Verification Report

Rotaheater Micro and Pico

IN20180154UK03E

24 January 2023

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Report Number: IN20180154UK03E

Date of Issue: 24 January 2023

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1. Introduction

1.1 Name of technology and unique identifier of the technology being verified

Rotaheater Micro and Pico.

Rotaheater Micro:

Serial # 2200001

Model Identifier M-ETV

Rotaheater Pico:

Serial # 2100001

Model Identifier P-ETV

1.2 Name and contact of proposer

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1.4 Organisation of verification including experts, and verification process

Verification Body: BRE Global

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External Expert: Dr Colin Cunningham

Test Body: Rotaheat Limited (witnessed by BRE Global)

Internal Expert: Dr Robert Sutton

Proposer: Rotaheat Limited

Internal Experts: Robert Thompson

1.5 Deviations from the specific verification protocol

Amendment #1

The Micro and Pico model devices under test (DUT) were repeatedly reconfigured during testing to test a range of product variants. Variants differed by the number of magnets included within the assembled DUT.

To facilitate reconfiguration of the DUT, the assembly process was amended. The standard assembly process includes a step to permanently bond magnets within the assembly, which would prevent the magnets being removed. The bonding serves as a barrier to customers attempting to disassemble production models. The amended assembly process skipped the step of bonding the magnets within the assembly and enabled the reconfiguration of the same DUT with different sets of magnets. Magnets were kept secure and fixed through the use of mechanical fastenings which are integral to the product's design.

It is not considered this amendment to the assembly process impacted the observed performance, and consequently BRE Global is satisfied that the DUT is representative of production models.

Amendment #2

Production models of Rotaheat products are surrounded by a thermal jacket. This reduces the risk of nearby operators inadvertently touching a hot device. The thermal jacket also reduces heat loss.

To facilitate testing, the DUT was not surrounded by a thermal jacket. This amendment would result in heat being radiated from the DUT and lower the observed and claimed efficiency when compared to a product fitted with a thermal jacket.

No correction was made to subsequent calculations for any heat lost meaning the calculated efficiencies would be expected to be lower than when the thermal jacket was in place.

Consequently, this deviation is also considered acceptable.

Amendment #3

The Test Plan[1] called for devices to be tested at rotational speeds from 100 – 2000 RPM in steps of 100 RPM.

This was not possible for the M4[5] configuration of the Micro platform as the test facility was unable to provide more than 200kW of stable motive power. Consequently, due to its high heat output, testing of this configuration of the Micro platform was limited to rotational speeds up to and including 1400 RPM.

Since this limitation was brought about by the test facility and not the DUT this amendment is considered acceptable.

A consequence of this amendment is that the performance of the M4 configuration of the Micro platform may be verified up to 1400 RPM only.

2. Description of the technology and application

2.1. Summary description of the technology

The Rotaheater is a heat generator which converts motive power to thermal energy.

This is achieved by utilising the Joule heating effect of eddy currents generated within a metallic disc rotated between arrays of fixed magnets. The heat generated is captured in a fluid forced through the Rotaheater device by the pumping effect of the rotating disc.

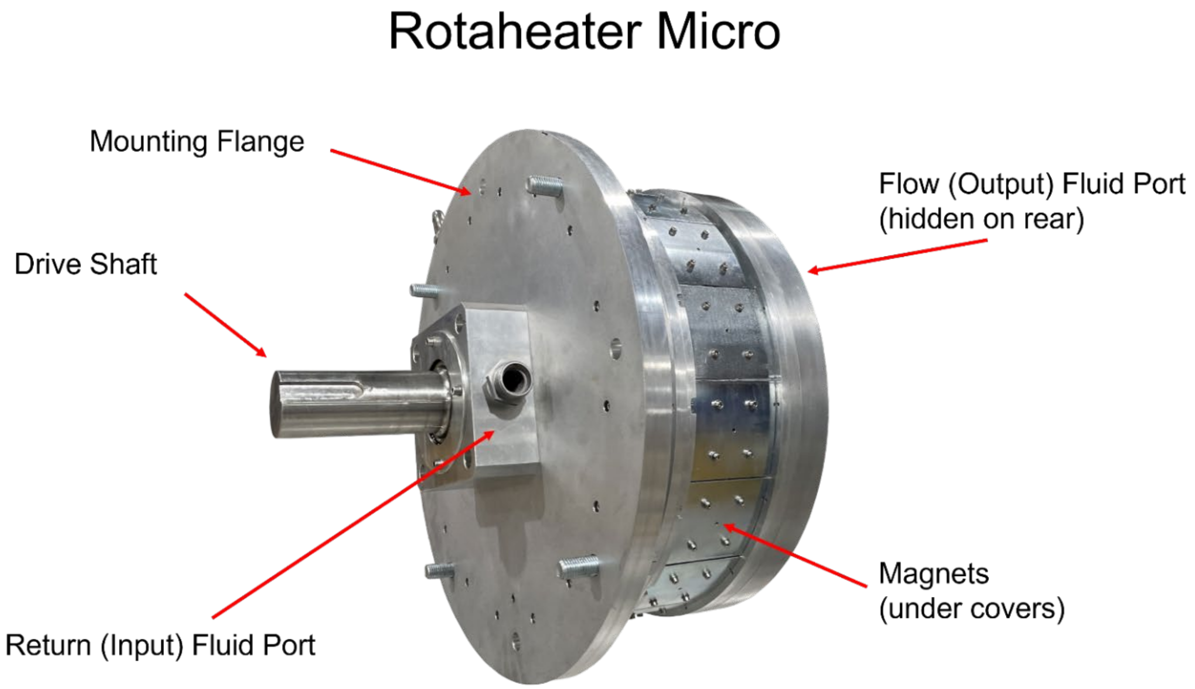

Figure 1 - Rotaheater Micro

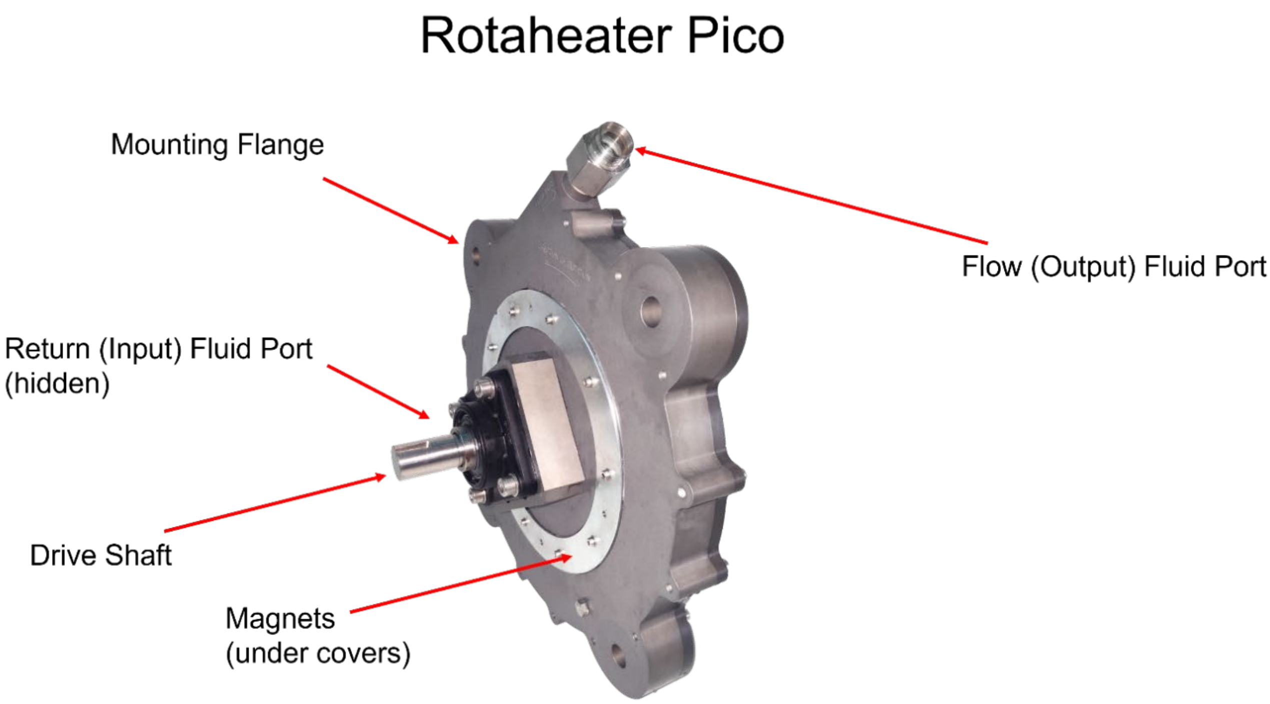

Figure 2 - Rotaheater Pico

Rotaheater Model Naming Convention

Rotaheater models are identified by a 6-character alphanumeric reference based on the following:

Character position	Representing	Option
1st	Model	M = Micro P = Pico
2nd	Max Operating Temperature	L = Up to 110°C
3rd	Max operating Pressure	L = Up to 0.3 MPa (3 bar) when the 1st character is M Up to 0.6 MPa (6 bar) when the 1st character is P
4th	No. Magnet Pairs/ Nominal Output	See Micro or Pico factsheets[2]
5th	Port Fitting	N = 1” Female NPT when the 1st character is M ¾” Male NPT when the 1st character is P S = 28 mm Swagelok compression when the 1st character is M 22 mm Swagelok compression when the 1st character is P
6th	Elastomers	E = Ethylene Propylene Diene Monomer (EPDM) [default] V = Viton [optional]

Model name examples:

MLL3NE – designates a Rotaheater Micro with a maximum operating temperature of up to 110°C, maximum operating pressure of up to 0.3 MPa, 72 magnet pairs, 1” NPT port fitting and an EPDM elastomer.

PLL4SV – designates a Rotaheater Pico with a maximum operating temperature of up to 110°C, maximum operating pressure of up to 0.6 MPa, 16 magnet pairs, ¾” NPT port fitting and a Viton elastomer.

DUT Designation

Throughout this Verification Report and the associated Statement of Verification, the Rotaheater DUTs are designated using the notation Nn where:

- N is the model coding (M=Micro, P=Pico)
- n defines the number of magnet pairs – see below:

Micro Designation	n Magnet Pairs
M1	24
M2	48
M3	72
M4	96

Pico Designation	n Magnet Pairs
P1	4
P2	8
P3	12
P4	16
P5	20

The DUTs all used EPDM elastomers and Swagelok compression fittings and would be equivalent to:

- PLLnSE (with n being 1 to 5)
- MLLnSE (with n being 1 to 4)

Further details are available from the respective Rotaheater Micro or Pico factsheets.

2.2. Intended application (matrix, purpose, technologies, technical conditions)

Application: Heat generation from a rotational input.

Matrix: Heating systems.

Purpose: Efficient energy conversion of motive power to heat.

Technologies: Thermal engineering, electrical engineering, mechanical engineering.

Technical conditions: A reliable, controllable, and measurable rotational input is required.

2.3. Parameter definitions

2.3.1. Verification parameters

Input power: Motive power supplied to the Rotaheater DUT

This is determined from the equation:

$$W_{\text{in}} = \tau\omega C_1$$

Where:

τ = applied torque

ω = RPM of the input shaft

C_1 is a constant (2π /60)

Output power: Thermal power provided by the Rotaheater DUT

This is determined from the equation:

$$W_{\text{therm}} = \dot{m} c_{\text{p}} \Delta T$$

Where:

$\dot{m}$ = mass flow rate of fluid in the heating circuit

c_{p} = specific heat capacity of fluid in the heating circuit

ΔT = difference between flow and return temperature of fluid in the heating circuit

Device efficiency: Ratio of output power/input power expressed as a percentage

2.3.2. Additional Parameters

Applied torque: Torque applied to Rotaheater (measured by torque transducer)

Input shaft rotational speed: Rotational speed of Rotaheater (also measured by torque transducer)

Heating circuit flow temperature: Temperature of fluid leaving the Rotaheater (measured by temperature sensor)

Heating circuit return temperature: Temperature of fluid entering the Rotaheater (measured by temperature sensor)

Heating circuit flow rate: Mass flow rate of fluid in the heating circuit (measured by flow meter)

Heating circuit fluid density and specific heat capacity: Known parameters and data.

