around 45 seconds over the three step increment of flow rate to 4.5 L/min. It is also apparent that when flow rate was increased rapidly from a lower to a higher level, the output temperature dropped from the set output temperature. When the flow rate was decreased rapidly from a higher to a lower level, the output temperature first exceeded the set output temperature and then came back to desired output temperature. It took around 8 to 10 seconds for output temperature to become stabilise when flow rate change from one level to another higher or lower level. In total six gradual ramp-up flow tests were conducted for test 1. The remaining result graphs for the other similar ramp-up tests are given in Appendix C.

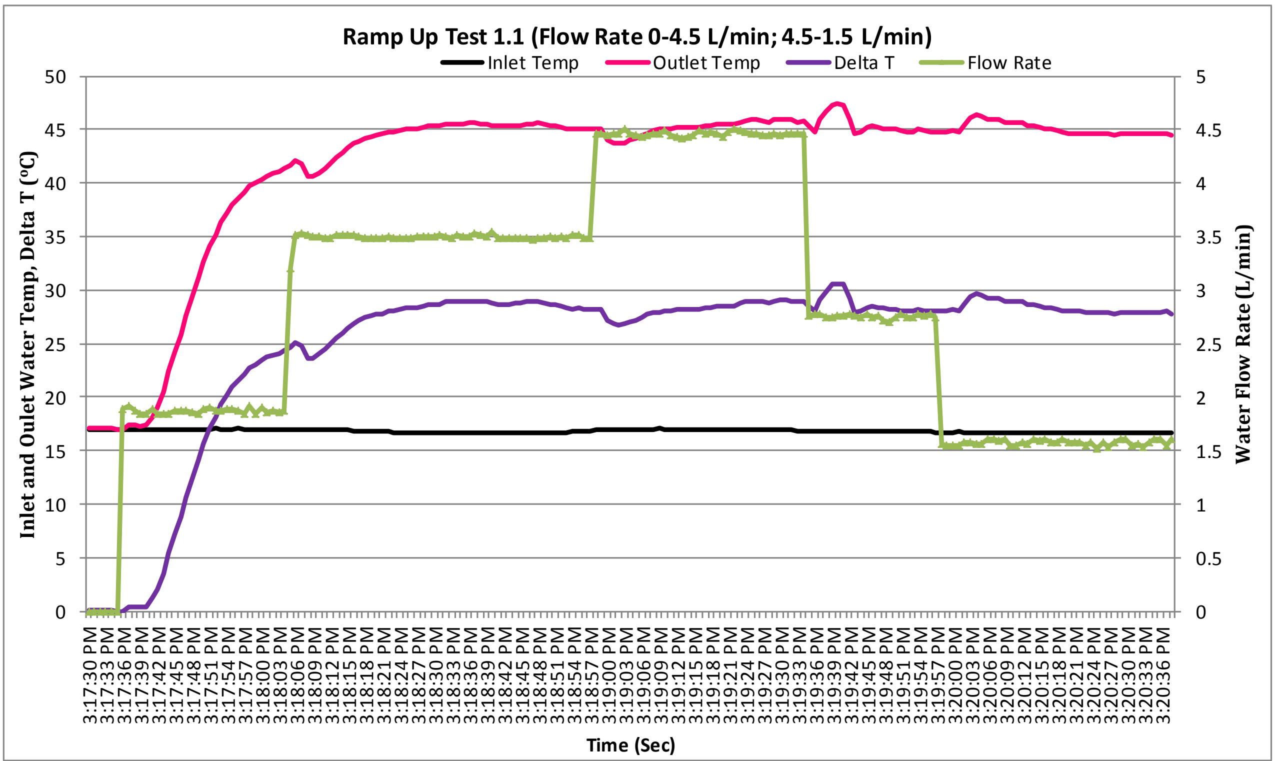

Fig. 10: Gradual increase ramp-up flow test of Series 1 unit (test 1.1).

3.3.2 Rapid increase of flow rate (test 2)

Results obtained from the ramp-up flow test 2.1 for the Series 1 unit by one step increase in flow rate are shown in Figure 11. For the test 2.1 the flow rate was increased from 0 to 3.7 L/min in one step and the average conductivity of water was 100 µS. From Figure 11 it can be seen that at a tank ambient temperature of 16.6°C, it took around 30 seconds to reach the desired set output temperature of 45°C. It is also apparent that the output temperature remained almost constant with ±0.5°C variation once it reached the set output temperature. A total of six tests were conducted for the straight increase ramp-up flow test 2 with the Series 1 unit. The results and graphs for the other five tests are given in Appendix D.

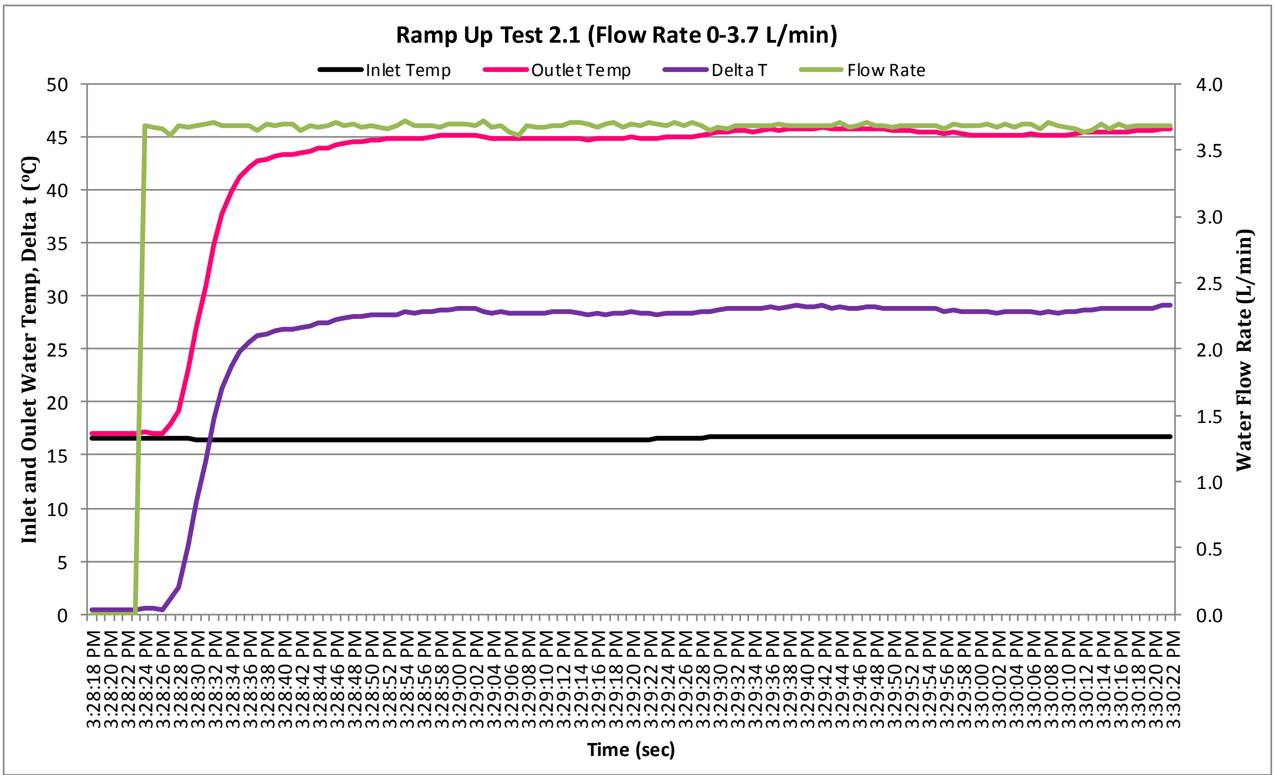

Fig. 11: Rapid increase ramp-up flow test of Series 1 unit (test 2.1).

3.4 RESULTS FOR STANDBY ENERGY CONSUMPTION OF SERIES 1 UNIT (PREMIUM COVER & STANDARD COVER UNITS)

Results obtained for these tests are shown in Table 19. The premium unit which has an exterior cover that includes the temperature setting and flow rate display panel were tested for 16.7 hours and the standby energy consumption rate was found to be 0.94 W, that was, only 0.01% of its maximum power consumption. The standard unit without display panel was tested for 1.52 hours and the standby energy consumption rate was found to be 0.61 W. In standby mode the both the premium cover and standard cover Series 1 units were found to be very energy efficient.

Results Standby Test (Series 1 Unit)			
Unit Type	Total Test Time	Total Energy Consumption	Energy Consumption Rate on Standby Mode
	hrs	Wh	Wh/h = W
Premimum	16.7	15.68	0.94
Standard	1.52	0.92	0.61

Table 19: Results for standby energy consumption test for Series 1 unit.

3.5 RESULTS FOR STEADY-FLOW TESTS OF SERIES 2 UNIT

A sample set of results for steady-flow test 1 for the Series 2 unit is shown in Table 20. The overall efficiency measured for test 1 is 99.8%. In total nine tests were conducted for the Series 2 unit in the steady-flow condition and a summary of the test results is provided in Table 21.

MicroHeat CFEWH Analysed Results

Specific Heat of Water	4186	J/kg^oC

Note: Correction factor for flow rate:

Flow meter was giving reading higher value than actual flow rate up to 7 L/min but for higher flow rate flow meter gave more accurate reading

Flow meter calibrated for different flow ranges

For 4 L/min flow range the factor is 0.11 L/min less

Flow meter Reading	Calibartion Factor	Calibrated Flow rate
L/min	L/min	L/min
4	0.11	3.89

Definition of each term in results	
$(T_{in}-T_{out})$	Outlet and Inlet water temperature difference (Delta T)
P_{th}	Theoretical power required to heat up the water
η_{inst}	Instantaneous efficiency of the unit at each data point
E_{act}	Total actual electrical energy consumed to heat up the water
E_{th}	Total theoretical total energy required to heat up the water
$\eta_{ov\ all}$	Overall effciency of the unit in the experiemntal period

Results for Test 1 (Steady Flow Test, Series 2 Unit)

Calibrated Flow Rate	Delta T	Theoretical Power Required	Instantaneous Efficiency	Actual Total Energy Consumed	Theoretical Total Energy Required	Overall Efficiency	Standard deviation of overall effieincy (%points)
	$(T_{in}-T_{out})$	P_{th}	η_{inst}	E_{act}	E_{th}	$\eta_{ov\ all}$	
L/min	°C	W	%	Wh	Wh	%	
4.19	27.4	8009.6	99.8	664.0	662.4	99.8	0.61
4.21	27.5	8077.2	100.5				
4.19	27.4	8009.6	100.0				
4.2	27.5	8058.1	101.3				
4.18	27.4	7990.5	100.1				
4.13	27.4	7894.9	98.4				
4.12	27.4	7875.8	97.5				
4.16	27.5	7981.3	100.4				
4.14	27.4	7914.1	99.6				
4.13	27.6	7952.6	99.9				
4.11	27.7	7942.7	99.6				
4.13	27.6	7952.6	100.0				
4.11	27.6	7914.1	99.5				
4.15	27.6	7991.1	99.1				
4.12	27.5	7904.6	98.6				
4.13	27.5	7923.7	99.3				
4.12	27.5	7904.6	99.2				
4.11	27.6	7914.1	99.3				
4.14	27.6	7971.8	100.1				
4.13	27.6	7952.6	99.6				

Table 20: Results for steady-flow test 1 with Series 2 unit.

Summary of Results for Test 1 to 9 (Steady Flow Test, Series 2 Unit)							
Test No	Time (min)	Avearge Flow Rate (L/min)	Average Water Conductivity (uS)	Average Inlet Temp. (°C)	Average Outlet Temp. (°C)	Average Actual Power Consumed (W)	Overall Efficiency (%)
1	5	4.1	114.3	17.3	44.9	7968.5	99.8
2	5	7.0	100.2	16.8	44.2	13276.7	100.9
3	5	11.9	104.8	17.1	44.8	22973.1	100.3
4	5	11.8	91.1	17.2	49.6	26515.1	100.5
5	5	4.1	115.9	24.7	45.3	5789.1	100.9
6	5	7.0	97.9	24.6	44.4	9708.7	100.2
7	3	4.0	609.3	18.8	44.6	7304.4	99.6
8	160 Sec	7.0	597.7	17.7	44.5	12928.2	100.5
9	3	11.5	592.0	17.2	44.8	21960.5	100.4

Table 21: Summary of test results for the steady-flow test of the Series 2 unit.

