Accurate Calorimetric Measurement of Efficiency of a Frequency Converter

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Abstract

Quantitative knowledge of electrical device's power loss aids in understanding the device's operation, and in identifying the major causes of losses. They also serve as relevant markers for future design processes for device optimization. Calorimetry is gaining ground as a viable means for power-loss measurement of electrical machinery and other electrical devices. In this paper, we present a closed-cycle, water-cooled calorimeter to measure losses of highly efficient power converters (power class <1 kW). A 0.75 kW frequency converter was tested calorimetrically and its efficiency was confirmed to total to 97 %, with measurement accuracy of 1.1 %.

Introduction

As devices of higher power density and accuracy are desired by the industry, the need to accurately measure these parameters becomes increasingly important. In electric machinery, the dominant methods of loss analysis and quantification are: Input-Output Method, Segregated Loss Method, and Calorimetric Method. While the first relies heavily on the measurement system accuracy, the segregated losses procedure involves measuring loss components separately. However, calorimeters enable precise measurement of the Device Under Test's (DUT) net heat-dissipation and thus allow accurate determination of the total power loss, as illustrated by existing systems in [1]-[3]. It has also been adapted for segregated loss measurement of machine stator losses and stray losses as reported in [4] and [5] respectively.

Overview

Calorimeters employed in electrical engineering can be classified broadly into two, firstly based on their heat-exchange mechanism and secondly on their design. The mechanism of heat-exchange from the DUT to coolant can be direct or indirect. In an ideal calorimeter, the heat absorbed by the coolant will equal the power lost by the machine. An air-cooled calorimeter is a directly cooled, open system, which is simple enough but inaccurate due to the tendency of air's thermal properties to fluctuate over a period of time. Alternatively, an indirectly-cooled, water-cooled calorimeter is considered more reliable, owing to the predictable and controllable nature of the thermal and physical properties of water. Water circulates through a radiator to absorb heat from air, which is heated directly due to the operation of the DUT.

On the basis of design, calorimeter's architecture maybe described as one of the following four kinds: balanced, series, parallel and double-jacketed. The balanced air-cooled calorimeter in [6] was first tested with a known power source, thus calibrating the calorimeter and solving the open-type calorimeter's biggest drawback. Nevertheless, the issue remained that the conditions during the calibration test and actual test of the machine differ. The series or double-chamber calorimeter (DCC) [7] addressed this effectively, but was riddled with higher heat leakages in the second chamber with the DUT, and was expensive to build too, due to the larger volume. A new concept of parallel calorimeter was introduced in [8]. It performs the actual calorimetric test with DUT and balance test with reference heater parallelly in separate chambers, while maintaining a constant coolant temperature gradient and duplicating the coolant flow conditions in the balance chamber.

The Double Jacketed Calorimeter (DJC) [2], [3] is a water-cooled, closed calorimeter which employs a novel concentric, double chambered construction and intervening air-gap's temperature control to prevent heat leakage through the calorimeter walls. The recorded measurement times for the DJC are lesser than DCC's, but may require more elaborate systems of control, depending on the level of automation. Electronic ballasts of compact fluorescent lamps and phone chargers were also tested for their efficiency with the DJC in [9] to successfully do so with an accuracy of ± 0.1 W for 25 W of power loss.

The best accuracy of closed calorimetric systems was 0.2% for 50 W measured, as reported in [3]. Accuracy of 1% was achieved in measuring losses of 10-100 W for power electronic systems with full range power between 1-10 kW, also with a Closed DJC in [1]. In most such systems, the coolant flow rate has been controlled with a flow sensor and a pump. A commonly observed disadvantage of this is the inlet water temperature fluctuations, resulting in reduced measurement accuracy at lower power levels. Additionally, the specialized calorimeters such as in [9] are highly individualistic with a narrow measurement range where they are able to perform with respectable accuracy. A wide-range calorimeter which can measure power losses ranging from tens to few hundreds of watts with an accuracy of at least 1% has not been fully realized yet.