3. Existing test data

Although Cranfield University conducted a technical feasibility study of the Pico and Micro Rotaheater platforms during 2018 the resulting data were not considered acceptable. Hence no existing data were used in this verification.

4. Evaluation

4.1. Calculation of verification parameters including determination of uncertainty

Input power was calculated from the torque and input shaft rotational speed data obtained from the calibrated torque transducer. This is detailed in equation 1 below. The uncertainty associated with the determination of this parameter is discussed in section 4.3.1.

$$W_{\text{in}} = \tau\omega C_1 \qquad (1)$$

Where:

W_{in} = input power

τ = applied torque

ω = measured RPM

C_1 = 2π/60.

Output power was calculated using flow and return temperature data and data for the mass flow rate of water around the test rig. This is described in equation 2 below.

$$W_{\text{therm}} = m\,\Delta\,h = mc_{\text{p}}\,\Delta\,T \qquad (2)$$

Where:

m = Mass flow rate of fluid in heating circuit (equal to the product of the fluid flow rate and fluid density)

c_{p} = Specific heat capacity of heating fluid

$\Delta\,T$ = Difference in temperature of heating fluid entering and leaving the Rotaheater

Each of the parameters that determine W_{in} and W_{therm} were measured using calibrated equipment (see Appendix 1) except for the specific heat capacity and density of the heating circuit fluid where reference data at different temperatures were used.

Device thermal efficiency was determined by dividing the output power by the input power ($W_{\text{in}}/W_{\text{therm}}$) and expressing this as a percentage.

4.2. Evaluation of test quality

The test method is described in the Rotaheater Test Plan[1]. This was reviewed by BRE Global and considered acceptable for the testing required for the performance verification of the Rotaheater Micro and Pico models. A sample of the testing was also witnessed and audited by BRE Global.

Each test run included a sequence of sampling periods during which data were collected for the Rotaheater operating at a series of fixed rotational speeds. Sampling periods began when the Rotaheater was operating at 100RPM and were repeated at 100RPM steps up to 2000RPM meaning there were 20 sampling periods for each test run. An exception to this, as described in Section 1.5 Amendment #3, was testing of the M4 configuration of the Micro platform where testing was limited to rotational speeds up to and including 1400 RPM.

4.2.1. Control data

Before each sampling period, a stabilisation period was implemented. This was to ensure that all primary conditions (rotational speed and the difference between the flow and return temperatures) were within acceptable limits.

These conditions were also monitored throughout each sampling period, and the acceptable variance conditions applied. Where these conditions deviated by more than the acceptable limits data collection was abandoned and the sampling period repeated.

The stabilization period began with confirmation that ambient conditions are stable, before subsequently initiating the motive power reference condition controlled via rotational speed (RPM).

The ambient condition is a measure of the return temperature of the fluid, which was to be maintained within 20°C of the return fluid's nominal reference temperature (20°C). The temperature of the return fluid influences the value of the specific heat and density of the fluid, used to calculate the thermal power. This primary condition is presented in the table below, along with additional primary conditions.

Table 1 - Test stability criteria

Test Type	Primary Condition(s)	Variance
Pump	Motive Drive	Higher of ± 5 reference RPM or ± 1% of reference RPM
Heat Generation	Motive Drive	Higher of ± 5 reference RPM or ± 1% of reference RPM
	Temperature Differential	± 0.25°C Micro model ± 0.05°C Pico model T_{Ret} = 20 °C (ambient) ±20°C

The stabilization period was also used to measure the offset torque applied to the torque transducer at zero RPM. This torque offset was applied to the torque values recorded during the sampling period to attain the applied torque values.

The stabilization period ran for a minimum of 180 seconds. In the scenario where parameter stability had not been reached within this time frame, the stabilization period continued until stability was attained.

After the test runs, data for each sampling period were also analysed by determining the instantaneous efficiency of the DUT for each of the data points within a sampling period. If the plot (against time) of these instantaneous efficiencies showed excessive deviation from the average efficiency for the sampling period then the data for the sampling period were reviewed, and if data for two or more sampling periods triggered a review, then data for the entire test run were rejected and the test run repeated.

This approach is similar to that described in BS EN 14511-3:2018[3] for the determination of steady state conditions for the testing of heat pumps.

4.2.2. Audits

The manufacturer's calibration procedure for the torque transducer was witnessed by BRE Global via video call on 22 September 2020.

Rotaheat Ltd's test procedure for the Pico platform using their 30kW test rig was witnessed by BRE Global via video call on 16 November 2020. However, due to difficulties experienced in testing at the top end of the rig's capacity it was later decided by Rotaheat to conduct all testing of the Pico platform using their 250kW test rig. The results obtained from testing using the 30kW test rig were not used in the determination of the performance of the Pico model.

Consequently, a sample of Rotaheat Ltd's testing of the Pico platform using a 250kW test rig was also audited by BRE Global via video call on 13 May 2021. The testing was conducted using a custom, dedicated, test rig situated in workshop facilities owned by a company called SPECIFIC based in Port Talbot, West Glamorgan. The same test rig and procedure were used for testing of the Micro platform.

A number of documents were provided by Rotaheat to support the testing process. These included a description of the test rig, instrument specifications and calibration certificates, test reports and data, responsibilities of personnel, company information and procedures.

Rotaheat approached and conducted the testing with considerable care and rigour. Significant effort was expended to understand the testing process and results (including understanding error and uncertainty). High quality instrumentation was purchased, calibrated and (when testing was delayed) recalibrated.

Following the witnessed testing and review of the supporting documentation it was recommended that the test results obtained by Rotaheat be accepted as evidence to verify their performance claims.

4.2.3. Deviations

A number of minor amendments to the original Test Plan were implemented following the commissioning of the test rig, including calibrated sensors. The amendments were:

Rotaheater Micro:

1. The maximum number of magnet pairs presented in the test plan was increased from 64 to 96. This was a consequence of a redesign to the Rotaheater Micro platform following the preparation of the Test Plan. This was considered acceptable.

2. The Test Plan outlines the intention to utilise an IFM SM8000 magnetic flow meter. A second flow meter with a larger measurement range and higher resolution was utilised for the ETV testing program; IFM SM 8120. As this instrument was appropriately calibrated this was considered acceptable.

3. The test plan outlines the intention to use a torque transducer rated up to 2000 Nm. Whilst this was the case for most of the testing, a transducer rated to 500Nm was implemented for magnet configurations with 24 magnet pairs (whereby the maximum torque generated was suitable for the smaller transducer and ensured a smaller system error). As this additional torque transducer was appropriately calibrated this was considered acceptable.

4. Torque Offset Period. An initial sampling step was introduced prior to the stabilization period whilst the motor provided zero RPM. The purpose of this step was to establish the zero offset torque being applied to the torque transducer, which was subsequently subtracted from the logged torque readings during the sampling periods to determine the accurate torque values. The zero offset torque varied across transducers and test runs. The zero offset torque was typically 1.3 Nm and 0.8 Nm for the 500 Nm and 2000 Nm transducer, respectively. This was considered acceptable.

5. The ‘stabilization period’, outlined in the Test Plan was conducted at 75rpm.The duration of this stabilization period was 180s (not 120s as outlined in the Test Plan). Prior to this stabilization period the torque offset period was completed, as outlined above. This was considered acceptable.

6. The operational criteria relating to the maximum fluid delta temperature was increased from 0.1°C to 0.25°C. This deviation was implemented to allow tests to progress in a timely manner. Given the magnitude of the fluid delta temperatures achieved with the Micro platform this was considered acceptable.

7. Due to the high heating capacity of the Micro platform the return temperature differential was increased from 20ºC ± 15ºC to 20ºC ± 20ºC. This deviation was implemented to allow tests to be completed within the permitted return temperature differential. Given the high heating capacity of the Micro platform this was considered acceptable.

8. The Test Plan outlines the intention to test the Rotaheater Micro platform up to and including 2000RPM for all magnet configurations. This was not possible due to the electrical supply of the test facility, which was limited to 400A ‑ approximately 200kW of motive power supplied to the DUT. Where this restriction became apparent, testing was limited to the highest possible RPM within the range. This was considered acceptable, although performance verification will be limited to the maximum RPM achieved during testing.

Rotaheater Pico:

1. The Test Plan involved completing the ETV testing of the Rotaheater Pico on a 30 kW test rig. As previously explained, due to technical limitations of the 30 kW test rig, it was not possible to complete all planned tests on the 30 kW rig. As such, all planned tests were completed on the larger 250 kW rig where the technical restrictions were not apparent. This was considered acceptable.
2. The Test Plan indicated the intention to utilise the IFM SM8000 flow meter to determine the rate of water expelled from the Rotaheater device. A second magnetic flow meter, IFM SM8120, was utilised alternatively, offering a larger measurement range and higher resolution. This was considered acceptable.
3. A ‘Torque Offset Period’ was introduced prior to the stabilization period whilst the motor provided zero RPM. The purpose of this step was to establish the offset torque being applied to the torque transducer, which was subsequently subtracted from the logged raw torque readings during the sampling periods prior to determining the normalised torque values. This was considered acceptable.
4. The ‘stabilization period’, outlined in the Test Plan was conducted at 75rpm. The duration of this stabilization period was 180s and not 120s as outlined in the Test Plan. This was considered acceptable.
5. The sampling periods were conducted as outlined in the Test Plan with one minor adjustment. For 100 and 200 RPM, the sampling periods were extended from 120s to 180s to ensure the body of the DUT had stabilised its temperature after being exposed to the relatively modest amounts of heat generated at low shaft speeds. This change was purely functional. From a data processing point of view, the final 120s of valid data was extracted for analysis. Due to the relatively low heating capacity of the Pico platform at these RPM this was considered acceptable.
6. The sampling period was increased from 120s to 125s, to ensure that there was 120s of stable data for analysis. This was considered acceptable.
7. The operational criteria relating to the fluid delta temperature was reduced from 0.1 °C to 0.05 °C. This deviation reduced the variance of temperature readings throughout the sampling period. This was considered acceptable.

Rotaheater Micro and Pico:

1. Within the submitted Test Plan, it is indicated that the calibration adjustments required for the temperature and flow sensors would be applied to the raw data during analysis by a simple numerical adjustment (e.g. ± 0.2 °C). Appendix 1 presents the accurate calibration relationships attained from the UKAS accredited laboratory calibration certificates. The accurate readings from the calibrated sensors were determined from the relationships presented in the same appendix. This was considered acceptable.
2. The Test Plan outlined a methodology for calculating the error associated with the efficiency calculations, accounting for the associated errors of the measuring equipment. This approach was also adopted for the determination of systematic errors. An additional independent methodology was also presented (see section 4.3.1) to establish the confidence limits in the results - a measure of the repeatability of the attained results. This was considered acceptable.

4.3. Verification results (verified performance claim)

With the deviations described above applied, a Rotaheater Micro product and a Rotaheater Pico product were tested as otherwise described in the Rotaheater Micro ETV Test Report and Rotaheater Pico ETV Test Report, respectively (commercially sensitive).

Testing was conducted using a bespoke test rig and test procedure. Both were audited by BRE Global and found to be in accordance with the requirements of GVP 1.3[4].

Test data were collected using appropriately specified, positioned and calibrated instrumentation.

These data were used to determine device performances which in turn were used to form the basis of the revised performance claim. The revised performance claim is detailed in section 4.4

Essentially input power was determined from the product of the torque applied to the DUT and the rotational speed of the DUT – applying an appropriate constant. Output power was determined from the temperature rise (flow temperature – return temperature in the fluid of the heating circuit) again applying appropriate known parameters.

Device thermal efficiency was then determined from the output power divided by the input power. This is expressed as a percentage.

4.3.1. Description of statistical methods used

A number of methods were applied. These included confirmation of the stability of test instruments during each test run, 'z' distribution confidence limit assessment of the data points recorded for each RPM interval during each test run and 't' distribution confidence limit assessment for the test results obtained for each RPM interval.

4.3.1.1. Error/Uncertainty calculation process

The error/uncertainty associated with the test results was broken down into two distinct areas: systematic errors and confidence. The latter is a measure of experimental repeatability, whereas the former is function of the test method itself, the equipment used to measure and record the relevant parameters, along with their resolution and calibration. Although, both systematic errors and confidence are linked, they are calculated and presented separately.