From this table it can be seen that for the Series 2 unit the overall efficiency was around 100.3 ±2% irrespective of the input conditions of water flow rate, conductivity and inlet temperature. Test 4 was conducted at the unit's maximum rated capacity (27 kW_e), and for this test also it was found that the efficiency around 100.5 ±2%.

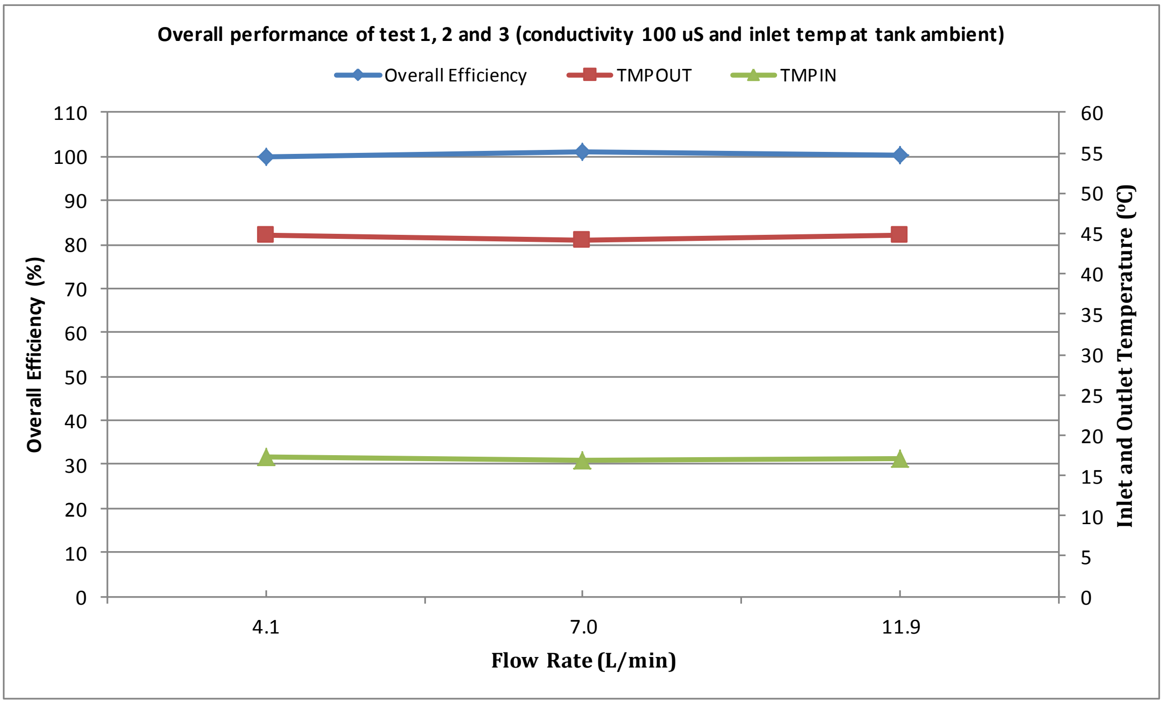

Fig. 12: Overall performance of Series 2 unit at different water flow rates.

Figure 12 shows the overall efficiency and set output temperatures of the Series 2 unit at 4.1, 7 and 11.9 L/min water flow rates for tests 1, 2 and 3 respectively. The inlet water temperature was tank ambient, that was around 17°C with ±0.4°C variation, and conductivity was around 100 µS with ±5 µS variation. The overall steady-state efficiency of Series 2 unit was 99.8%, and the output temperature was fairly constant at 44.5 ^{0}C with ±0.4°C variation.

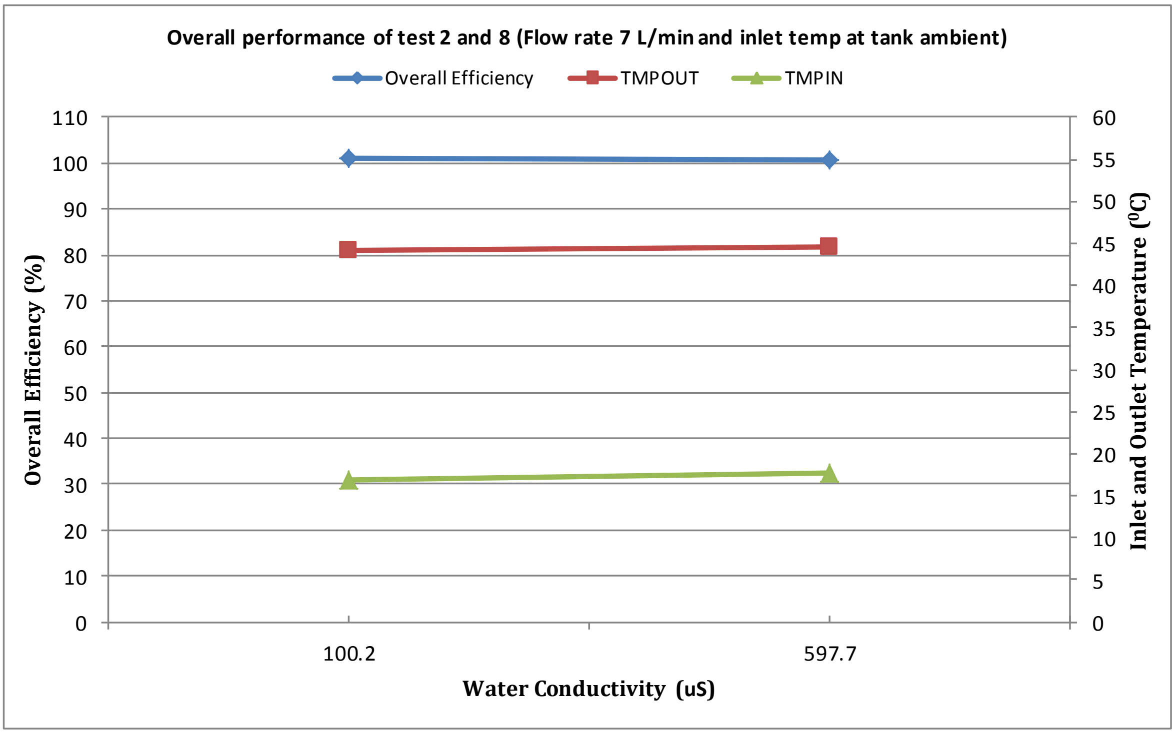

Fig. 13: Overall performance of Series 2 unit at different water conductivities.

The effect of water conductivity on the overall efficiency of the Series 2 heater can be seen in Figure 13. Graphs are plotted for overall efficiency at two average water conductivities: 100 and 600 µS for tests 2 and 7 respectively. For these tests the average inlet water temperature was tank ambient, that was 17.2 with ±0.4°C variation, and the flow rate 7 L/min. From this figure it is also apparent that overall efficiency was around 100 ± 0.4%, and constant set output water temperature of about 44.3°C with ±0.2°C variation.

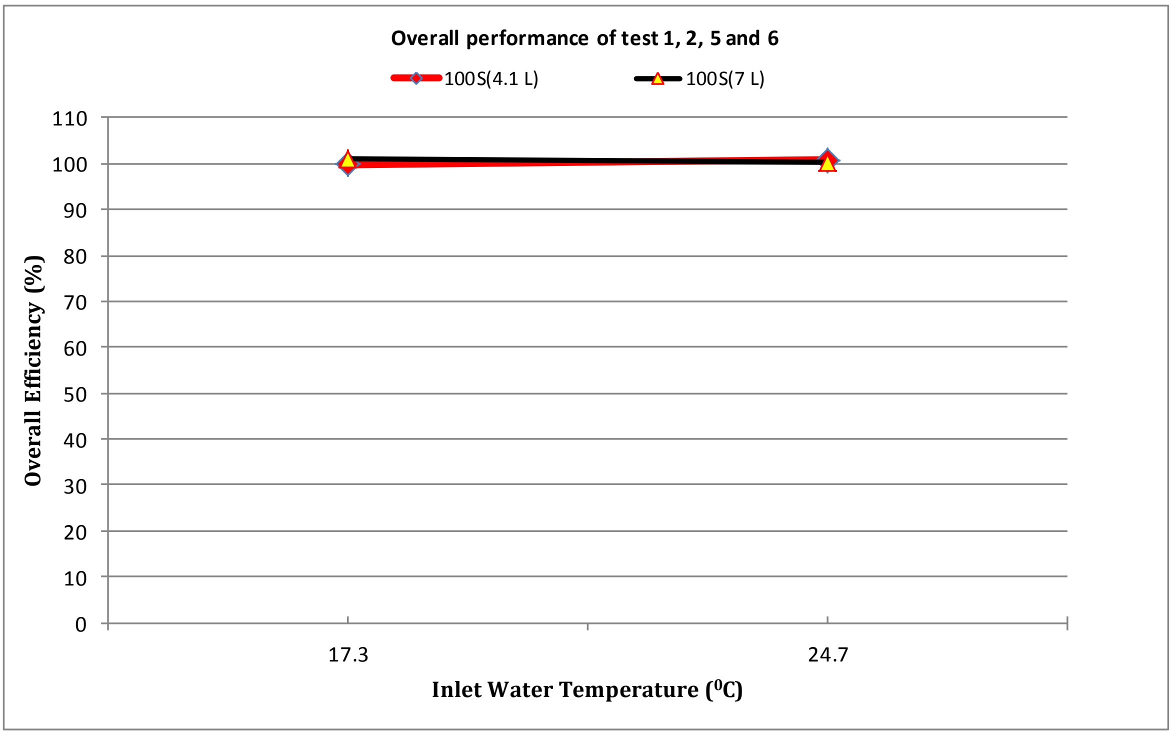

Fig. 14: Overall performance of Series 2 unit at different inlet water temperatures.

Figure 14 shows the effect of inlet water temperature on the overall efficiency of the Series 2 unit. Graphs are plotted for two inlet water temperatures: 17.3 and 24.7°C. The unit was tested for two flow rates: 4.1 and 7 L/min, and the average water conductivity was 100 µS with ±10 µS variation. The overall efficiency was found 100 ± 0.4% in all the cases irrespective to inlet water temperatures.

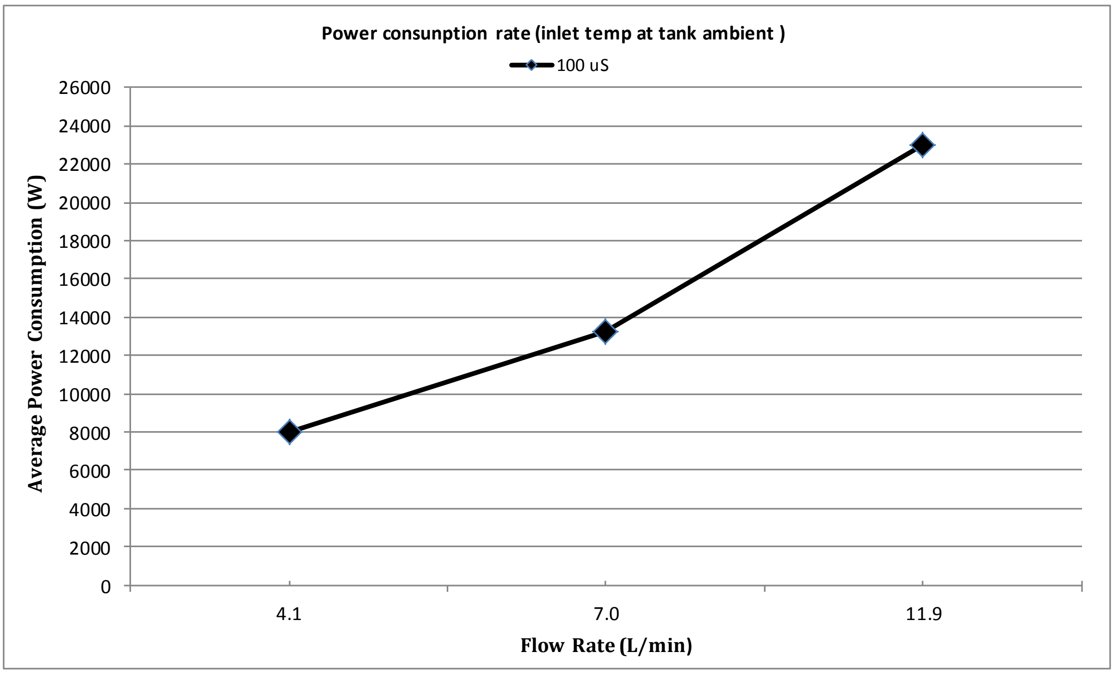

Fig. 15: Average power consumption for the Series 2 unit at different water flow rates.