Objectives

The aim of this work is to address these lacunae by constructing a highly efficient calorimeter to test high-efficiency power converter devices of up to 1 kW rated power, with measurement accuracy of 0.5 %. The wider measurement range and simpler construction is meant to make it an acceptable alternative to the automated Double Jacketed Calorimeter (DJC) [2] with wall temperature-control. The design objective is simplicity and versatility. To fulfill these requirements, a water-cooled, single-chambered, single-jacketed calorimeter, dimensioned suitably to make measurements of different small-sized power converters and other electrical devices of rated power of 0.5-1 kW was built. The following sections describe the calorimeter's design procedure and the measurement results. A key feature of this calorimeter is input water temperature control.

Methodology

Operating Principle

In an ideal system, the power lost by the device P_{loss}, is absorbed completely by the water coolant P_{water}. Thus,

$$P_{\text{loss}} = P_{\text{water}} = \dot{V}\rho c_p \Delta T. \quad (1)$$

Here $\dot{V}$, ρ, c_p are the volume flow-rate, density and specific heat capacity of water. A 0.75 kW frequency converter is chosen to serve as a median for the calorimeter's measurement range, with reported efficiency of 95-98 % at nominal power. If its power loss is around 75 W it will result in water temperature rise of about 5 ℃, assuming inlet water temperature is 15 ℃. The water flow rate would be around 220 ml/min.

Design Considerations

A calorimeter should be built to the specifications of the device(s) that is to be tested. Therefore, the target test devices and their dimensions, efficiency, cooling requirements etc. have to be known before a suitable calorimeter design can be decided upon. Certain factors of importance in the calorimeter design are:

- Calorimeter's inner heat transfer volume.
- Insulation thickness.
- Coolant temperature limits.
- Heat-exchanger capacity.
- Choice of instruments which sense, control and record the process parameters.

The inner calorimetric chamber should be spacious enough to accommodate DUT's of varying sizes and also to allow proper mixing of air. Nevertheless, being too expansive can increase the system's response time. Hence, an optimum dimensioning suitable to the experimental study should be decided. This can be accomplished through a thorough analysis of the previous works and a process of trial and error. Also metal parts inside the test chamber should be avoided to prevent additional eddy-current losses.

Physical Design

A single chambered, water-cooled design for the calorimeter was chosen. An optimal wall-thickness provides sufficient insulation, while at the same time minimizes the time-constant of the measurement system. The DUT here is a high-efficiency device, and since the overriding objective of this work is to attain the maximum possible calorimetric accuracy, the insulation along the four walls was doubled to prevent heat leakages, at the risk of higher settling times. The calorimeter design which resulted opened like a box from the top. This is an additional means to trap the heat which might otherwise escape through the wall joints.

This calorimeter has two shells:

1. The inner calorimetric shell (100 cm x 80 cm x 60 cm) with top open.

2. The outer calorimetric shell (120 cm x 100 cm x 60 cm) acting as the lid.

Both shells are made of extrusion-compressed polystyrene sheets of 10 cm thickness each. The outer box is constructed to just fit over the inner shell, leaving the least gap between the walls. This structure offers better accessibility to the calorimeter's interior, thus allowing easy alterations and maintenance. All electrical, coolant and sensor circuitry are channeled to the outside through two insulated tunnels on lower bottom of calorimeter walls. Figure 1 shows the inside layout of the calorimeter.