4.3.1.2. Systematic Errors

The calculation of efficiency is a function of multiple measured (dependent) variables. Each one of these variables has an uncertainty margin associated with it, which will depend on the resolution of the sensing equipment utilised. The total error within the efficiency calculations was found by taking the modulus (magnitude) of each individual contributing variable:

$$\partial\eta = \sqrt{\left[\frac{\partial\eta}{\partial\tau}\delta\tau\right]^2 + \left[\frac{\partial\eta}{\partial\omega}\delta\omega\right]^2 + \left[\frac{\partial\eta}{\partial T_{in}}\delta T_{in}\right]^2 + \left[\frac{\partial\eta}{\partial T_{out}}\delta T_{out}\right]^2 + \left[\frac{\partial\eta}{\partial\dot{m}}\delta\dot{m}\right]^2} \qquad (3)$$

Where, $\delta\tau$, $\delta\omega$, δT_{in}, δT_{out} and $\delta\dot{m}$ are the error associated with sensing equipment measuring torque, RPM, flow and return temperatures and mass flow rate, respectively.

The error associated with individual variables was found by taking the partial derivative of the efficiency with respect to the variables, as shown in the equation below:

$$\frac{\partial \eta}{\partial \alpha} = \frac{W_{therm}}{W_{in}\alpha} \tag{4}$$

Where α refers to the variable under analysis.

The error for each individual contributing component was determined and substituted into the relevant equation.

4.3.1.3. Confidence Interval

The confidence interval of a sample range, for a given confidence level, is measure of uncertainty of the measured sample mean. For large sample sizes (> 30 sample points), the confidence interval can be determined from:

$$C.I(\alpha) = \bar{x} \pm z * \frac{\sigma}{\sqrt{n}} \tag{5}$$

Where α is the selected confidence level (i.e. 95), $\bar{x}$, is the mean value from the sample, z, is a constant relating the confidence interval for a z-distribution (large sample size)[a] , σ is the standard deviation, and n, is the number of samples within the data set. $\frac{\sigma}{\sqrt{n}}$, is also known as the Standard Error Mean (SEM). It is well understood that the margin of error/standard mean error decreases in size as the sample size increases.

If the sample size is small (<30 sample points), the confidence interval can be determined from:

$$C.I(\alpha) = \bar{x} \pm t * \frac{\sigma}{\sqrt{n}} \tag{6}$$

Where, t, is the constant relating to the confidence level for a t-distribution (small sample size).

Constants for a z-distribution are standard for a range of confidence levels, as presented in the following table:

Table 2 - Z-values for a standard confidence levels[b]

Confidence Level (1-α)	z-value
0.9	1.645
0.95	1.96
0.99	2.58

t-values are obtained from a t-distribution table[c] using a value derived from the desired confidence level and the sample size (n).

The standard deviation, σ, can be calculated from:

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[a] Z-values for a given confidence level can be found using standard z tables.

[b] Taken from: https://www.simplypsychology.org/confidence-interval.html (Accessed 01/06/2022)

[c] https://www.statisticshowto.com/probability-and-statistics/confidence-interval/#CISample (Accessed 16/01/2023).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{(n-1)}} \qquad (7)$$

Where, i, refers to the sample points with the sample set.

For the statistical analysis relating to the testing a 95% confidence was applied.

As each test run was completed 5 times, there were 5 sample periods for each configuration and shaft speed combination.

As the sample periods had 120 data points (depending on the data sampling rate), a z-distribution confidence interval was calculated. Consequently $z = 1.96$. For each sample period (120 s at given input shaft speed (RPM)), the average efficiency was calculated ($\overline{Eff}$), and the standard deviation using Equation 7.

Applying the values to Equation 5, an example of the resulting values associated with the statistical analysis are presented in the table below:

Table 3 - Z-Value confidence analysis for M1 configuration @1000RPM (Example Analysis)

Run	$\overline{Eff}$	σ	n	z	SEM	CI(95)
1	98.99	0.4587	120	1.96	0.0419	0.0821
2	100.19	0.4830	120	1.96	0.0441	0.0864
3	99.25	0.3979	120	1.96	0.0362	0.0712
4	100.35	0.3911	120	1.96	0.0357	0.0700
5	99.33	0.4562	120	1.96	0.0416	0.0816

As can be seen in the table above, the standard error means are exceedingly small for each of the sample periods. This is due to the large sample sizes. The average efficiencies with the error bars applied can be seen in *Figure 3.*

A 95% confidence interval means that if the test was repeated 100 times under the same circumstances, with the same ambient conditions, the average efficiency of 95 of these tests would fall within the associated confidence level.

Figure 3 shows there is a difference between each sample period for each test run. This is due to varying environmental and ambient conditions under which the test runs were completed.

The average confidence interval across the 5 independent runs (sampling periods) was determined using a t-distribution. The average efficiency can be calculated by taking the average of each efficiency and the standard deviation using Equation 7. The t-value can be determined from the alpha value and the df (degrees of freedom) value. The alpha value for 95% confidence level is 0.025 ($\frac{1-0.95}{2}$). The df value is determined by subtracting 1 from the sample size: $df = 5 - 1 = 4$. These values are combined and used to look up a t-value in a t-distribution table, resulting in a t-value of 2.776[c]. The relevant values and outputs from Equation 6 can be seen in the table below.

Table 4 - Confidence Interval using t-distribution for overall average (example)

$\overline{Eff}$	σ	n	t	SEM	CI(95%)
99.62	0.6059	5	2.776	0.2710	0.7522

Figure 3 also shows the average efficiency with the applied confidence error bars. The shaded region shows the confidence interval for each independent sample period (run 1 – 5), falls within the 95% confidence interval of the overall average.

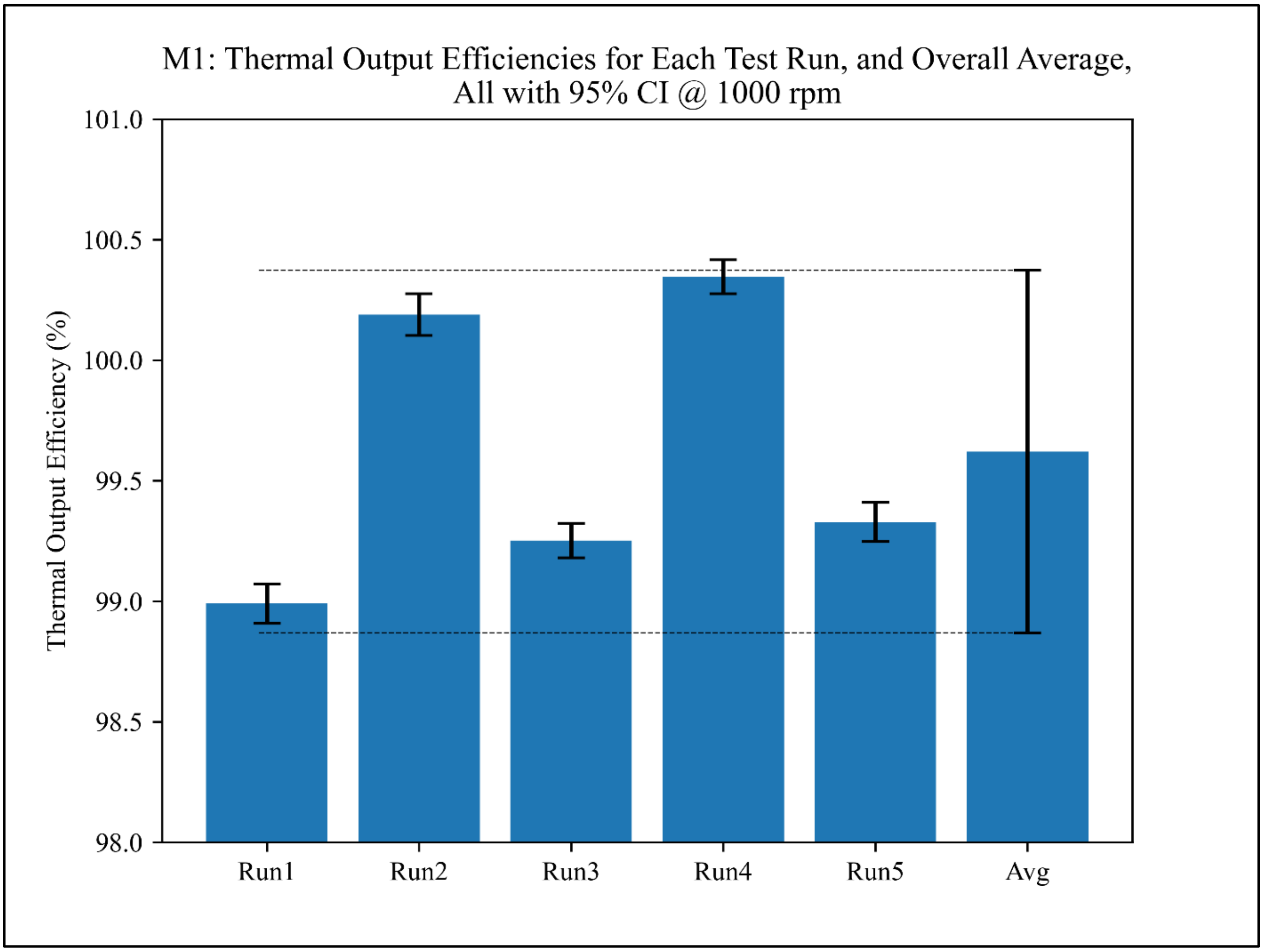


Figure 3 - Sample period efficiencies for M1@1000RPM, along with overall average, and associated confidence intervals using z and t distribution methods.

4.3.2. Verification parameters

Table 5 - Verification parameters

Parameter	Units	Determination method
Input power	kW	Calculation from additional parameters
Output power	kW	Calculation from additional parameters
Device thermal efficiency	%	Calculation from additional parameters

Full details of the calculation of the above parameters are described in section 4.1.

4.3.3. Additional parameters, with comments or caveats where appropriate

Table 6 - Additional parameters

Parameter	Units	Determination Method
Input power torque	Nm	Direct measurement
Input shaft rotational speed	RPM	Direct measurement
Heating circuit flow temperature	K	Direct measurement
Heating circuit return temperature	K	Direct measurement
Heating circuit flow rate	l/s	Direct measurement
Heating circuit fluid specific heat capacity	kJ/(kgK)	Reference data
Heating circuit fluid density	kg/m^3	Reference data

With the exception of the heating circuit fluid specific heat capacity and density (which are well characterised parameters) the above parameters were measured using calibrated instruments. Details of the calibration of these instruments are given in Appendix 1.

4.4. Recommendations for the Statement of Verification

The following tables and graphs present data that BRE Global is satisfied reflects the performance of the Rotaheater Micro and Pico models exceeded with 95% confidence (the revised performance claims) when operated using the equipment and process audited by BRE Global. Consequently, it is recommended that these performance tables and graphs be referenced in the Statement of Verification for these Rotaheater models.

The magnetic configurations referred to in these tables and graphs are defined in documents ‘Guide to Magnet Configurations – Rotaheater Micro’[5] and ‘Guide to Magnet Configurations – Rotaheater Pico’[6] respectively.

The Statement of Verification should also make reference to the build status, including the relevant Bills of Materials and technical drawings of the tested devices.

In addition, the data presented should also include the associated mass flow and flow temperature.