To see the effect of water flow rate on the power requirement to heat the water in the Series 2 unit, a graph has been plotted for average power consumption for three different flow rates of water: 4.1, 7 and 11.9 L/min (Figure 15). For these tests the average inlet water temperature was tank ambient, which was around 17°C with ±0.3°C variation, and average output temperature was 44.6°C with ±0.4 ^{0}C variation. This heater too draws power according to the flow rate of water. For example, when the flow rate was 4.1 L/min the power consumption was 7968 W, and for the flow rate of 11.9 L/min power consumption was 22973 W. So, the power consumption of the unit is optimised according to the flow rate of the water, and the overall efficiency is very close to 100% under both conditions.

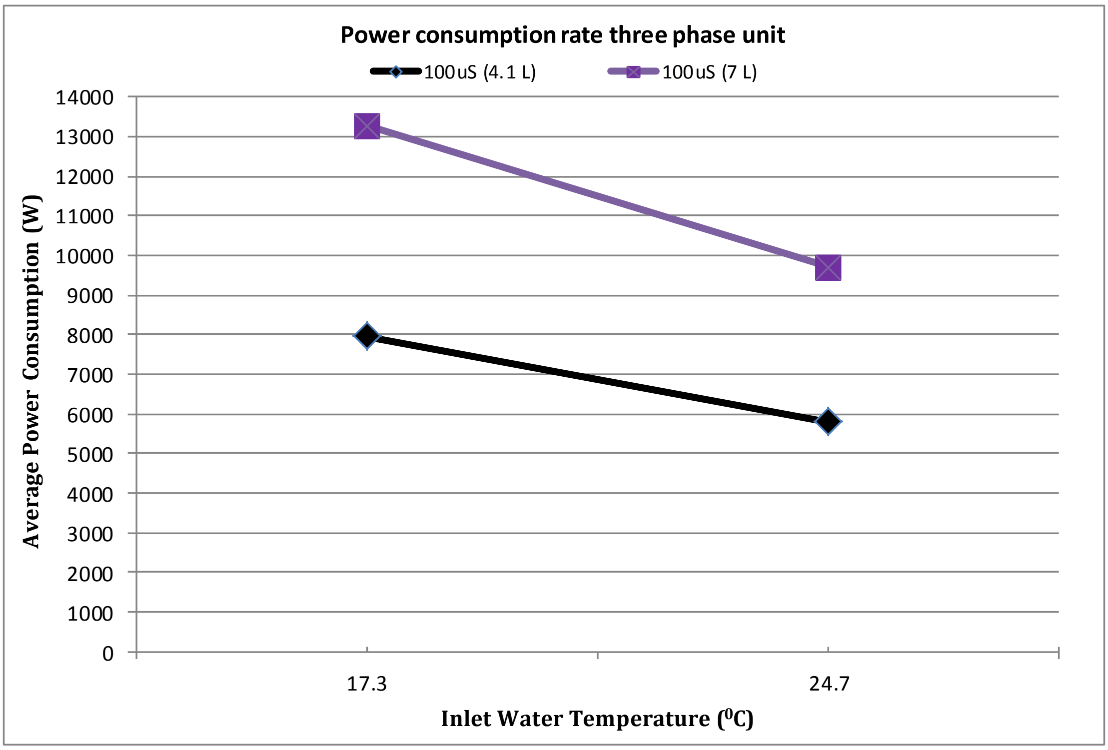

Fig. 16: Average power consumption for the Series 2 unit at different inlet water temperatures.

The effect of inlet water temperature on the power required to heat the water for Series 2 unit is shown in Figure 16, where a graph has been plotted for average power consumption for two different average inlet temperatures of water that correspond to winter and summer ambient water temperature conditions: 17°C ±0.3°C and 24.6°C ±0.1°C. For these tests the water flow rates were 4 L/min and 7 L/min, and the water conductivity was 100 µS. From this graph it can be seen that there was a significant reduction in power consumption when the inlet water temperature was increases for the same flow rate of water. For example, when the water flow rate was 4.1 L/min and inlet water temperature 17.3°C, the average power consumption was 7968 W for a 45°C output temperature. For the same flow rate and same output water temperature when the inlet water temperature was 25°C the average power consumption was reduced to 5789 W. So again as expected, the unit uses substantially less power in summer compared to winter.

3.6 RESULTS FOR RAMP-UP TESTS OF SERIES 2 UNIT

3.6.1 Gradual increase and decrease of flow rate (test 1)

Results obtained from the ramp-up flow test 1.2 for the Series 2 unit with gradual increase and decreases of flow rate are shown in Figure 17. For the Series 2 unit the heater did not start operating until it reached the minimum flow rate of 4 L/min. For this test the flow rate was increased in steps from 0 to 5.2, 7.2, 8.6 and 9.8 L/min, and then stepped down from 9.8 to 8.1, 6.1 and 3.7 L/min. For this test the average conductivity of water was 100 μS. From Figure 17 it can be seen that for flow rate 5.2 L/min from inlet water temperature 25°C to reach the desired set output temperature 45°C, it took around 18 seconds. It is also apparent that when flow rate increased rapidly from a lower to a higher level, the output temperature dropped from the set output temperature. When the flow rate was decreased rapidly from a higher to a lower level, the output temperature first exceeded the set output temperature and then came back to desired output temperature. It took around 10 to 12 seconds for output temperature to become stabilise when flow rate change from one level to another higher or lower level. In total four gradual ramp-up flow tests were conducted for test 1. The remaining result graphs for the other similar ramp-up tests are given in Appendix E.

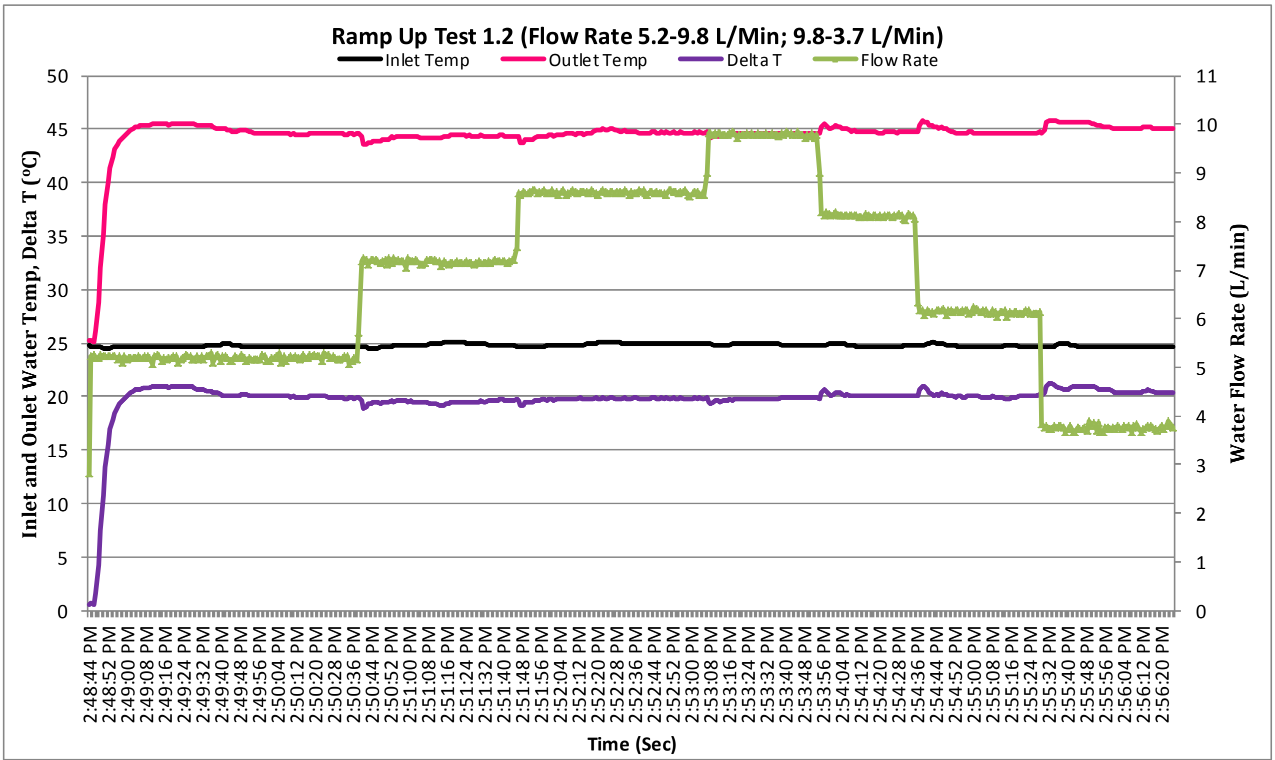

Fig. 17: Gradual increase ramp-up flow test of Series 2 unit (test 1.2).

3.6.2 Rapid increase of flow rate (test 2)

Results obtained from the ramp-up flow test 2.2 for the Series 2 unit by one step increase in flow rate are shown in Figure 18. For the test 2.2 the flow rate was increased from 0 to 9.8 L/min in one step and the average conductivity of water was 100 μS. From this figure it can be seen that from inlet water temperature of 25°C, it took around one minute and 45 seconds to reach desired set output temperature 45°C ±0.5°C. It was also apparent that the output temperature remained almost constant with ±0.5°C variation once it reached the set output temperature. A total of four tests were conducted for the straight increase ramp-up flow test 2 with the Series 2 unit. The results and graphs for the other five tests are given in Appendix F.

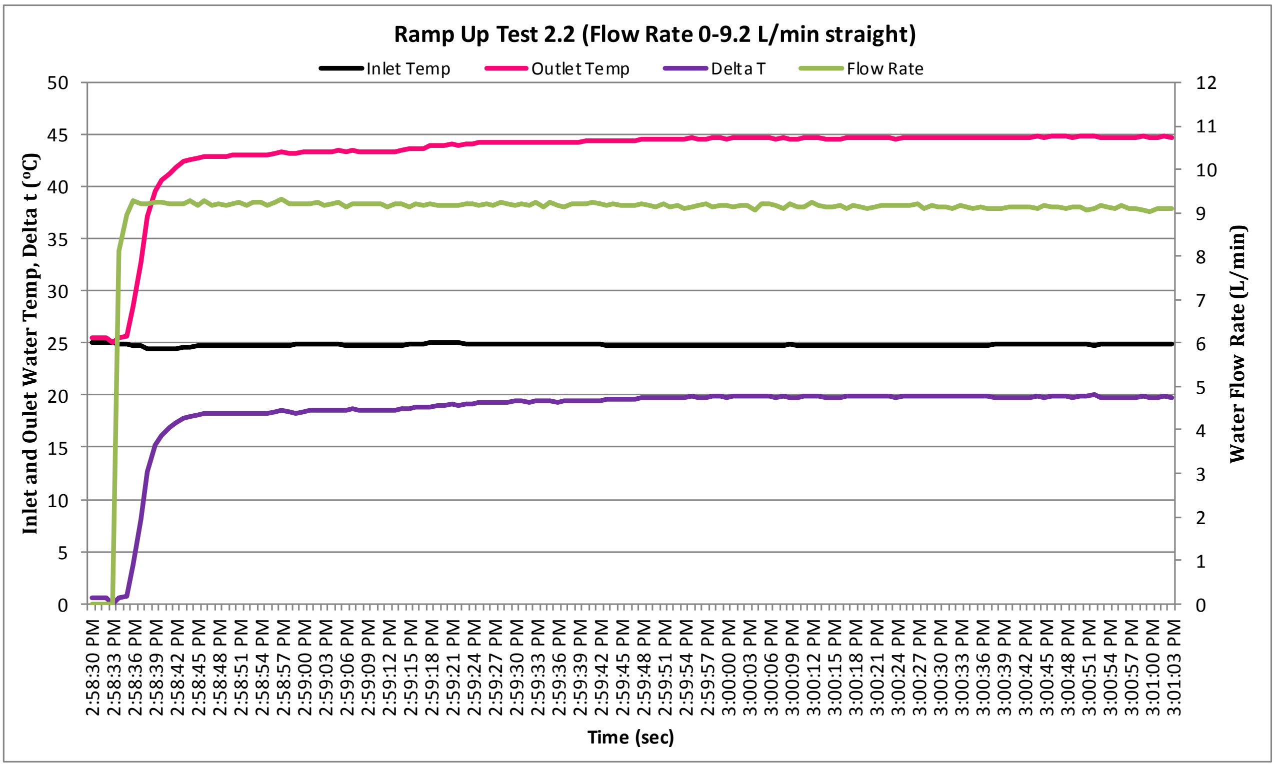

Fig. 18: Rapid increase ramp-up flow test of Series 2 unit (test 2.2).

4. CONCLUSIONS

A wide range of tests were conducted for both the Series 1 and Series 2 unit to measure their performance. In total 18 performance tests were conducted for the Series 1 unit at steady state under different inlet conditions:

- two average inlet water temperatures around 17 and 25°C with ±0.5°C variation;
- three average flow rates 1.6, 3 and 4 L/min; and
- three average water conductivities around 100, 300 and 700 µS.

Across all the steady-flow tests of the Series 1 unit, the measured mean steady-state efficiency was 99.7%, which is very close to 100%, irrespective to the input condition of water flow rate, conductivity and inlet temperature. The random error range of the calculated efficiency was estimated to be in the range of ±2%.

As expected, water flow rate had a significant effect on power consumption of the Series 1 unit. For example, when the flow rate was 1.6 L/min, the power consumption was around 3096 W with ±30 W variation, and for the flow rate of 4 L/min power consumption was around 7830 W with ±45 W variation. So, the power consumption of the unit was optimised according to the flow rate of the water. It was also found that the energy consumption rate was effectively the same for any particular flow rate of water irrespective of the water conductivities.

For the Series 1 unit it was also found that there was a significant reduction in power consumption when the inlet water temperature was increased. For example, when the water flow rate was 4 L/min and inlet water temperature was 17°C the average power consumption was around 7830 W with ±45 W variation for 45°C output temperature. For the same flow rate and same output water temperature, when the inlet water temperature was 25°C the average power consumption was reduced to around 5628 W with ±15 W variation. So, as expected there is substantially lower energy consumption in summer by this unit.

A gradual increase and decrease ramp-up test for Series 1 unit shows that when the flow rate was increased rapidly from a lower to a higher level, the output temperature dropped from the set output temperature. When the flow rate was decreased rapidly from a higher to a lower level, the output temperature first exceeded the set output temperature and then came back to desired output temperature. It took around 8 to 10 seconds for output temperature to stabilise after the flow rate changed from one level to another higher or lower level. For the straight increase ramp-up flow test 2.1, when the flow rate increased from 0 to 3.7 L/min in one step, it was found that, at a tank ambient temperature of 16.6°C, it took around 30 seconds to reach the desired set output temperature of 45°C. It is also apparent that the output temperature remained almost constant with ±0.5°C variation once it reached the set output temperature. It was also found that the output temperature was almost constant once it reached the set output temperature.

In standby mode operation the premium unit, which has an exterior cover that includes the temperature setting and flow rate display panel, was tested for 16.7 hours and the energy consumption rate was found to be 0.94 W, that was, only 0.01% of its maximum power consumption. The standard unit without display panel was tested for 1.52 hours and the energy consumption rate was found to be 0.61 W. In standby mode the both the premium cover and standard cover Series 1 units were found to be very energy efficient.

In total nine performance tests were conducted for the Series 2 unit at steady state under different inlet conditions:

- two average inlet water temperatures around 17 and 25°C with ±0.4°C variation;
- three average flow rates 4, 7 and 12 L/min; and
- two average water conductivities around 100 and 600 µS.

Across all the steady-flow tests of the Series 2 unit, the measured mean steady-state energy efficiency was 100 ±2% (that is, between 98 and 100% given that efficiency cannot exceed 100%) irrespective of the input conditions of water flow rate, conductivity and inlet temperature.

For the Series 2 unit as well, it draws power according to the flow rate of water, which optimises the power consumption by the heater. For example, when the flow rate was 4.1 L/min the power consumption was 7968 W, and for the flow rate of 11.9 L/min power consumption was 22973 W.

It was also found that there was a significant reduction in power consumption in the Series 2 unit when the inlet water temperature increased. For example, when the water flow rate was 4.1 L/min and inlet water temperature 17.3°C, the average power consumption was 7968 W for a 45°C output temperature. For the same flow rate and same output water temperature when the inlet water temperature was 25°C the average power consumption was reduced to 5789 W. So again as expected, the unit uses substantially less power in summer compared to winter.

The Series 2 unit yielded a similar pattern of results to those for the Series 1 unit in the gradual increase and decrease ramp-up flow tests. For example, in the rapid increase ramp-up flow test 2.2, when flow rate increased from 0 to 9.8 L/min in one step, from inlet water temperature of 25°C, it took around one minute and 45 seconds to reach desired set output temperature 45°C ±0.5°C. It was also apparent that the output temperature remained almost constant with ±0.5°C variation once it reached the set output temperature.

Clearly both Series 1 and Series 2 units are very highly efficient electric water heating equipment. They deliver near exactly the amount electrical energy required to heat the water to the set outlet temperature depending on the inlet conditions.

REFERENCES

BSI 1995, *Vocabulary of Metrology: Part 3. Guide to the expression of uncertainty in measurement*, British Standards Institution, London.

APPENDICES

Appendix A: Error analysis of flow measurement

The accuracy of flow rate calculation can be estimated as follows:

Volume flow rate can be calculated as $\dot{Q} = \frac{Q}{t}$

The combined standard uncertainty of flow rate measurement, $u(\dot{Q})$, can be expressed as:

$$u(\dot{Q}) = \sqrt{\left[\frac{\partial \dot{Q}}{\partial Q}\right]^2 \times u^2(Q) + \left[\frac{\partial \dot{Q}}{\partial t}\right]^2 \times u^2(t)}$$

$$= \sqrt{\left[\frac{1}{t}\right]^2 \times u^2(Q) + \left[-\frac{Q}{t^2}\right]^2 \times u^2(t)} \qquad (3)$$

Sample calculation for first measurement of flow rate (test 1, reading 1):

Volume measured (Q): 985 mL; time taken (t): 37.41 Sec

Uncertainty of volume measurement $u(Q)$: ±2 mL = ±0.002 L

Uncertainty of time measurement $u(t)$: ±0.5 sec = ±0.008 min

Uncertainty of flow rate measurement, $u(\dot{Q})$

$$u(\dot{Q}) = \sqrt{\left[\frac{1}{\left(37.41/60\right)}\right]^2 (0.002)^2 + \left[-\frac{\left(985/1000\right)}{\left(37.41/60\right)^2}\right]^2 (0.008)^2} = \pm 0.02 \text{ L/min}$$

Uncertainty of different calculated flow rates is shown in the table A-1.

				Uncertainty Calculation of Flow Measurements		
Test No	Reading No	Measured Water Vol (mL)	Time Taken (Sec)	Uncertainty of Vol Measurement (Lit)	Uncertainty of Time Measurement (min)	Overall Uncertainty of Flow Rate Measurement (L/min)
1	1	985	37.41	0.002	0.008	0.02
	2	1150	44.01			0.02
	3	978	37.13			0.02
2	1	1813	36.91			0.04
	2	1818	37.06			0.04
	3	1818	36.95			0.04
3	1	1818	27.31			0.07
	2	1820	27.43			0.07
	3	1830	27.7			0.07
4	1	1720	14.80			0.24
	2	1715	14.43			0.25
	3	1775	14.83			0.24
5	1	1440	7.43			0.78
	2	1420	7.36			0.79
	3	1638	8.38			0.70

Table A-1: Uncertainty of flow rate measurements.

Appendix B: Error Analysis for the efficiency calculation

List of possible sources of error

1. Large correction factor applied for flow rate measurements as the flow sensor always gave higher readings (system error)
2. Error in time measurement in calibrating the flow sensor
3. Error in volume measurement for calibrating the flow sensor
4. Error in temperature measurement
5. Error in voltage and current measurement

Uncertainty of actual power measurement

Power, P_{act} = V x I

Accuracy of voltage measurement is ±0.2% full scale, u(V) = ±0.002 V

Accuracy of current measurement is ±0.2% full scale, u(I) = ±0.002 A

Uncertainty of actual power measurement, $u(P_{act})$

$$u(P_{act}) = \sqrt{\left[\frac{\partial P_{act}}{\partial V}\right]^2 \times u^2(V) + \left[\frac{\partial P_{act}}{\partial I}\right]^2 \times u^2(I)}$$

$$= \sqrt{I^2 \times u^2(Q) + V^2 \times u^2(t)} \quad (4)$$

Test No, Reading No	V Volt	I Amp	u(V) Volt	u(I) Amp	$u_{(Pact)}$ W
T1, R1	239.94	12.49	0.480	0.025	±8.48
T2, R1	240.58	24.56	0.481	0.049	±16.71
T3, R1	230.47	34.21	0.461	0.068	±22.30

Table B-1: Uncertainty of actual power measurement.

Uncertainty of required theoretical power estimation

Theoretical power, $P_{th} = m*C_p*\Delta T$

Accuracy of temperature measurement with RTD is ±0.3°C

Accuracy of flow measurement is ±0.02 L/min when flow rate is 1.5 to 2 L/min

Accuracy of flow measurement is ±0.04 L/min when flow rate is 3.0 to 3.5 L/min

Accuracy of flow measurement is ±0.07 L/min when flow rate is 4.0 to 4.5 L/min

Uncertainty of theoretical power estimation, $u(P_{th})$

$$u(P_{th}) = \sqrt{\left[\frac{\partial P_{th}}{\partial \dot{m}}\right]^2 \times u^2(\dot{m}) + \left[\frac{\partial P_{th}}{\partial C_p}\right]^2 \times u^2(C_p) + \left[\frac{\partial P_{th}}{\partial \Delta T}\right]^2 \times u^2(\Delta T)}$$

$$= \sqrt{(C_p \Delta T)^2 \times u^2(\dot{m}) + 0 \times u^2(C_p) + (\dot{m} C_p)^2 \times u^2(\Delta T)} \qquad (5)$$

Test No,	Calibrated flow rate	C_p	ΔT	u(ΔT)	u(m)	$u(P_{th})$
Reading No	L/m	J/kg°C	oC	oC	L/m	W
T1, R1	1.6	4186	28.1	0.3	0.02	±53.61
T2, R1	2.95	4186	28	0.3	0.04	±99.59
T3, R1	3.99	4186	28.2	0.3	0.07	±161.06

Table B-2: Uncertainty of theoretical power estimation.

Uncertainty of efficiency estimation

Efficiency, $\eta = P_{th}/P_{act}$

Uncertainty of efficiency estimation, $u(\eta)$

$$u(\eta) = \sqrt{\left[\frac{\partial \eta}{\partial P_{th}}\right]^2 \times u^2(P_{th}) + \left[\frac{\partial \eta}{\partial P_{act}}\right]^2 \times u^2(P_{act})}$$

$$= \sqrt{\left[\frac{1}{P_{act}}\right]^2 \times u^2(P_{th}) + \left[-\frac{P_{th}}{P_{act}^2}\right]^2 \times u^2(P_{act})} \qquad (6)$$

Test No,	P_{th}	P_{act}	$u(P_{act})$	$u(P_{th})$	u(η)	η	u(η) %
Reading No	W	W	W	W			
T1, R1	3136.7	2939	8.48	53.61	0.0185	1.067	±1.73
T2, R1	5762.73	5884	16.71	99.59	0.0172	0.979	±1.75
T3, R1	7850.01	7866	22.30	161.06	0.0207	0.998	±2.07

Table B-3: Uncertainty of efficiency estimation.