Rotaheater Micro Platform

95% Confidence Level* Performance of Rotaheater Micro, Magnetic Configuration M1

Shaft Rotation Speed (RPM)	Drive Torque (Nm)	Mass Flow (Kgs^{-1})	Specific Heat Capacity ($NmKg^{-1}K^{-1}$)	Delta T (K)	Power Output (kW)	95% Confidence Interval (+/- kW)	Power Conversion Efficiency (%)	95% Confidence Interval (+/- %)	Flow Temp (ºC)
100	71.13	0.141	4187	0.925	0.624	0.037	79.019	6.944	19.6
200	138.49	0.319	4187	2.053	2.775	0.063	93.999	1.848	20.5
300	197.22	0.488	4186	2.938	6.031	0.104	96.103	1.225	21.4
400	246.39	0.655	4186	3.666	10.130	0.133	96.689	1.227	22.2
500	285.98	0.801	4185	4.056	14.711	0.273	97.757	0.959	23.0
600	316.76	0.835	4184	5.090	19.707	0.271	98.460	0.730	24.7
700	340.19	0.867	4184	6.287	24.791	0.268	98.607	0.789	26.1
800	359.22	0.907	4183	7.115	29.970	0.289	98.991	0.697	27.3
900	374.09	0.928	4182	7.974	35.211	0.180	98.928	0.725	28.7
1000	386.43	0.932	4182	9.037	40.327	0.259	98.869	0.752	30.2
1100	397.48	0.922	4181	10.438	45.682	0.262	99.001	0.754	32.1
1200	407.75	0.933	4180	11.650	51.123	0.276	98.894	0.839	33.7
1300	417.14	0.953	4180	12.478	56.598	0.449	99.291	0.477	35.2
1400	424.14	0.969	4179	13.390	62.131	0.653	99.106	0.647	37.0
1500	433.35	0.981	4179	14.633	67.864	0.814	99.101	0.627	38.7
1600	433.47	0.918	4178	16.821	72.000	1.831	98.911	0.688	42.4
1700	444.52	0.929	4178	18.563	78.582	1.562	98.909	0.669	44.4
1800	452.09	0.924	4177	19.964	84.552	1.947	98.874	0.702	47.0
1900	463.02	0.944	4177	20.951	91.470	2.172	98.794	0.705	49.2
2000	474.56	0.965	4177	22.238	98.454	2.595	98.823	0.714	51.4

*Performance exceeded with 95% confidence level

95% Confidence Level* Performance of Rotaheater Micro, Magnetic Configuration M2

Shaft Rotation Speed (RPM)	Drive Torque (Nm)	Mass Flow (Kgs^{-1})	Specific Heat Capacity ($NmKg^{-1}K^{-1}$)	Delta T (K)	Power Output (kW)	95% Confidence Interval (+/- kW)	Power Conversion Efficiency (%)	95% Confidence Interval (+/- %)	Flow Temp (°C)
100	147.36	0.151	4187	2.276	1.436	0.031	92.753	0.782	20.2
200	281.35	0.320	4186	4.268	5.749	0.083	97.059	0.389	22.2
300	396.69	0.487	4185	5.978	12.232	0.185	97.850	0.361	24.0
400	489.62	0.654	4184	7.386	20.292	0.320	98.819	0.267	25.5
500	562.54	0.745	4183	8.169	29.113	0.558	98.596	0.951	27.9
600	615.73	0.750	4182	11.462	38.533	0.402	99.414	0.265	31.2
700	654.56	0.807	4181	12.858	47.792	0.425	99.570	0.165	33.4
800	680.87	0.829	4180	13.821	56.903	0.395	99.661	0.163	36.3
900	698.36	0.851	4179	15.765	65.591	0.543	99.549	0.356	39.0
1000	709.46	0.844	4178	18.513	74.013	0.611	99.567	0.261	42.2
1100	717.45	0.851	4177	21.296	82.318	0.608	99.530	0.234	45.2
1200	722.08	0.861	4177	23.218	90.434	0.617	99.475	0.262	48.1
1300	724.56	0.853	4177	25.007	98.038	0.707	99.338	0.280	51.5
1400	723.97	0.839	4176	27.670	105.634	0.566	99.250	0.352	55.3
1500	723.81	0.834	4176	30.219	112.770	0.739	99.103	0.334	58.7
1600	725.89	0.849	4177	31.875	120.830	0.665	99.122	0.368	61.5
1700	727.47	0.867	4177	32.939	128.620	0.713	99.161	0.203	64.5
1800	726.50	0.867	4178	34.091	135.993	1.196	98.974	0.327	68.2
1900	728.02	0.877	4179	35.511	143.368	1.615	98.781	0.338	72.0
2000	732.81	0.887	4179	37.492	151.914	1.680	98.893	0.269	74.8

*Performance exceeded with 95% confidence level

95% Confidence Level* Performance of Rotaheater Micro, Magnetic Configuration M3

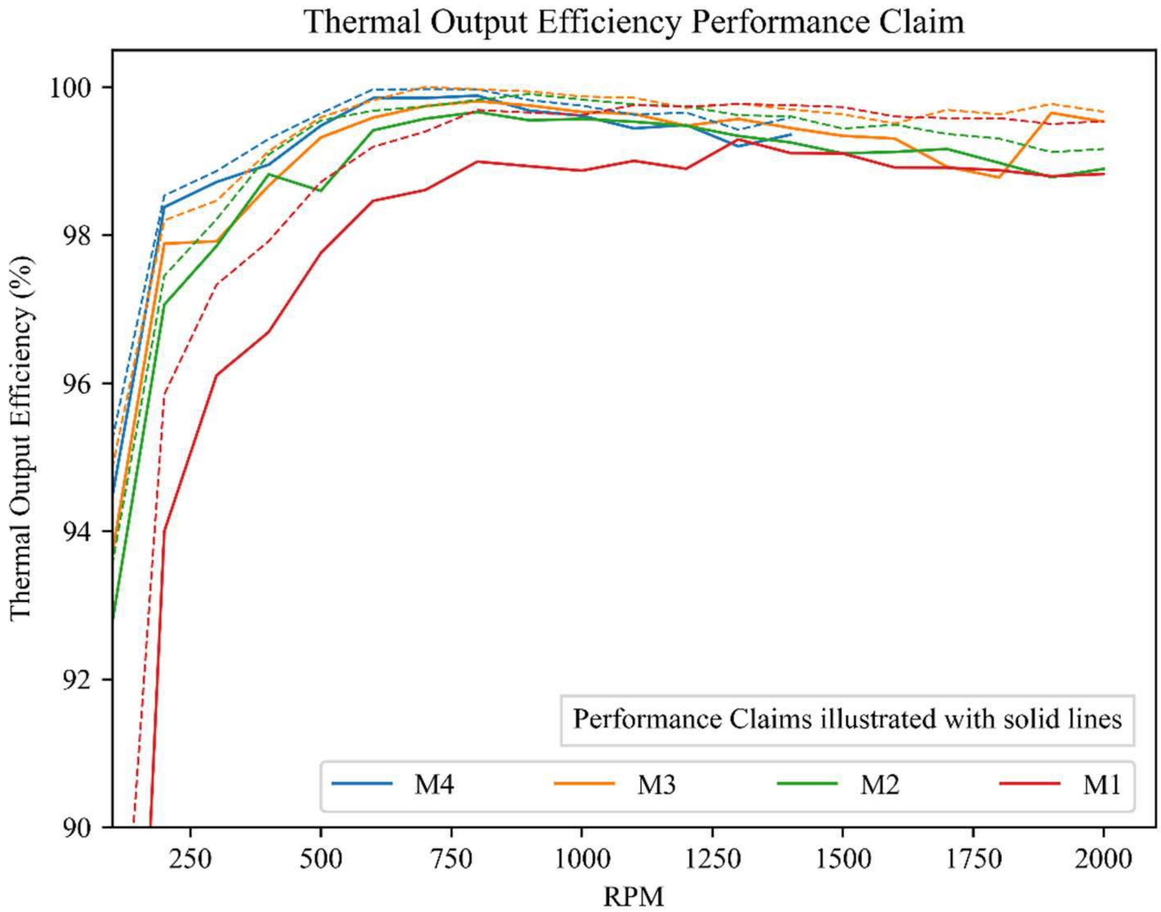
Shaft Rotation Speed (RPM)	Drive Torque (Nm)	Mass Flow (Kgs^{-1})	Specific Heat Capacity ($NmKg^{-1}K^{-1}$)	Delta T (K)	Power Output (kW)	95% Confidence Interval (+/- kW)	Power Conversion Efficiency (%)	95% Confidence Interval (+/- %)	Flow Temp (^oC)
100	222.81	0.152	4188	3.410	2.200	0.059	93.676	1.165	20.0
200	428.32	0.323	4187	6.516	8.819	0.089	97.884	0.314	22.5
300	596.44	0.491	4185	8.963	18.394	0.343	97.914	0.549	25.7
400	739.06	0.660	4184	11.099	30.609	0.358	98.665	0.466	27.4
500	833.62	0.784	4183	11.416	43.499	0.657	99.317	0.272	30.7
600	910.86	0.751	4181	17.095	56.981	0.848	99.585	0.235	36.1
700	959.40	0.831	4180	18.787	70.233	1.183	99.741	0.260	38.9
800	996.35	0.909	4179	21.665	83.425	1.180	99.807	0.160	40.8
900	1016.01	0.938	4178	23.352	95.703	1.354	99.749	0.190	44.1
1000	1024.06	0.938	4178	26.022	106.879	2.048	99.661	0.209	48.0
1100	1030.63	0.926	4177	29.454	118.342	1.815	99.636	0.217	52.5
1200	1035.53	0.944	4177	32.325	129.540	1.892	99.475	0.240	55.1
1300	1032.45	0.981	4177	33.759	139.934	2.168	99.567	0.208	58.2
1400	1032.66	0.984	4177	34.598	150.479	2.289	99.445	0.251	60.6
1500	1017.04	1.000	4177	36.848	158.698	3.543	99.339	0.291	64.9
1600	1020.20	0.992	4177	38.554	169.636	2.746	99.302	0.203	67.3
1700	1001.21	0.918	4178	43.260	176.734	4.380	98.922	0.768	72.9
1800	997.37	0.931	4179	45.346	186.627	4.567	98.776	0.854	77.1
1900	994.75	0.881	4181	52.760	197.363	1.436	99.649	0.120	84.6
2000	996.54	0.891	4182	54.173	207.158	1.517	99.531	0.134	88.2

*Performance exceeded with 95% confidence level

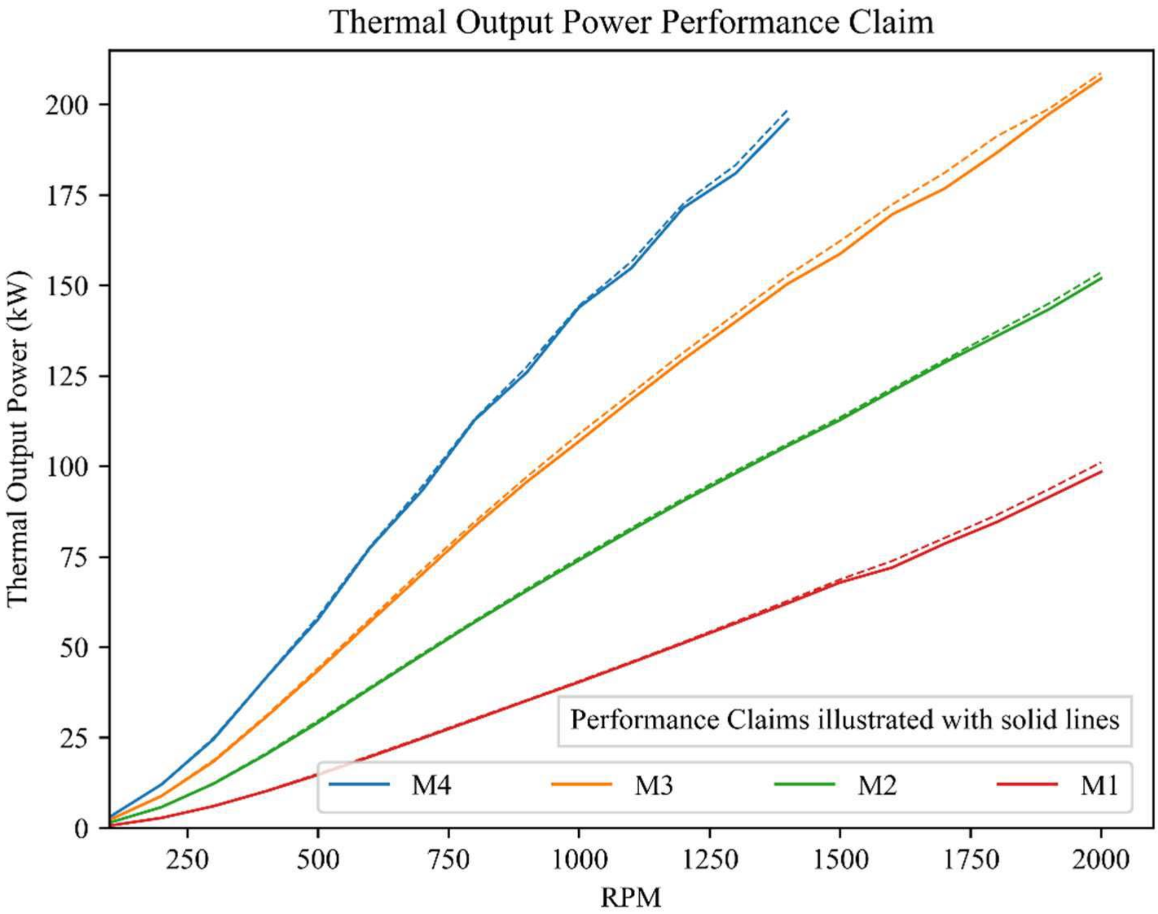
95% Confidence Level* Performance of Rotaheater Micro, Magnetic Configuration M4									
Shaft Rotation Speed (RPM)	**Drive Torque (Nm)**	**Mass Flow (Kgs^{-1})**	**Specific Heat Capacity ($NmKg^{-1}K^{-1}$)**	**Delta T (K)**	**Power Output (kW)**	**95% Confidence Interval (+/- kW)**	**Power Conversion Efficiency (%)**	**95% Confidence Interval (+/- %)**	**Flow Temp (ºC)**
100	296.88	0.152	4183	4.620	2.959	0.058	94.457	0.769	25.6
200	582.46	0.323	4187	8.891	12.006	0.064	98.376	0.157	23.4
300	789.81	0.491	4180	12.054	24.541	0.359	98.715	0.147	33.2
400	997.80	0.659	4184	14.999	41.442	0.185	98.950	0.347	29.9
500	1104.55	0.826	4179	16.850	57.669	0.762	99.476	0.167	38.7
600	1233.25	0.794	4179	22.349	77.505	0.324	99.848	0.119	40.5
700	1275.18	0.869	4177	25.655	93.363	1.147	99.850	0.121	49.4
800	1345.55	0.915	4177	28.816	112.739	0.333	99.882	0.087	47.9
900	1340.34	0.935	4176	31.923	125.969	1.528	99.679	0.142	57.9
1000	1376.07	0.931	4176	36.582	143.937	0.412	99.610	0.138	57.5
1100	1349.87	0.924	4177	39.439	154.743	1.781	99.440	0.184	68.6
1200	1369.38	0.929	4177	44.107	171.480	1.122	99.487	0.167	67.2
1300	1339.48	0.959	4179	43.709	180.965	2.311	99.198	0.224	76.7
1400	1343.02	0.999	4178	46.358	195.835	2.703	99.355	0.232	74.7