Appendix C: Graphs for the ramp-up test 1 (Series 1 unit)

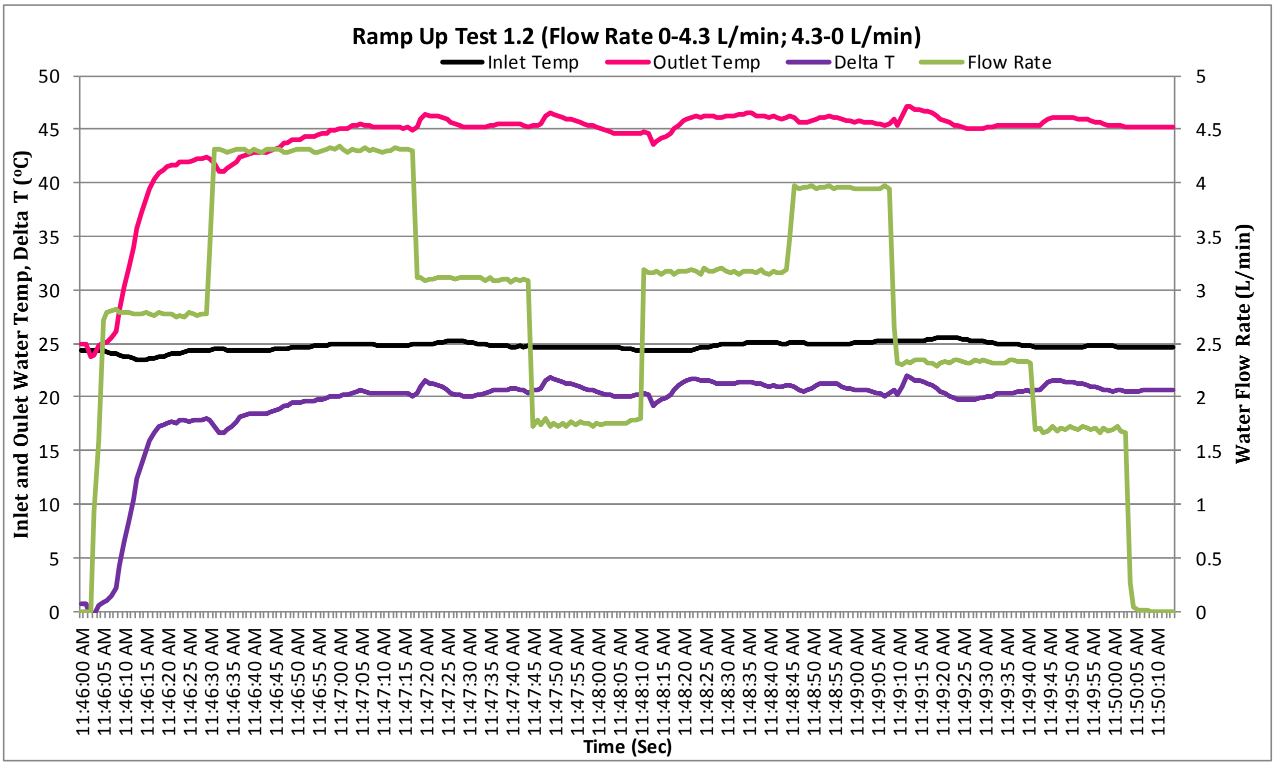

Fig. C-1: Gradual increase ramp-up flow test of Series 1 unit (test 1.2).

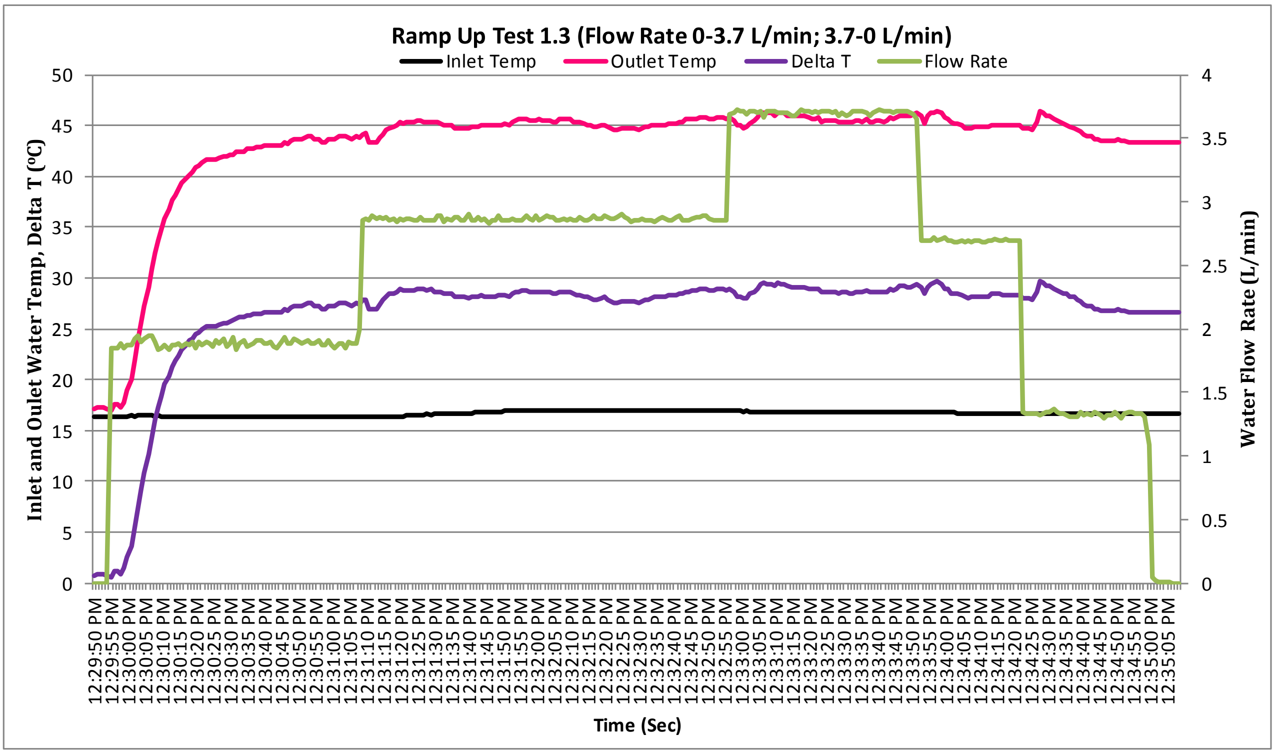

Fig. C-2: Gradual increase ramp-up flow test of Series 1 unit (test 1.3).

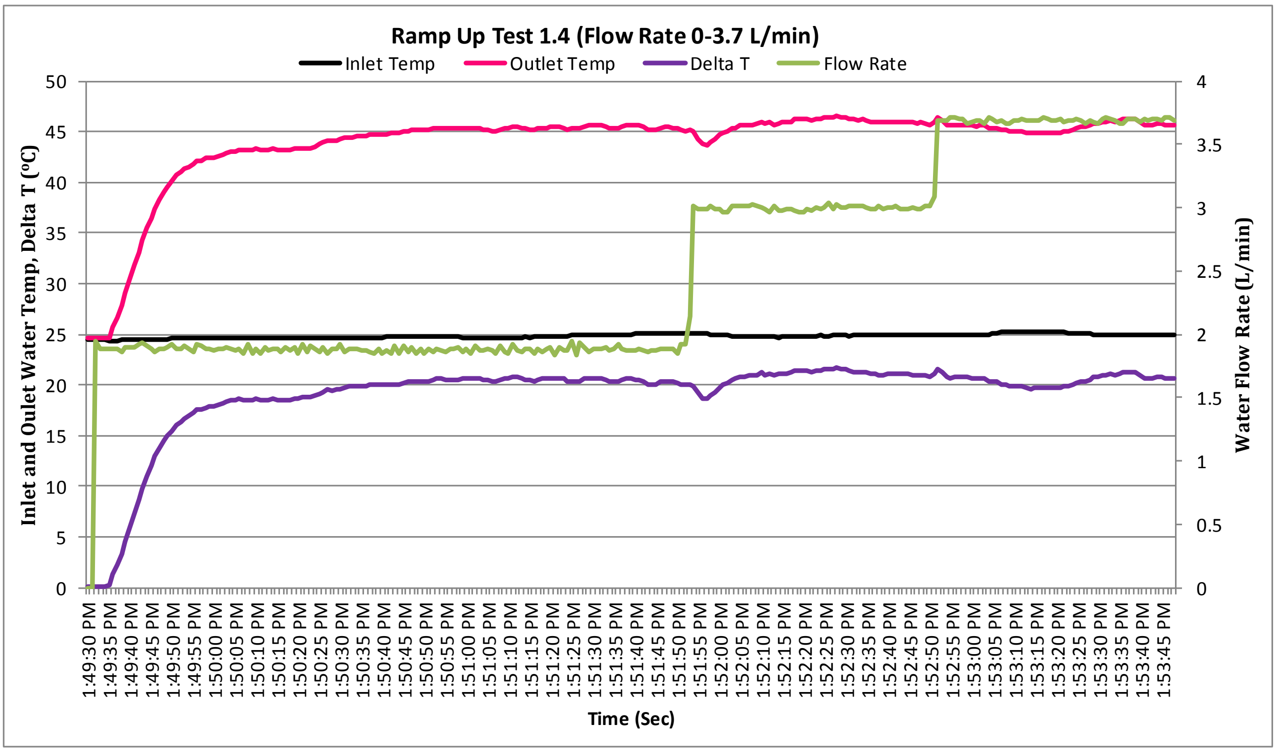

Fig. C-3: Gradual increase ramp-up flow test of Series 1 unit (test 1.4).

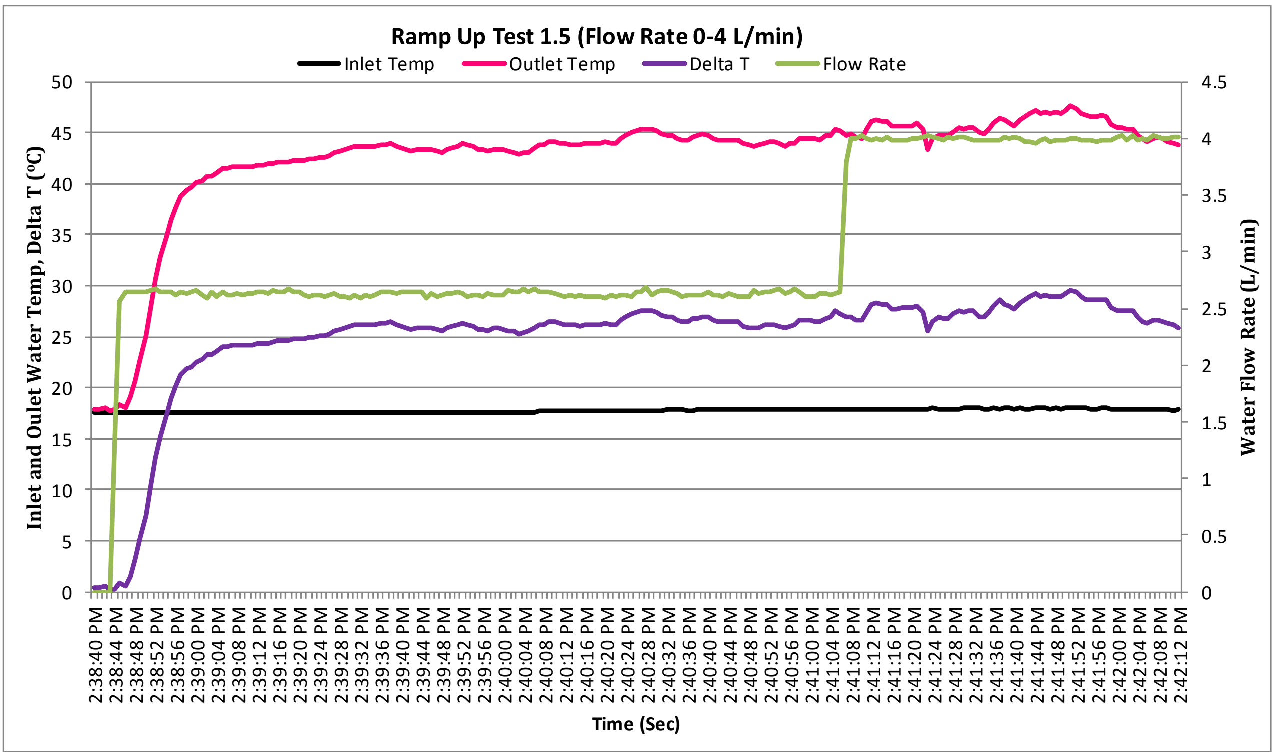

Fig. C-4: Gradual increase ramp-up flow test of Series 1 unit (test 1.5).

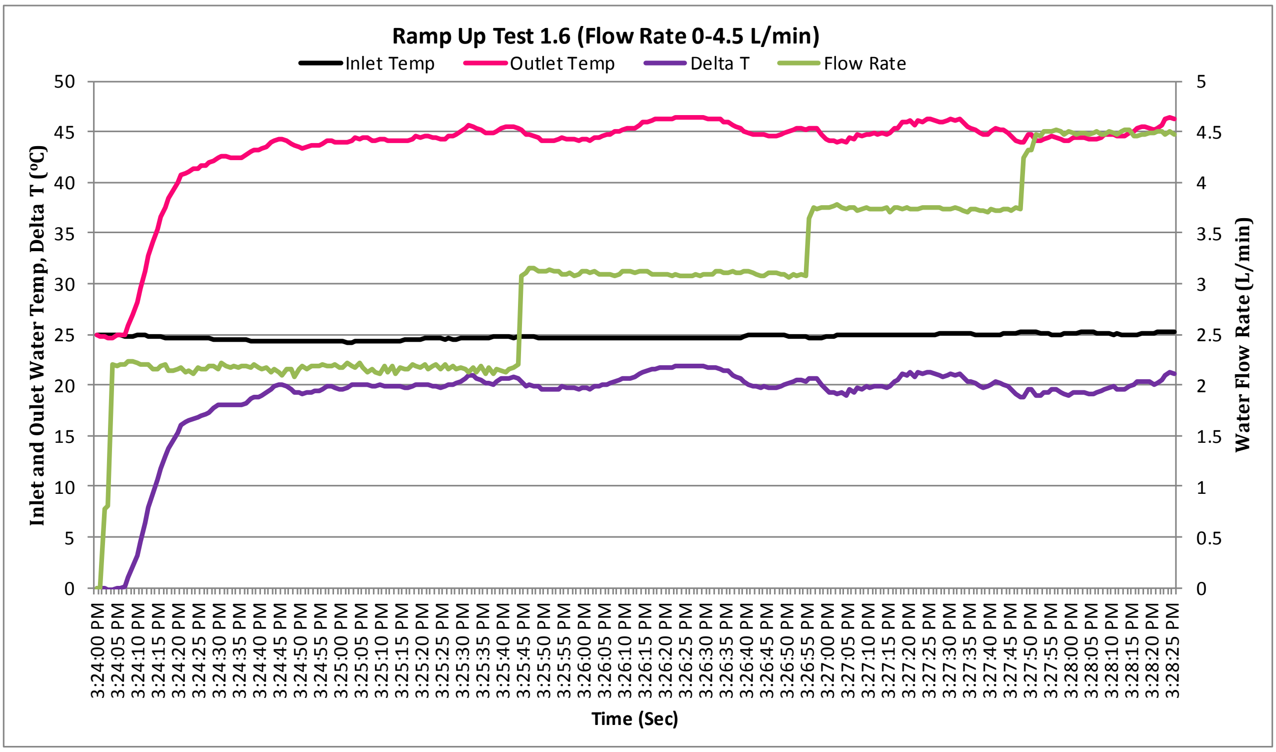

Fig. C-5: Gradual increase ramp-up flow test of Series 1 unit (test 1.6).

Appendix D: Graphs for the ramp-up test 2 (Series 1 unit)

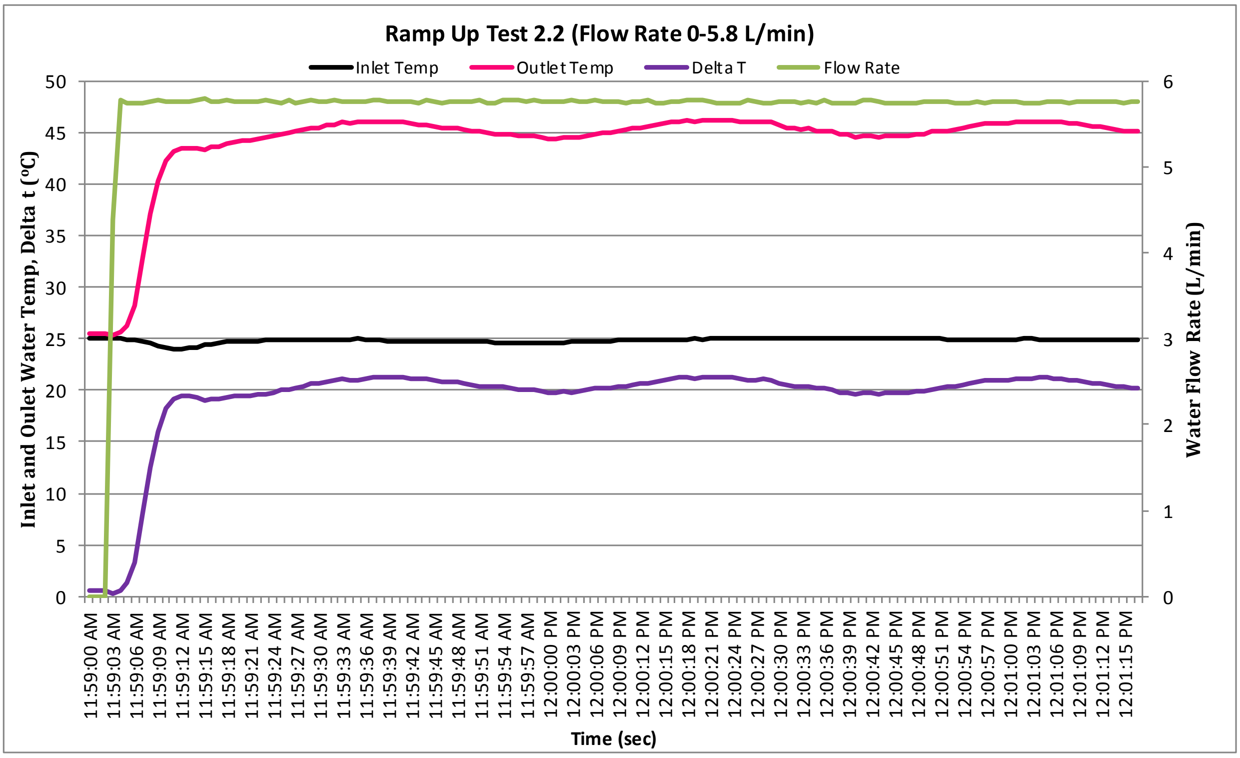

Fig. D-1: Rapid increase ramp-up flow test of Series 1 unit (test 2.2).

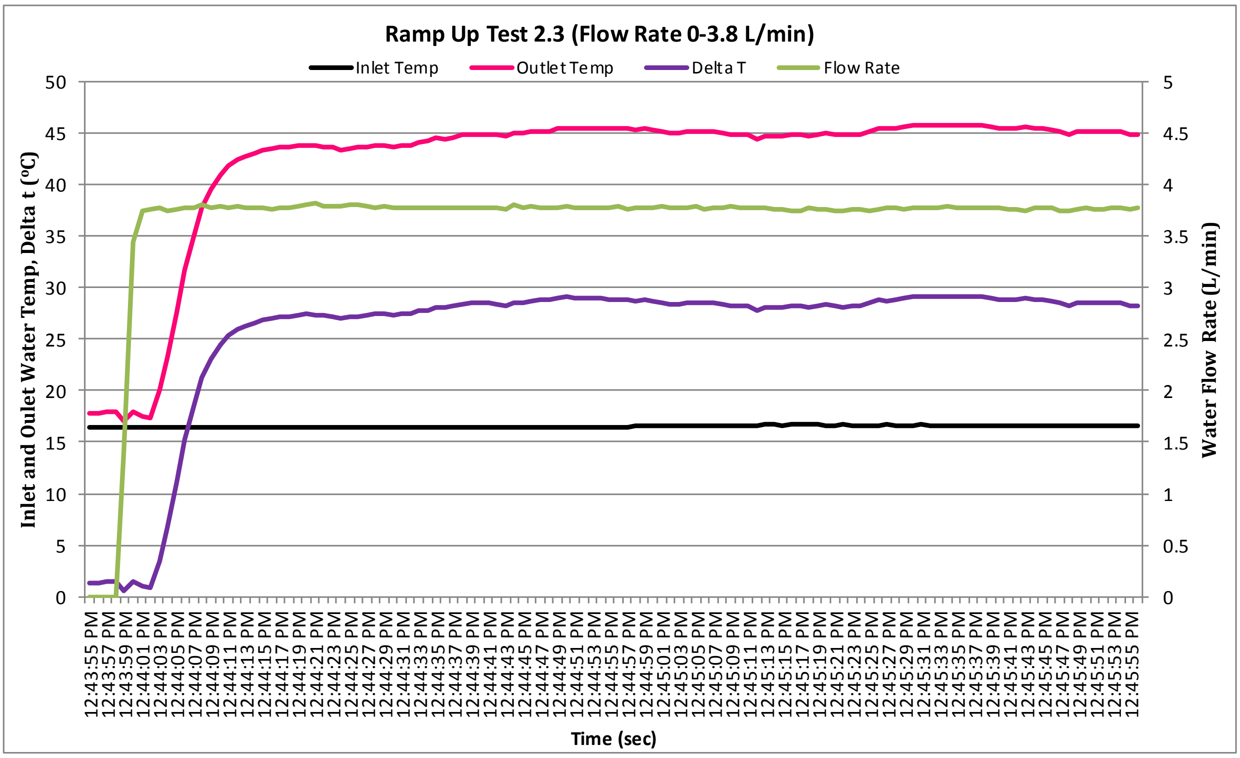

Fig. D-2: Rapid increase ramp-up flow test of Series 1 unit (test 2.3).

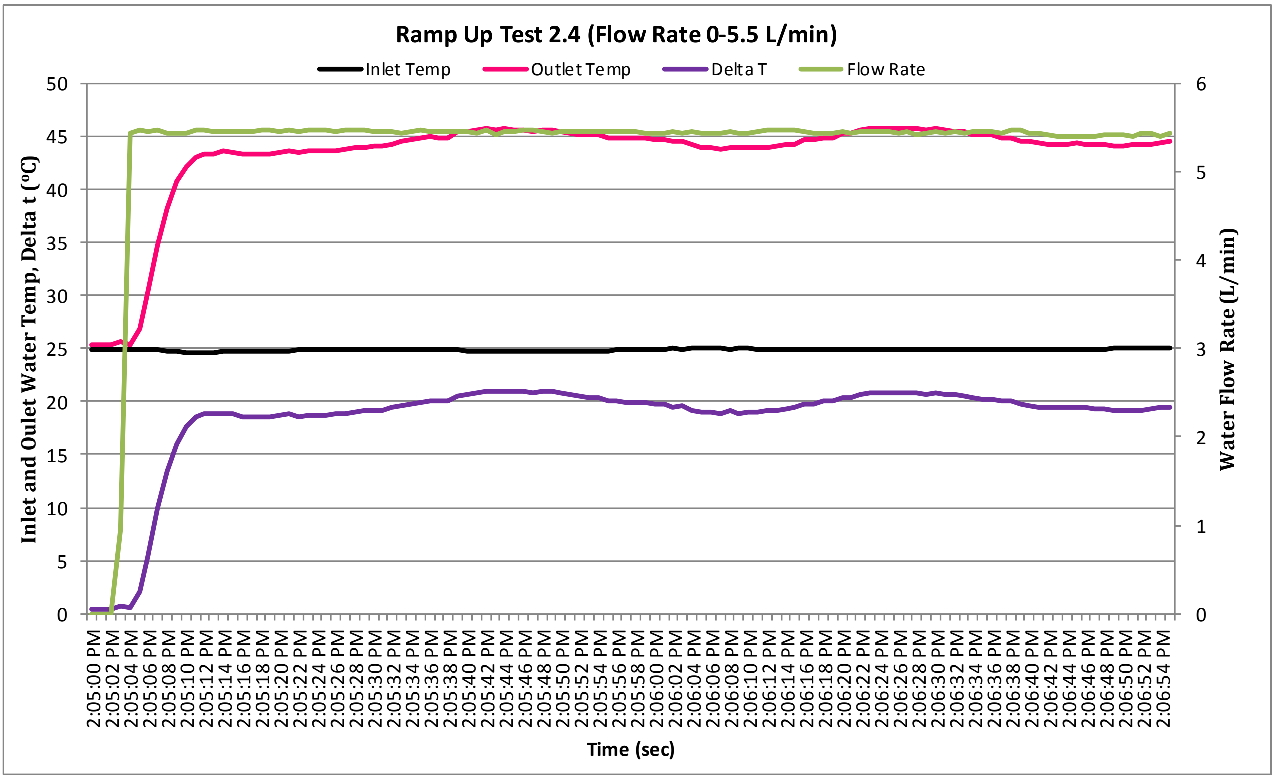

Fig. D-3: Rapid increase ramp-up flow test of Series 1 unit (test 2.4).