*Performance exceeded with 95% confidence level

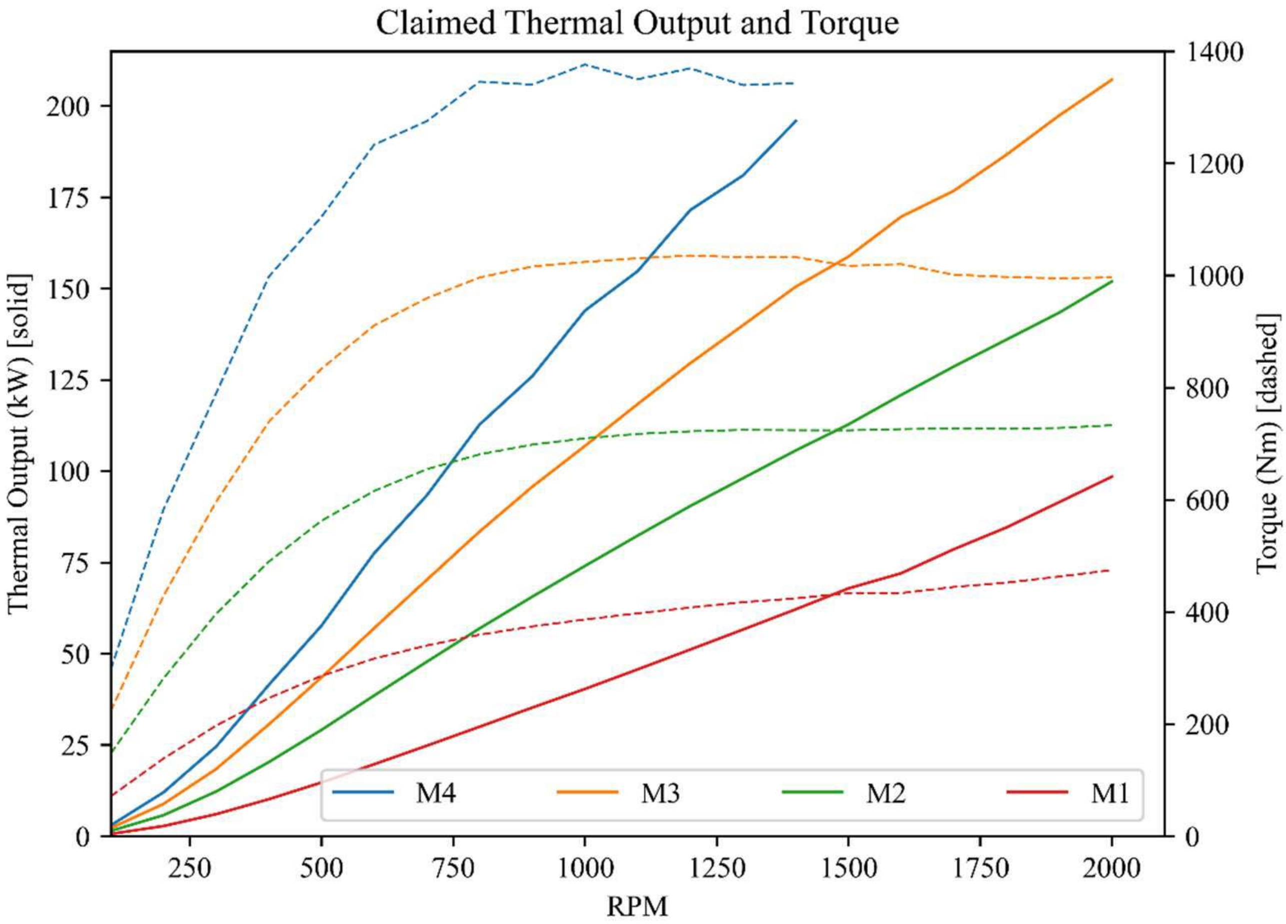
Rotaheater Micro Thermal Efficiency v's RPM



Rotaheater Micro Thermal Output v's RPM



Rotaheater Micro Thermal Output/Torque v’s RPM



Rotaheater Pico Platform

95% Confidence Level* Performance of Rotaheater Pico, Magnetic Configuration P1

Shaft Rotation Speed (RPM)	Drive Torque (Nm)	Mass Flow (Kgs^{-1})	Specific Heat Capacity ($NmKg^{-1}K^{-1}$)	Delta T (K)	Power Output (kW)	95% Confidence Interval (+/- kW)	Power Conversion Efficiency (%)	95% Confidence Interval (+/- %)	Flow Temp (^oC)
100	5.118	0.055	4184	0.035	0.007	0.013	12.26	23.18	21.7
200	9.938	0.116	4183	0.325	0.161	0.008	74.60	4.00	22.1
300	14.516	0.182	4183	0.523	0.398	0.007	85.32	1.97	22.3
400	18.448	0.248	4183	0.680	0.698	0.010	88.18	2.05	22.4
500	21.882	0.315	4183	0.817	1.068	0.013	91.11	1.85	22.6
600	24.811	0.381	4183	0.928	1.472	0.015	92.60	1.63	22.7
700	27.186	0.448	4183	1.016	1.900	0.015	93.65	1.40	22.8
800	29.127	0.516	4183	1.087	2.342	0.015	94.26	1.34	22.9
900	30.582	0.582	4183	1.143	2.785	0.021	94.79	1.44	23.0
1000	31.855	0.649	4183	1.192	3.235	0.015	95.13	1.24	23.1
1100	32.887	0.715	4183	1.224	3.664	0.022	95.44	0.91	23.2
1200	33.682	0.781	4183	1.253	4.102	0.029	95.61	0.91	23.2
1300	34.386	0.848	4183	1.278	4.538	0.035	95.70	0.96	23.3
1400	35.005	0.915	4183	1.301	4.984	0.037	95.96	0.77	23.3
1500	35.560	0.982	4183	1.322	5.439	0.036	95.84	0.95	23.4
1600	36.172	1.048	4183	1.342	5.888	0.047	95.82	0.95	23.4
1700	36.757	1.114	4183	1.363	6.361	0.049	95.90	0.89	23.5
1800	37.395	1.181	4183	1.382	6.836	0.060	95.85	0.85	23.5
1900	37.984	1.247	4183	1.405	7.333	0.070	95.86	0.85	23.6
2000	38.655	1.313	4183	1.428	7.857	0.079	95.86	0.80	23.7

*Performance exceeded with 95% confidence level

95% Confidence Level* Performance of Rotaheater Pico, Magnetic Configuration P2

Shaft Rotation Speed (RPM)	Drive Torque (Nm)	Mass Flow (Kgs^{-1})	Specific Heat Capacity ($NmKg^{-1}K^{-1}$)	Delta T (K)	Power Output (kW)	95% Confidence Interval (+/- kW)	Power Conversion Efficiency (%)	95% Confidence Interval (+/- %)	Flow Temp (ºC)
100	10.397	0.054	4182	0.195	0.045	0.021	41.72	16.63	23.1
200	20.141	0.115	4182	0.691	0.335	0.035	79.40	6.34	23.7
300	29.209	0.18	4182	1.080	0.817	0.042	88.94	3.46	24.1
400	37.131	0.246	4182	1.392	1.445	0.047	92.80	1.93	24.4
500	43.919	0.314	4182	1.648	2.193	0.040	95.27	0.86	24.7
600	49.397	0.381	4181	1.841	2.980	0.049	96.04	0.62	24.9
700	53.771	0.448	4181	2.012	3.835	0.044	97.30	0.25	25.1
800	57.201	0.514	4181	2.140	4.681	0.050	97.62	0.25	25.3
900	59.725	0.58	4182	2.240	5.522	0.048	98.03	0.08	25.4
1000	61.677	0.648	4181	2.325	6.347	0.052	98.26	0.06	25.5
1100	63.061	0.715	4181	2.378	7.153	0.037	97.85	0.33	25.6
1200	63.871	0.782	4181	2.406	7.910	0.056	98.13	0.26	25.7
1300	64.587	0.848	4181	2.430	8.665	0.056	98.10	0.26	25.8
1400	64.945	0.915	4181	2.443	9.400	0.055	98.10	0.35	25.8
1500	65.173	0.982	4182	2.450	10.112	0.061	98.16	0.32	25.9
1600	65.324	1.048	4181	2.453	10.818	0.053	98.00	0.45	26.0
1700	65.417	1.115	4181	2.455	11.508	0.059	97.96	0.45	26.0
1800	65.564	1.181	4181	2.456	12.194	0.064	97.93	0.42	26.1
1900	65.600	1.247	4181	2.458	12.879	0.074	97.78	0.48	26.2
2000	65.688	1.311	4181	2.464	13.577	0.076	97.72	0.53	26.3

*Performance exceeded with 95% confidence level

95% Confidence Level* Performance of Rotaheater Pico, Magnetic Configuration P3

Shaft Rotation Speed (RPM)	Drive Torque (Nm)	Mass Flow (Kgs^{-1})	Specific Heat Capacity ($NmKg^{-1}K^{-1}$)	Delta T (K)	Power Output (kW)	95% Confidence Interval (+/- kW)	Power Conversion Efficiency (%)	95% Confidence Interval (+/- %)	Flow Temp (ºC)
100	15.989	0.053	4185	0.457	0.101	0.026	59.10	14.66	20.9
200	30.760	0.115	4184	1.155	0.552	0.044	85.50	4.95	21.7
300	44.108	0.181	4183	1.688	1.262	0.078	90.99	3.63	22.3
400	55.904	0.248	4183	2.142	2.211	0.094	94.36	2.10	22.8
500	65.826	0.316	4183	2.510	3.309	0.116	95.89	1.62	23.2
600	74.095	0.383	4184	2.809	4.505	0.136	96.73	1.35	23.5
700	80.364	0.451	4183	3.046	5.746	0.153	97.51	1.04	23.8
800	85.323	0.518	4183	3.235	6.992	0.172	97.78	1.04	24.0
900	89.215	0.584	4183	3.372	8.216	0.188	97.72	1.34	24.2
1000	91.729	0.651	4183	3.470	9.417	0.189	98.04	0.99	24.4
1100	93.479	0.717	4183	3.537	10.580	0.193	98.11	1.03	24.5
1200	94.519	0.784	4183	3.572	11.675	0.201	98.15	0.97	24.6
1300	95.148	0.851	4183	3.594	12.746	0.199	98.24	0.97	24.7
1400	95.401	0.918	4183	3.600	13.768	0.200	98.24	1.01	24.8
1500	95.308	0.985	4183	3.598	14.753	0.204	98.25	1.13	24.9
1600	95.144	1.051	4183	3.590	15.709	0.191	98.30	0.97	25.0
1700	94.776	1.116	4183	3.583	16.625	0.192	98.27	0.98	25.1
1800	94.322	1.182	4183	3.567	17.527	0.196	98.27	1.04	25.2
1900	93.851	1.248	4183	3.547	18.426	0.189	98.33	0.93	25.3
2000	93.446	1.31	4183	3.528	19.271	0.207	98.20	0.94	25.4