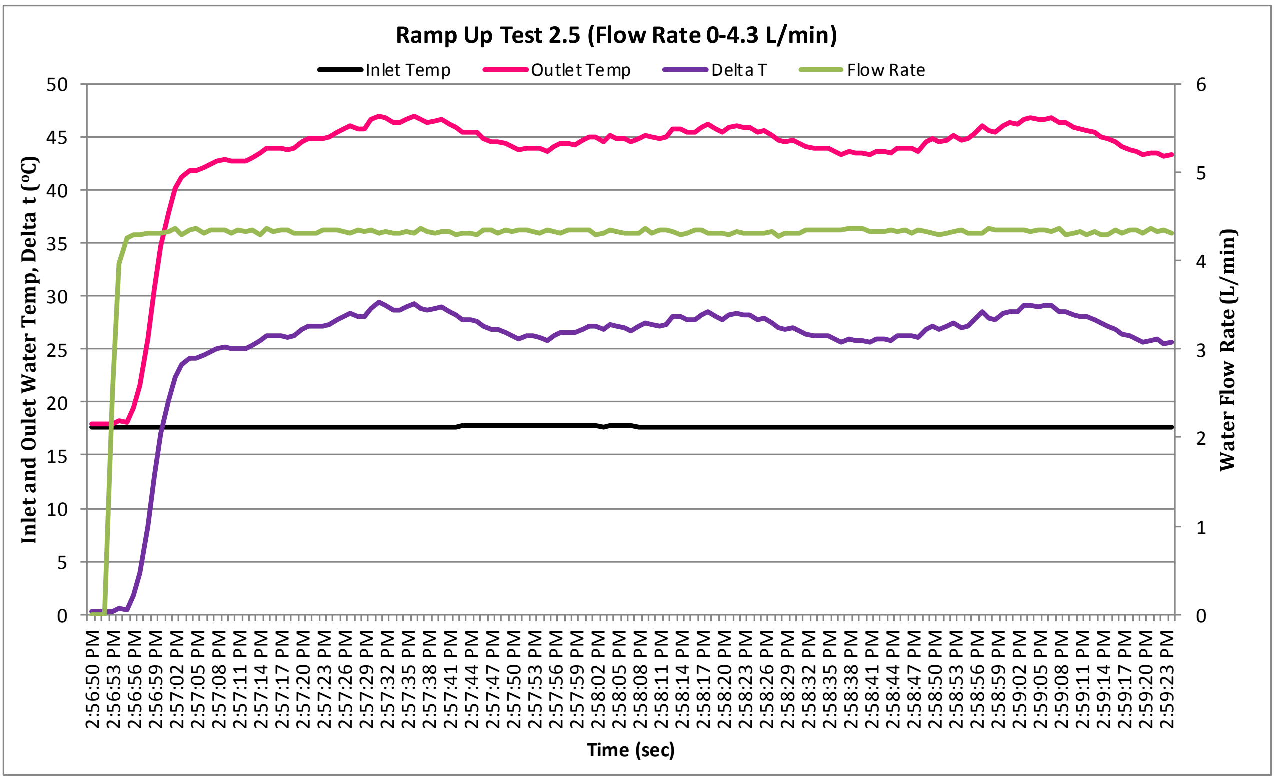

Fig. D-4: Rapid increase ramp-up flow test of Series 1 unit (test 2.5).

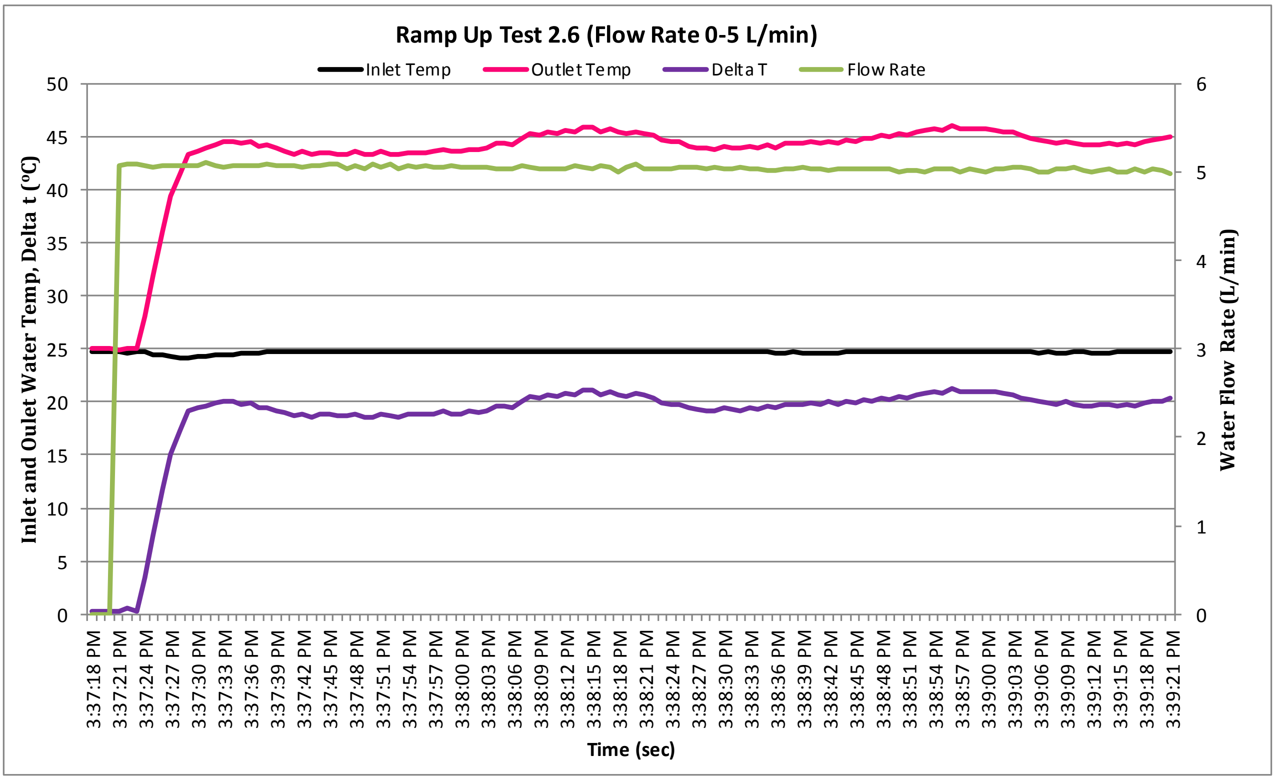

Fig. D-5: Rapid increase ramp-up flow test of Series 1 unit (test 2.6).

Appendix E: Graphs for the ramp-up test 1 (Series 2 unit)

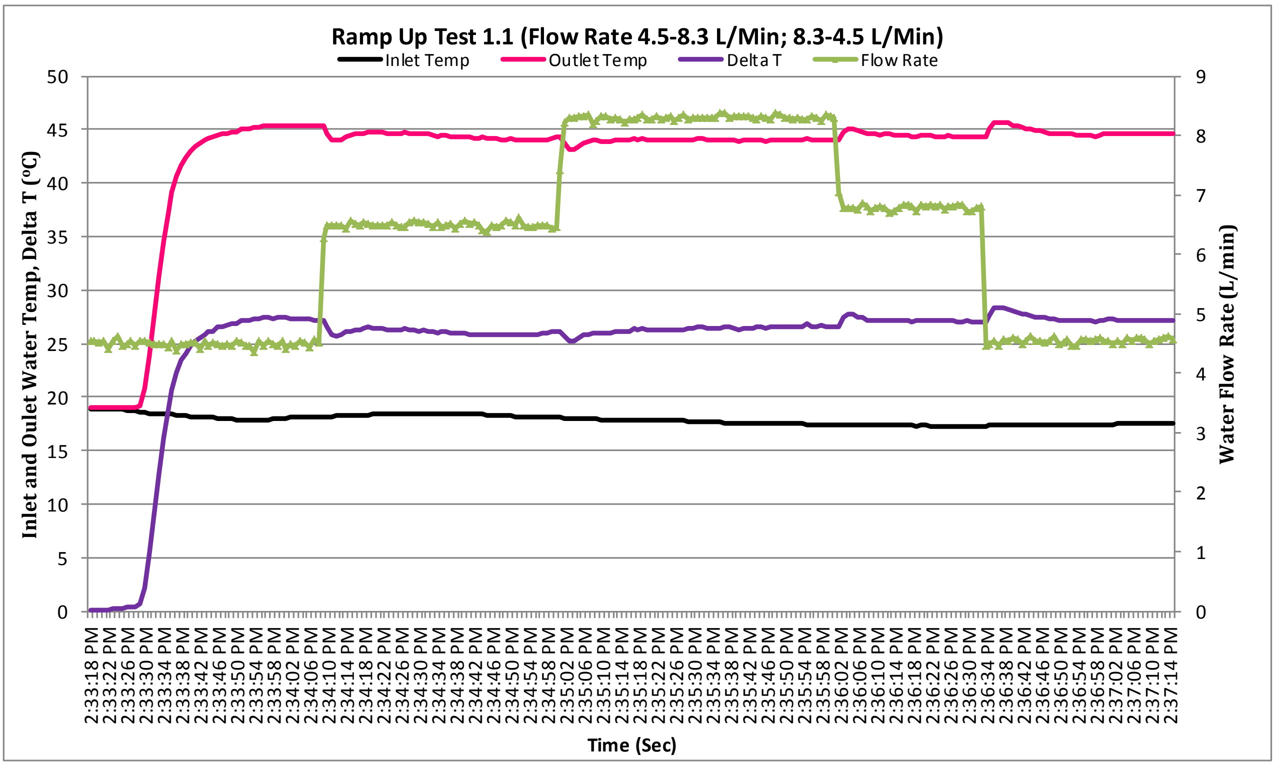

Fig. E-1: Gradual increase ramp-up flow test of Series 2 unit (test 1.1).

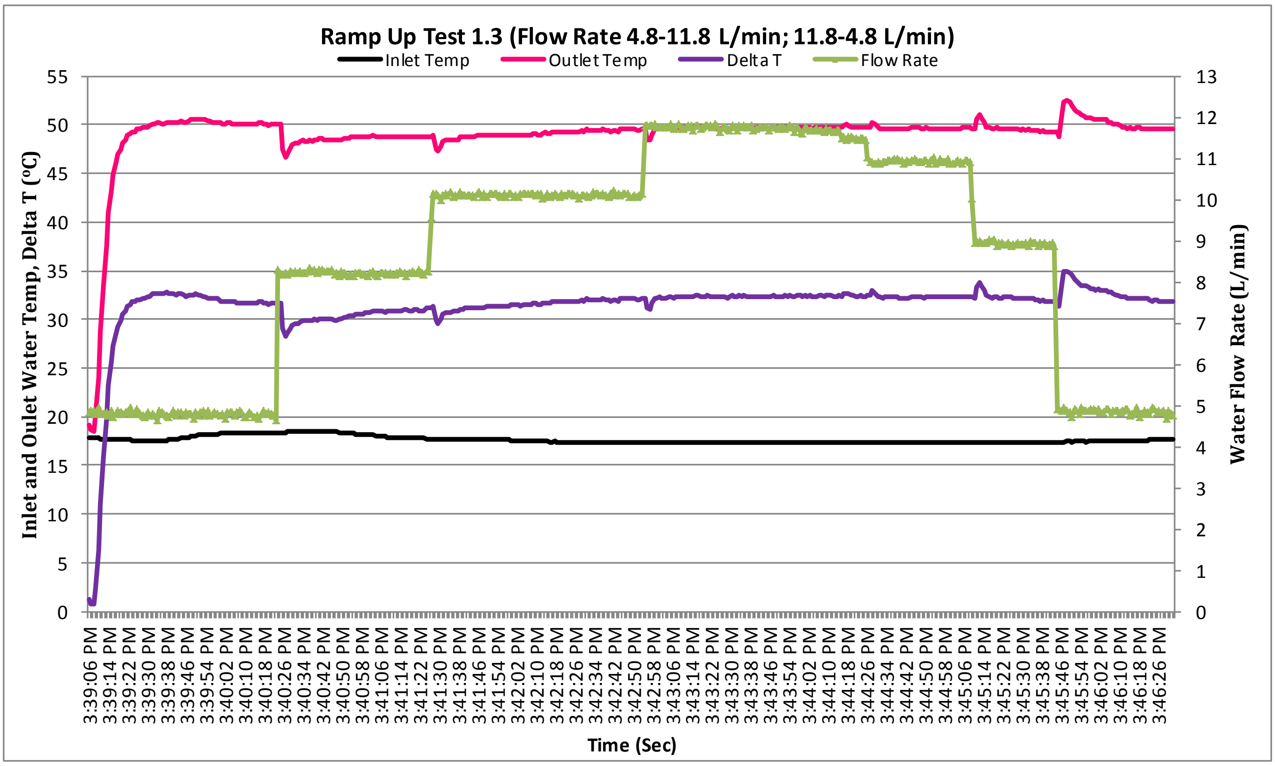

Fig. E-2: Gradual increase ramp-up flow test of Series 2 unit (test 1.3).