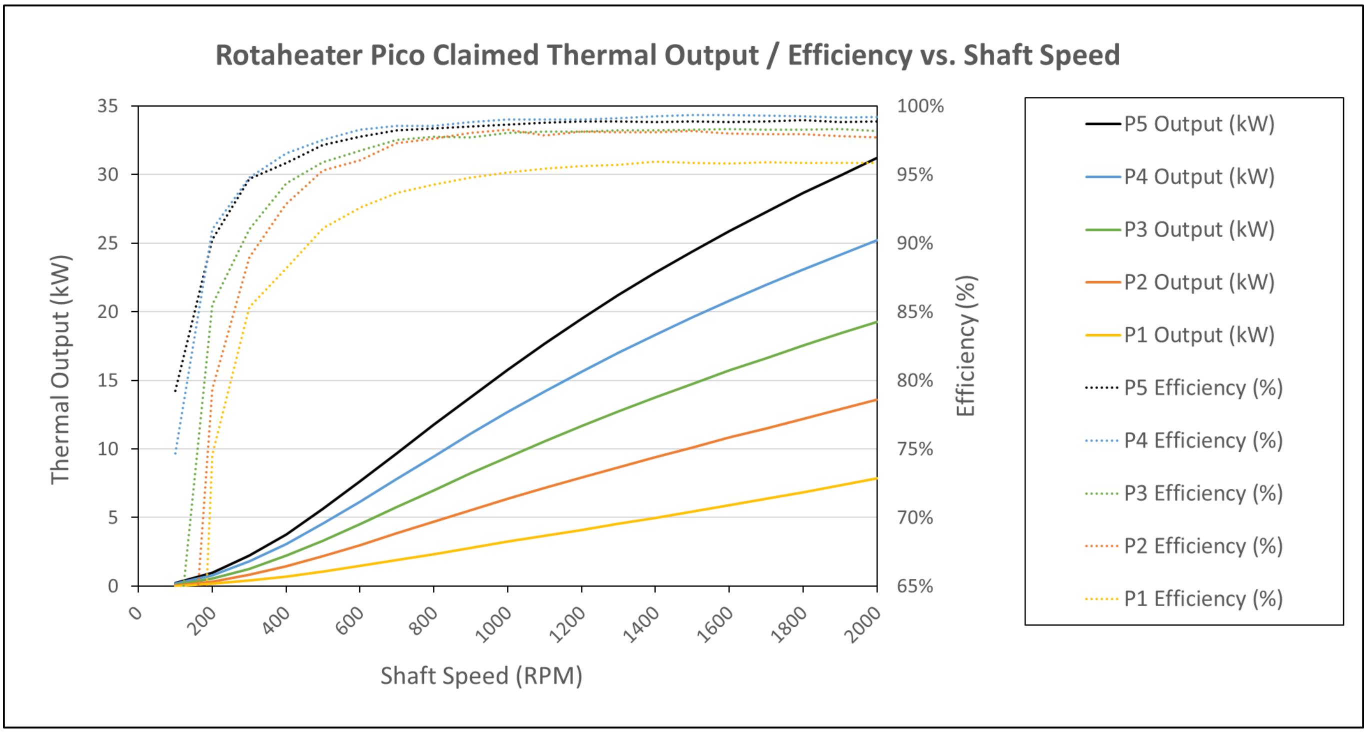
*Performance exceeded with 95% confidence level

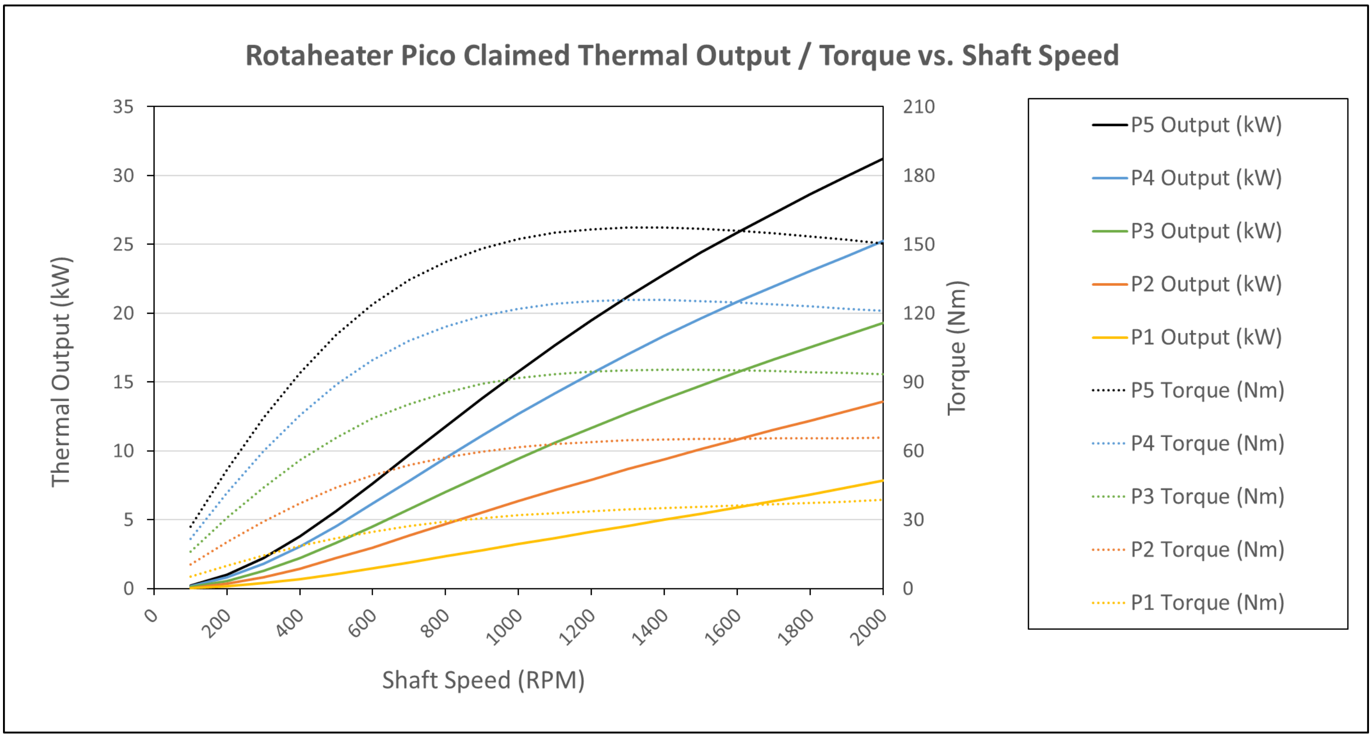
95% Confidence Level* Performance of Rotaheater Pico, Magnetic Configuration P4									
Shaft Rotation Speed (RPM)	**Drive Torque (Nm)**	**Mass Flow (Kgs^{-1})**	**Specific Heat Capacity ($NmKg^{-1}K^{-1}$)**	**Delta T (K)**	**Power Output (kW)**	**95% Confidence Interval (+/- kW)**	**Power Conversion Efficiency (%)**	**95% Confidence Interval (+/- %)**	**Flow Temp (ºC)**
100	21.723	0.052	4185	0.751	0.172	0.020	74.70	8.92	21.3
200	41.773	0.11	4183	1.518	0.802	0.025	91.02	2.94	22.2
300	59.808	0.175	4182	2.221	1.795	0.028	94.79	1.44	22.9
400	75.628	0.242	4182	2.855	3.074	0.039	96.56	1.12	23.5
500	88.815	0.312	4182	3.401	4.549	0.054	97.54	0.84	24.0
600	99.441	0.38	4182	3.831	6.157	0.053	98.28	0.43	24.4
700	107.848	0.447	4183	4.146	7.819	0.061	98.55	0.50	24.8
800	114.205	0.515	4182	4.381	9.459	0.095	98.57	0.65	25.1
900	118.869	0.583	4182	4.560	11.110	0.093	98.82	0.57	25.4
1000	121.969	0.649	4182	4.678	12.689	0.094	99.01	0.40	25.6
1100	124.052	0.716	4182	4.748	14.190	0.119	99.01	0.46	25.7
1200	125.226	0.782	4183	4.784	15.626	0.132	99.00	0.45	25.8
1300	125.768	0.849	4182	4.801	17.017	0.132	99.09	0.40	26.0
1400	125.679	0.916	4182	4.796	18.348	0.130	99.27	0.30	26.1
1500	125.274	0.983	4182	4.777	19.604	0.145	99.34	0.27	26.2
1600	124.668	1.05	4182	4.750	20.805	0.148	99.32	0.27	26.2
1700	123.862	1.116	4182	4.717	21.951	0.159	99.28	0.31	26.3
1800	122.977	1.183	4182	4.679	23.076	0.157	99.24	0.33	26.5
1900	121.988	1.248	4182	4.641	24.152	0.163	99.16	0.35	26.6
2000	121.010	1.314	4182	4.604	25.227	0.157	99.20	0.29	26.7

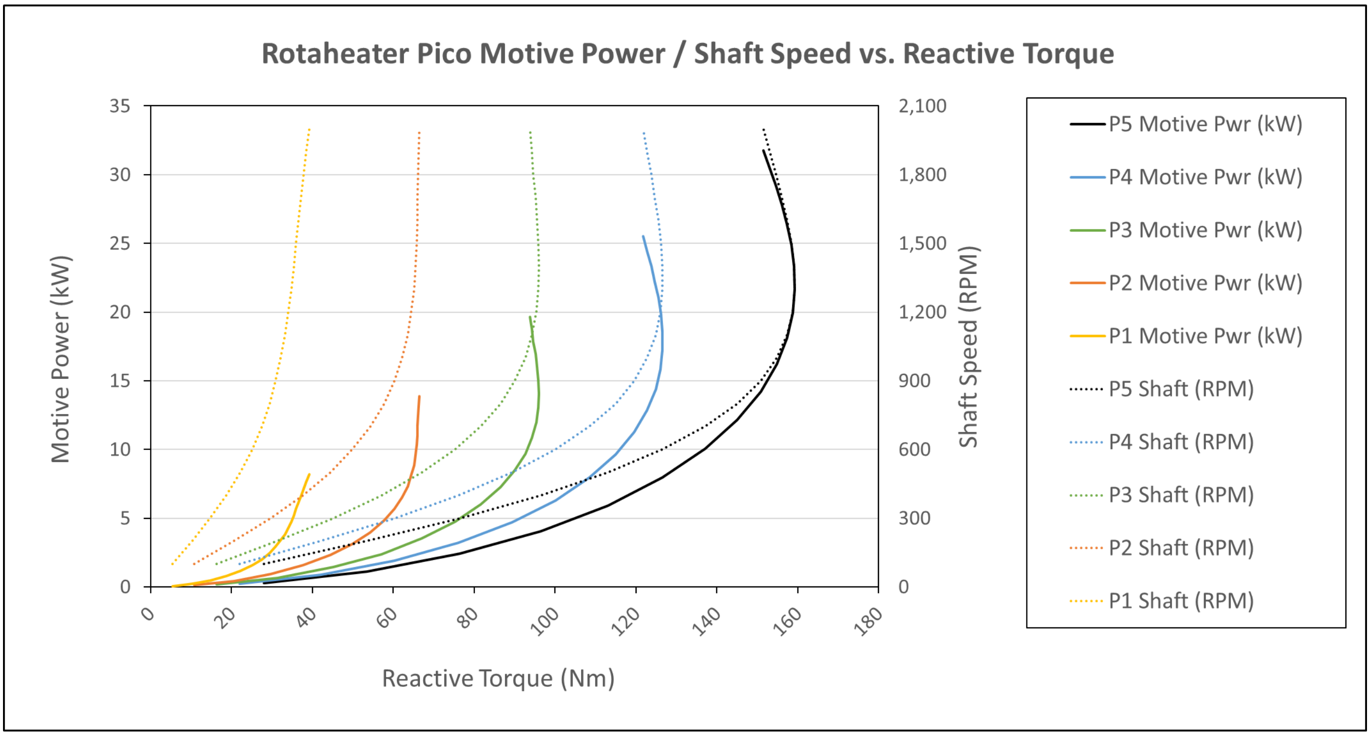
*Performance exceeded with 95% confidence level

95% Confidence Level* Performance of Rotaheater Pico, Magnetic Configuration P5									
Shaft Rotation Speed (RPM)	**Drive Torque (Nm)**	**Mass Flow (Kgs^{-1})**	**Specific Heat Capacity ($NmKg^{-1}K^{-1}$)**	**Delta T (K)**	**Power Output (kW)**	**95% Confidence Interval (+/- kW)**	**Power Conversion Efficiency (%)**	**95% Confidence Interval (+/- %)**	**Flow Temp (ºC)**
100	27.075	0.052	4185	1.045	0.227	0.018	79.21	4.45	21.2
200	51.927	0.115	4183	2.058	0.983	0.062	90.25	3.12	22.4
300	74.327	0.18	4183	2.934	2.211	0.103	94.66	1.64	23.3
400	93.989	0.247	4182	3.690	3.777	0.156	95.84	1.52	24.1
500	110.461	0.315	4183	4.309	5.626	0.189	97.13	1.07	24.8
600	123.748	0.382	4182	4.802	7.624	0.214	97.77	0.79	25.4
700	134.369	0.45	4182	5.163	9.689	0.257	98.23	0.73	25.9
800	142.366	0.517	4182	5.440	11.760	0.285	98.37	0.77	26.3
900	148.249	0.583	4182	5.652	13.787	0.321	98.52	0.73	26.6
1000	152.421	0.65	4182	5.805	15.761	0.347	98.62	0.73	26.8
1100	155.095	0.717	4182	5.899	17.675	0.357	98.77	0.72	27.1
1200	156.639	0.783	4182	5.951	19.483	0.369	98.87	0.66	27.3
1300	157.343	0.85	4182	5.971	21.209	0.378	98.88	0.70	27.4
1400	157.305	0.917	4182	5.966	22.824	0.395	98.84	0.72	27.5
1500	156.764	0.984	4181	5.943	24.395	0.386	98.89	0.71	27.7
1600	155.866	1.05	4182	5.910	25.866	0.396	98.85	0.75	27.8
1700	154.723	1.117	4182	5.863	27.272	0.398	98.88	0.70	28.0
1800	153.365	1.182	4181	5.828	28.652	0.372	98.97	0.61	28.1
1900	151.945	1.247	4181	5.790	29.932	0.388	98.83	0.69	28.3
2000	150.482	1.311	4181	5.751	31.223	0.366	98.87	0.66	28.5

*Performance exceeded with 95% confidence level


Rotaheater Pico Claimed Thermal Output / Efficiency vs. Shaft Speed
Thermal Output (kW)
Efficiency (%)
Shaft Speed (RPM)
35
30
25
20
15
10
5
0
100%
95%
90%
85%
80%
75%
70%
65%
0
200
400
600
800
1000
1200
1400
1600
1800
2000
P5 Output (kW)
P4 Output (kW)
P3 Output (kW)
P2 Output (kW)
P1 Output (kW)
P5 Efficiency (%)
P4 Efficiency (%)
P3 Efficiency (%)
P2 Efficiency (%)
P1 Efficiency (%)


Rotaheater Pico Claimed Thermal Output / Torque vs. Shaft Speed
Thermal Output (kW)
Torque (Nm)
Shaft Speed (RPM)
35
30
25
20
15
10
5
0
210
180
150
120
90
60
30
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
P5 Output (kW)
P4 Output (kW)
P3 Output (kW)
P2 Output (kW)
P1 Output (kW)
P5 Torque (Nm)
P4 Torque (Nm)
P3 Torque (Nm)
P2 Torque (Nm)
P1 Torque (Nm)



Since a degree of interpretation is required to extract data from graphs such as those presented above it is recommended that for the performance claim such graphical data be presented in addition to, rather than instead of, tabulated data.

5. Quality assurance

This verification was conducted according to the documented procedures of BRE Global. These procedures fall within the scope of BRE Global's Schedule of Accreditation to ISO/IEC 17020:2012 issued by the United Kingdom Accreditation Service (UKAS) and which includes internal and external review.

6. References

[1] Rotaheater Pico and Micro Performance Verification Test Plan 'Rotaheater Test Plan_10Sep20_ Final.pdf'
[2] Rotaheater Micro factsheet and Rotaheater Pico factsheet available from https://rotaheat.co.uk/product-range/
[3] ISBN 978 0 580 91337 2, BSI Standards Limited, London, 2018
[4] EU ETV General Verification Protocol 1.3 'eu-etv-gvp-1-3-web-version.pdf'
[5] Guide to Magnet Configurations - Rotaheater Micro_ 07Jan22.pdf
[6] Guide to Magnet Configurations - Rotaheater Pico_ 23Mar21.pdf

Appendix 1 Calibration of Sensors

Calibration Certificates

Return temperature sensor – Pico and Micro testing	8-153748-A-001 8Mar21.pdf
Flow temperature sensor – Pico and Micro testing	9-153748-A-002 8Mar21.pdf
Flow Meter – Pico and Micro testing	10-SM8120 4Mar21.pdf
Torque transducer (250Nm) Pico platform	11-SO159 SN135955 M425 S2 0-250Nm C
Torque transducer (500Nm) Micro platform	11-Certificate_of_Calibration_SN102398_
Torque transducer (2000Nm) Micro platform	12a-Certificate_of_Calibration_SN15111 12b-Certificate_of_Calibration_SN1511

Interpretation of Calibration Certificates

Confidence in the performance analysis and associated error margins is linked to the confidence in accuracy of calibrated sensors.

Generally, sensors were calibrated by third parties accredited by the United Kingdom Accreditation Service (UKAS). One sensor, the torque transducer, was calibrated by the manufacturer with BRE Global reviewing the calibration method and witnessing the calibration. The table below lists the calibrated sensors, and all relevent data related their calibration (i.e. schedule, certificate no., etc):

Sensor	Variable	Serial #	Calibration Body	Calibration Date	Expiry Date	Calibration Certificate No
Pt100	T_{RET}	158748-A-001	Young Calibration	08/03/2021	n/a	C133329
	T_{FLOW}	158748-A-002		08/03/2021	n/a	C133330
IFM SM8120	Flow Rate	R0132161219		04/03/2021	04/03/2022	C133135
Datum M425 2A	Torque	135955	Datum Electronics Ltd	22/09/2020	22/09/2021	135955
Datum M425 2B		102398	Datum Electronics Ltd	16/09/2021	16/09/2022	102398
Datum M425 3B		151112		24/11/2021	24/11/2022	151112

Traceable calibration data for calibrated sensors.

Prior to testing, a check was completed to ensure that the sensors being used were listed in the above table. This check also ensured that calibrated sensors had a valid calibration within date and was documented appropriately with a matching calibration certificate.

Calibration Relationships

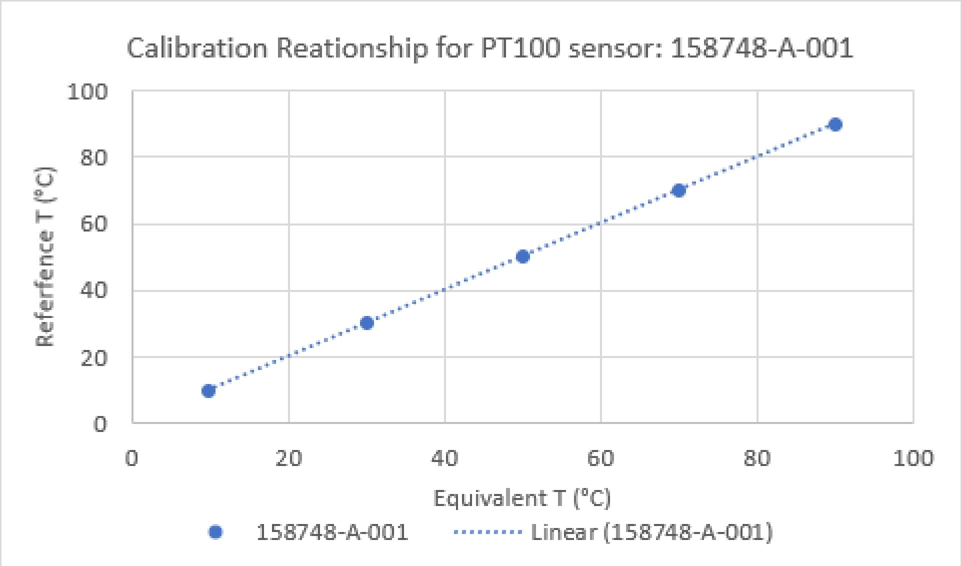
From the calibrated data sourced from the calibrations referenced in the above table the following relationships were established to adjust the measured values in line with the calibration data.

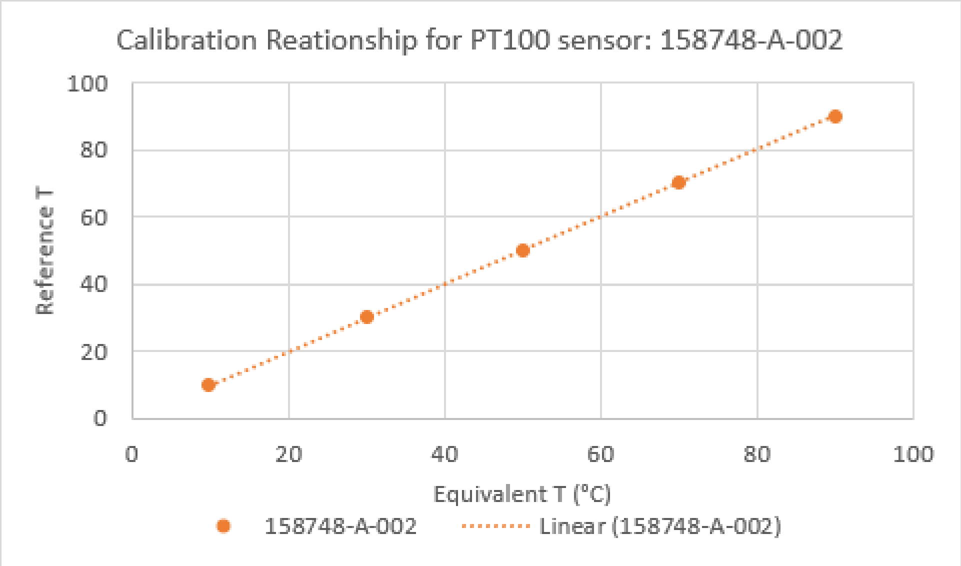
PT100 Sensors

The PT100 sensors are precision 4-wire RTD sensors

- consisting of a Pt100 element that meets IEC 60751 Class 1/10 : 2008, and
- an accuracy of element: ±0.03°C equating to a typical sensor accuracy of better than ±0.06°C at 0°C.