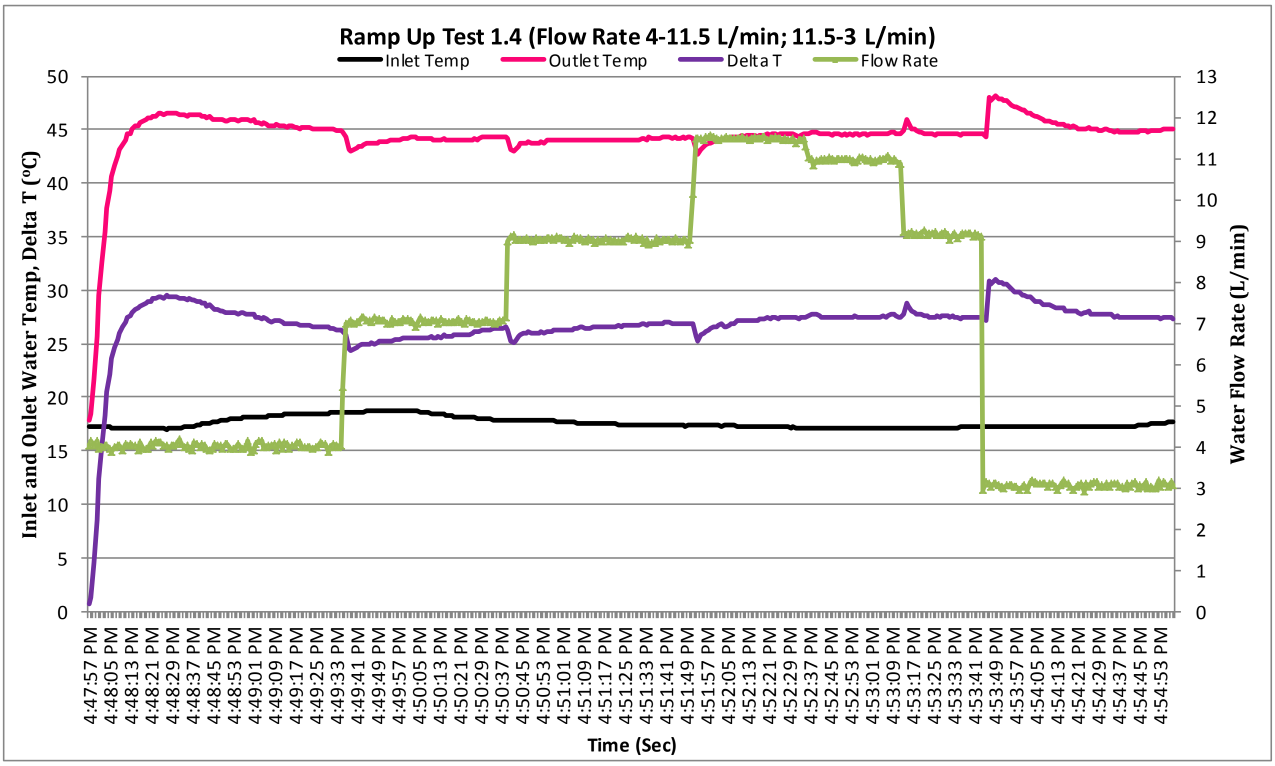

Fig. E-3: Gradual increase ramp-up flow test of Series 2 unit (test 1.4).

Appendix F: Graphs for the ramp-up test 2 (Series 2 unit)

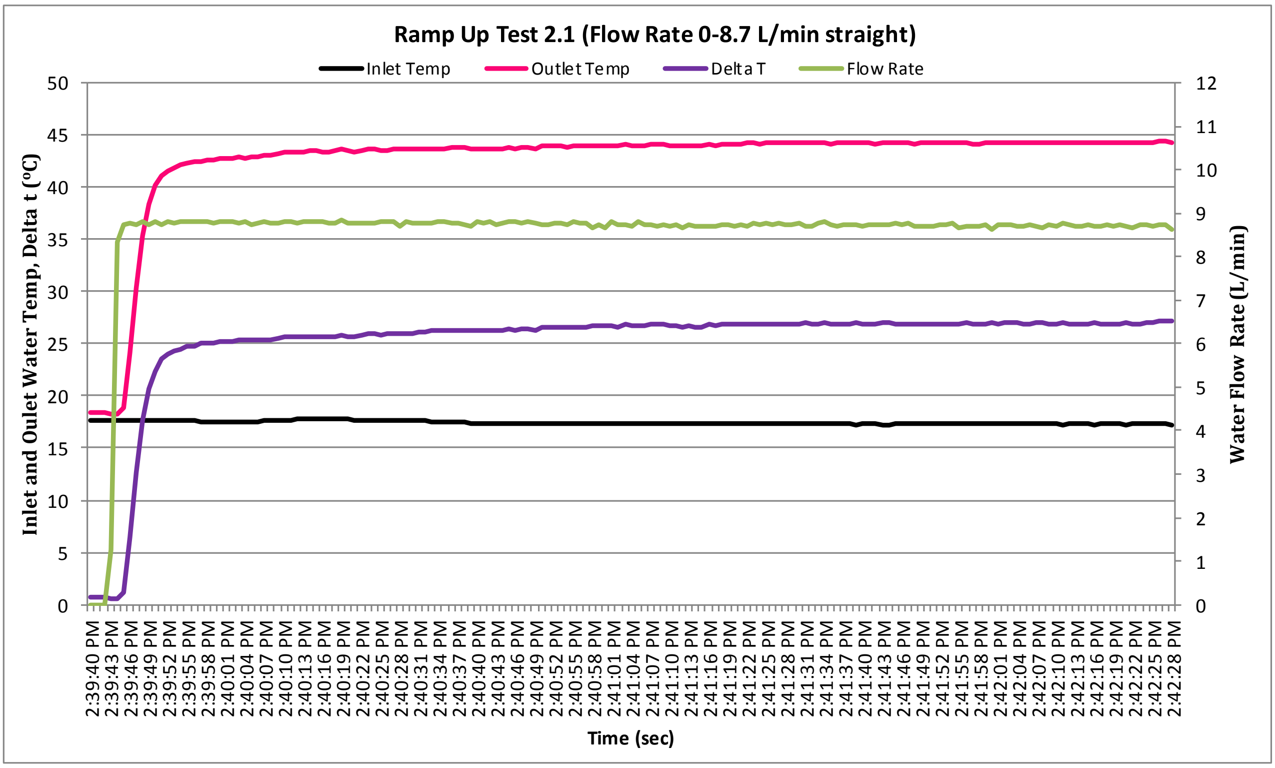

Fig. F-1: Rapid increase ramp-up flow test of Series 2 unit (test 2.1).

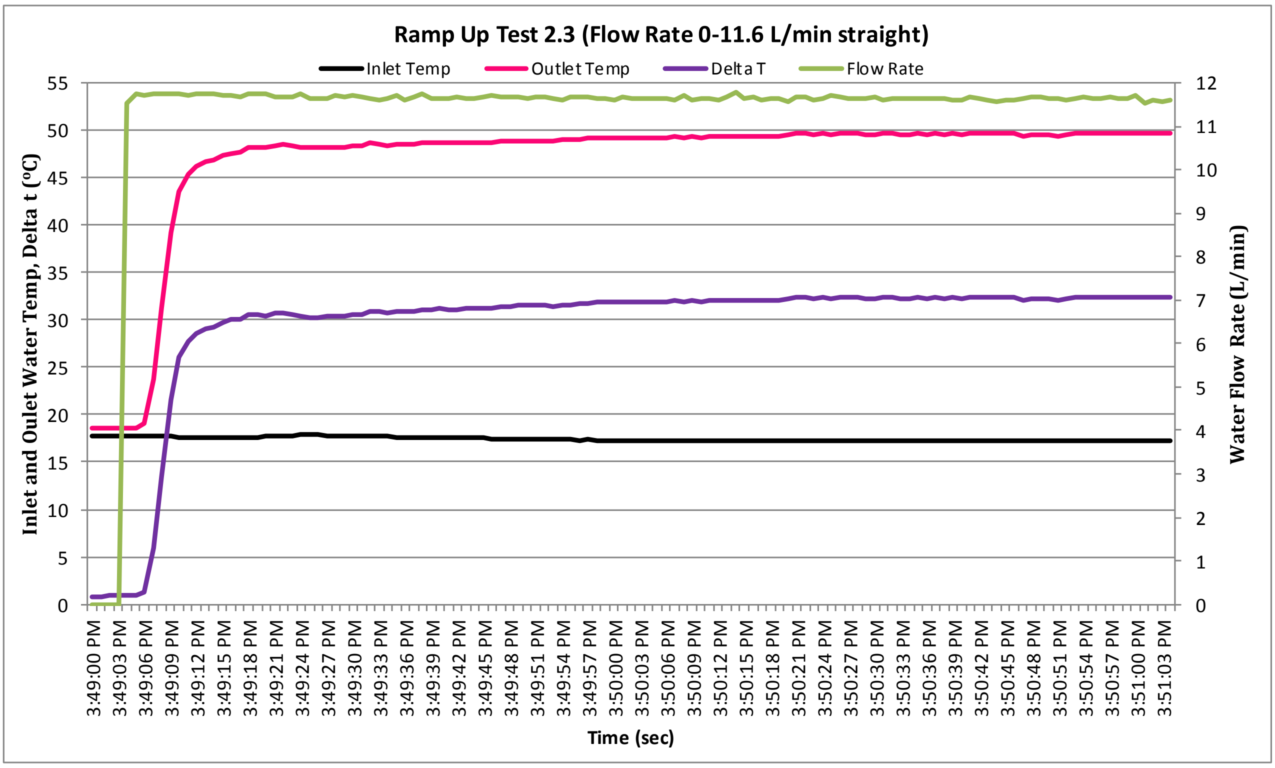

Fig. F-2: Rapid increase ramp-up flow test of Series 2 unit (test 2.3).

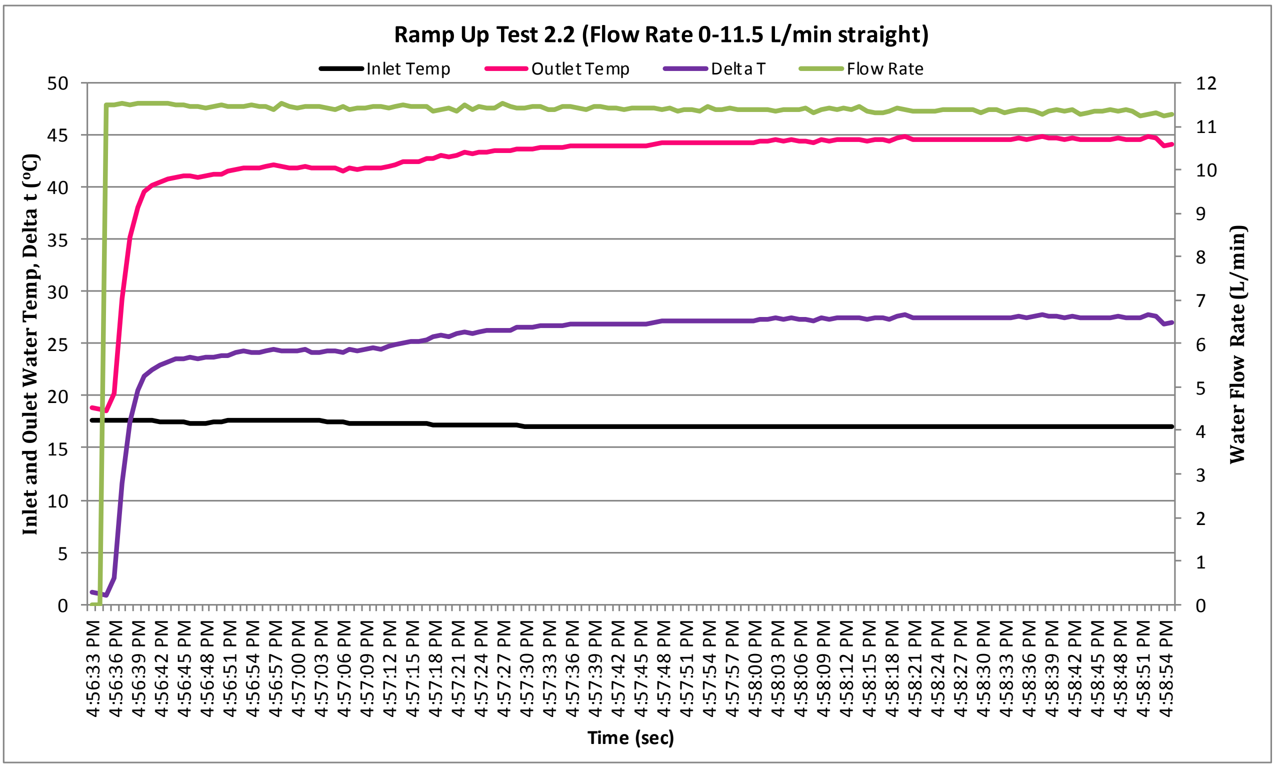

Fig. F-3: Rapid increase ramp-up flow test of Series 2 unit (test 2.4).