The PT100 sensors were each UKAS calibrated at 5 points, nominally 10°C, 30°C, 50°C, 70°C and 90°C – see below:

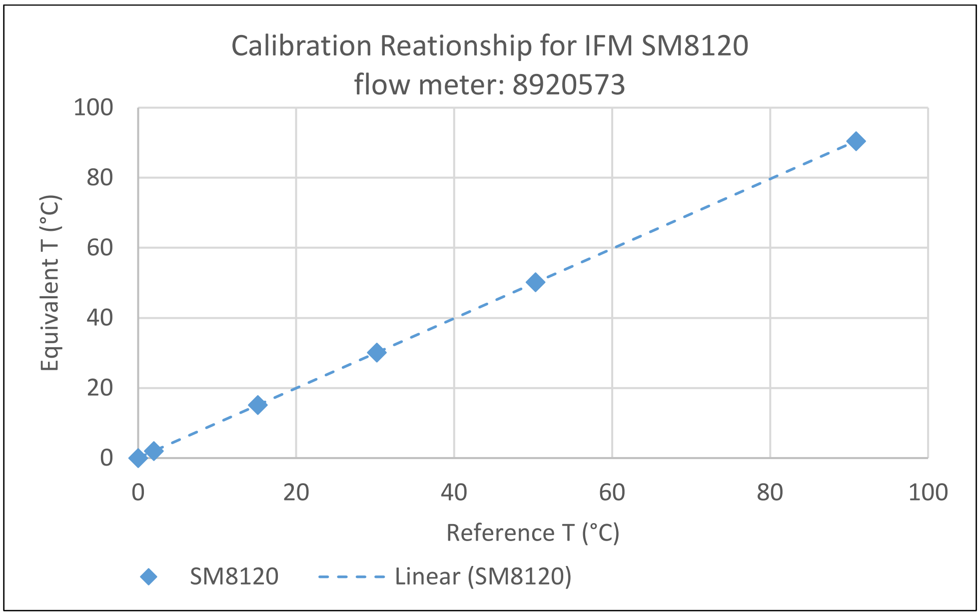




The calibration relationships for the PT100 sensors are linear, with a cooefficient of determination (R^2) very close to 1 (higher than 0.9999998).

IFM SM8120 (Flow Meter)

The SM8120 sensor was UKAS calibrated at 6 points, nominally 0L/min, 2 L/min, 15L/min, 30L/min, 50 L/min and 90L/min. To establish a relationship between the measured values and normalised values used during the analysis, all the calibration results were used as the measured flow rates recorded covered a large range encompassed by the calibration results.



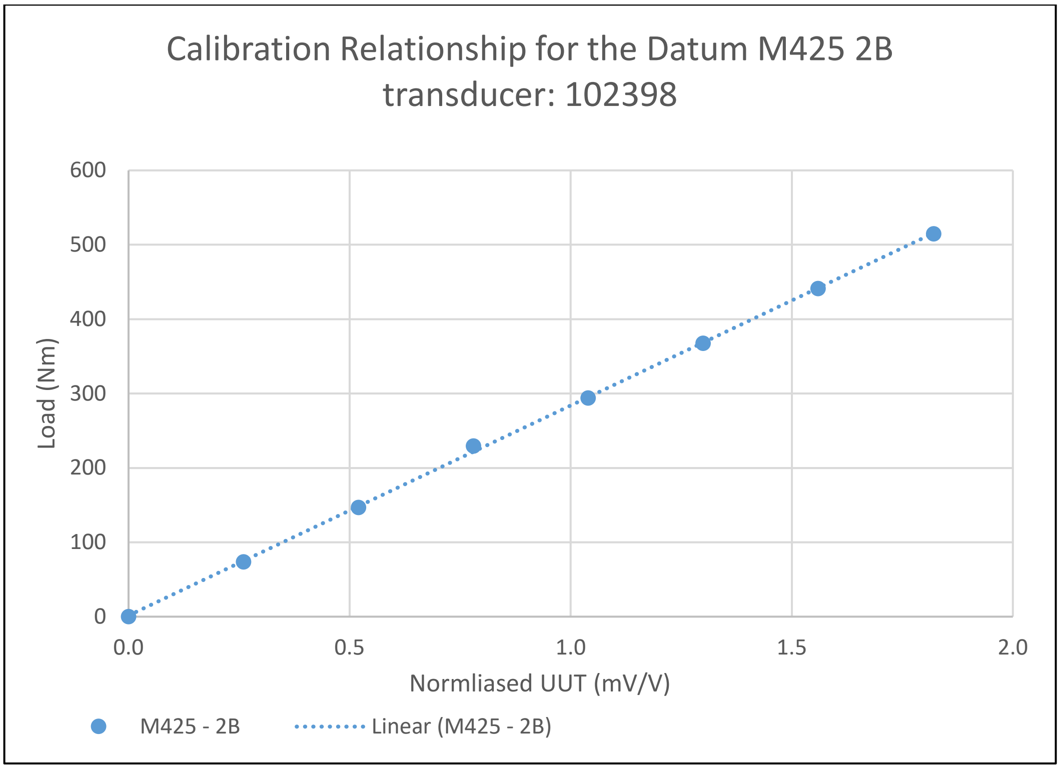
The calibration relationship for the SM8120 flow meter is linear with a least square value very close to 1.

Datum M425 2B and M425 3B

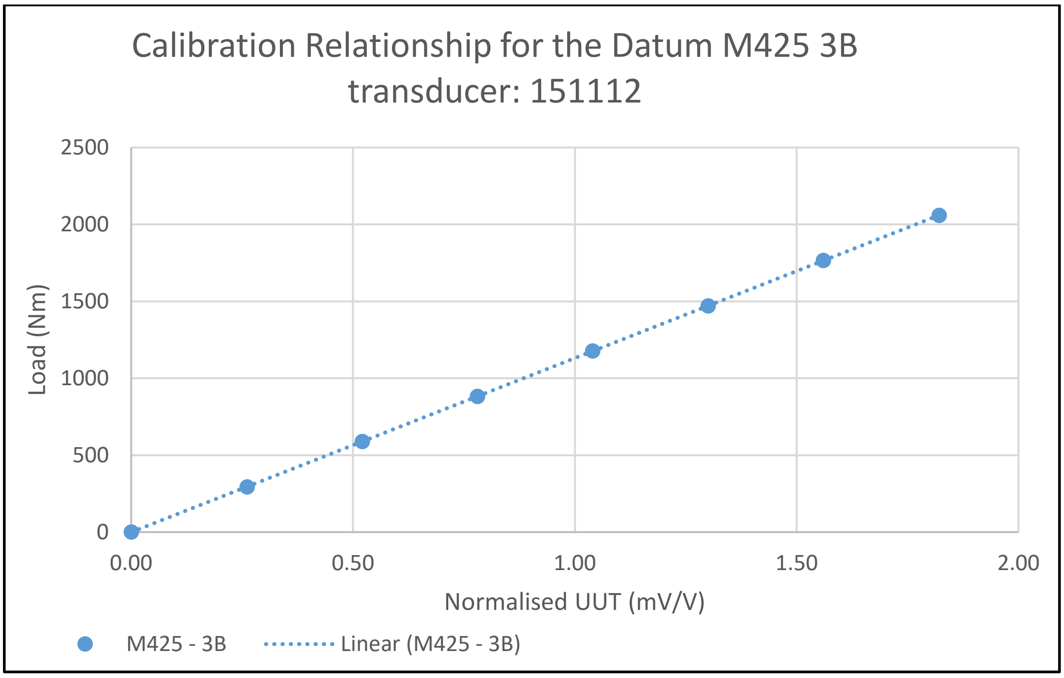
Device	Range
M425 – 2B	0 – 500 Nm
M425 – 3B	0 – 2000 Nm

Measurement ranges of the torque transducers implemented for the test program.

Both torque transducers were calibrated at 8 points, with loads applied from 0Nm through to their maximum range, as outlined in the above table. To establish a relationship between the measured values and normalised values used during the analysis, all the calibration results were used as the measured torque values recorded covered a large range encompassed by the calibration results.



Calibrated Data for the Datum M425 2B Torque transducer: 102398



Calibrated Data for the Datum M425 3B Torque transducer: 151112.

The calibration relationship for the Datum M425 2B and 3B Torque transducers are linear with a least square value close to 1.

Sensor measured vs. normalised adjustments

From the linear relationships presented in the above figures, the relationships presented in the table below can be established to adjust the measured values to the normalised readings.

Device	Serial	Data	Interpolation approach	Adjustment (y normalised, x measured)
PT100 Probe (T_{Flow})	158748-A-002	Analogue	Linear	$y = 0.999826x + 0.013900$
PT100 Probe (T_{ret})	158748-A-001	Analogue	Linear	$y = 0.998932x + 0.083007$
IFM SM8120 Flow Meter	8920573	Digital	Linear	$y = 1.004958x - 0.046855$
Datum M425 2B	102398	Digital	Linear	$y = 276.589684x + 0.161644$
Datum M435 3B	151112	Digital	Linear	$y = 1131.173842x + 0.188907$

Linear relationships between measured and normalised data for calibrated sensors.

RTD-PLC

The PT100 RTD sensors are coupled via 4-wire (2-pair) RTD cabling and connectors to the PLC. The PLC measures resistance of the UKAS calibrated RTDs and cabling to establish a temperature reading which can then be adjusted based on the above calibration data.

The post-processing analysis and calculation of the thermal output is dependent on reliably establishing the delta temperature, i.e.

$$\Delta T = T_{out} - T_{in} = T_F - T_R.$$

The cabling, connectors and PLC itself add some nominal resistance which will impact the measured and normalised values. To account for the additional resistance introduced by the cabling and PLC, additional calibrations were conducted to identify any additional offset that would be required to account for the cabling and PLC. Given the range of absolute temperatures which the testing is conducted over (centred around 20C), it was assumed that:

a) any adjustment could also be represented by a strong linear correlation, and

b) the range of temperatures covered being relatively small, then the adjustment could be considered a constant (K).

This additional resistance is unlikely to materially change during a test as the ambient conditions remain broadly constant. To account for the additional nominal resistance, the above equation can be rewritten as:

$$\Delta T = T_{out} - T_{in} = T_F - T_R = (C_{F1}T_{F1} + C_{F0} + K_F) - (C_{R1}T_{R1} + C_{R0} + K_R) \qquad (14)$$

Where:

T_{x1} is the measured value of the sensor x,

C_{xy} are the linear coefficients for converting sensor x's measured value to the normalised value, and

K_x is a constant reflecting the additional resistance of connectors, cabling and PLC for sensor x.

This equation can be rewritten to reflect a single constant representing the cabling, connectors and PLC for both the flow and return sensors:

$$\Delta T = T_F - T_R = (C_{F1}T_{F1} + C_{F0}) - (C_{R1}T_{R1} + C_{R0}) + K$$

Where:

$$K = K_F - K_R$$

As both C_{R1} and C_{F1} are close to 1 (see table of linear relationships above), we assume the measurement of each RTD as recorded by the PLC are good proxies for T_{x1}.

K can be established by simultaneously measuring both RTDs in the same environment, where ΔT can be expected to be zero and therefore:

$$K = (C_{R1}T_{R1} + C_{R0}) - (C_{F1}T_{F1} + C_{F0})$$

To establish K, the following procedure was followed:

1. Both the flow and return RTD were placed in a water bath and left to stabilise for 5 minutes
2. The PLC recorded simultaneous readings for both sensors across a 2-minute period with a frequency of 1Hz.
3. The cable connections adjacent to the RTDs were swapped, and the relevant equation becomes:

$$\Delta T = 0 = (C_{F1}T_{F1} + C_{F0}) - (C_{R1}T_{R1} + C_{R0}) - K$$

4. The PLC recorded simultaneous readings for both sensors across a 2-minute period with a frequency of 1Hz
5. Steps 1-3 were repeated
6. The value K was established for each test and averaged. The average of the tests was incorporated within the post processing analysis.

Using the above procedure, it was established that:

$$K = -0.01667°C$$

Errors

The systematic errors calculated are a function of the accuracy of the instrumentation used. This accuracy can be determined from one of two ways, from the manufacturer of the sensor, or from its calibration. The manufacturers accuracy is a function of the materials and components used in the production of the sensor, whereas accuracy from the calibration is more directly linked to the measurement capabilities of the sensor (relative to the references used by the calibration body). For the purpose of this testing program, the accuracies relating to the calibration of the sensors are used as the uncertainties for determining the systematic errors.

The table below references the uncertainties determined from the calibration certificates, which in most cases is the average of the uncertainties across each calibration reference point.

Variable	Device	Accuracy (±)
Temperature (dT)	PT100 Probes	0.343333 °C
Flow rate ($d\dot{m}$)	SM8120 flow meter	0.363333 lpm
Torque (dτ)	M425 – 2B transducer	3.529985 Nm
	M425 – 3B transducer	20.625338 Nm

Instrument uncertainty ascertained from calibration certificates.