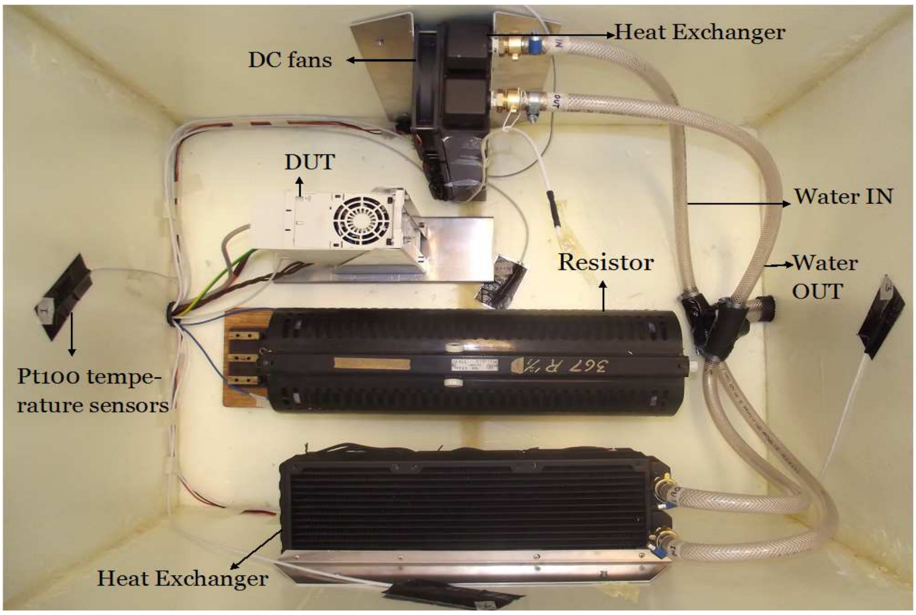

Figure 1: The calorimeter interior, top-view.

Thermal Resistance and Time Constant

Even though the material properties of an insulation sheet may be uniform throughout, the effective thermal resistance offered by the calorimeter is anisotropic due to the varying insulation thickness. It is important to observe how this can affect the heat flow patterns in the calorimeter. Based on the manufacturer's data on the insulation's thermal conductivity, the equivalent thermal resistance of the calorimeter is 1.11 K/W. Thermal resistance of insulation is,

$$R_{\mathrm{th}} = \frac{d_{\mathrm{wall}}}{\lambda A_{\mathrm{wall}}}, \tag{2}$$

where d_{wall} is its thickness, λ is the thermal conductivity and A_{wall} is the insulation slab surface area. The time constant of the calorimeter was determined to be around 3 hours, which indicates the delay at which changes in system parameters are reflected in the system performance. It is given by

$$\tau = \frac{C_{\text{th}}}{R_{\text{th}}} \ . \tag{3}$$

C_{th} is the calorimeter's heat capacity.

Heat-Exchanger and Coolant temperatures

Choosing a radiator is an important design decision, which has to be carefully made after considering factors like the maximum required water and air flow-rates, the maximum possible coolant temperature rise, calorimeter's measurement capacity, and the heat-exchanger's thermal resistance. Such an analysis will ensure good system performance, limit vital parameters and allow them to stabilize.

Fixing the upper-limit of coolant temperature rise based on the flow controller range can be a starting point. If the coolant flow-rate is too low, the heat will not be effectively transferred from the primary coolant (air) to the secondary (water) which can lead to overheating. Moreover, hotter the air within, greater is the incentive for heat to leak to the ambience. The maximum air temperature is limited by the insulation's temperature limit. Additionally, the inlet water has to be cooler than the air to immediately facilitate the heat transfer. The temperatures of the primary coolant is of importance in the heat exchanger performance (or 'effectiveness'), as seen from the expression;

$$E = \frac{P_{\text{actual}}}{P_{\text{max}}} = \frac{P_{\text{air}} \text{ or } P_{\text{water}}}{\min(\dot{C}_{\text{air}}, \dot{C}_{\text{water}}) \cdot (T_{\text{air,hot}} - T_{\text{air,cold}})} \tag{4}$$

Effectiveness E is the ratio of the actual heat transferred P_{actual} and the maximum heat transfer P_{max}. $\dot{C} = \dot{V}\rho c_p$ denotes the heat capacity rate of the respective coolant and $T_{\text{air,hot}}$, $T_{\text{air,cold}}$ represent the temperatures of hot air and cold air entering and leaving the heat exchanger respectively. The radiator should maintain a reasonably good effectiveness for different powers measured. After such an iterative design process, the maximum power measurable by the calorimeter was determined as 520 W, at a maximum water flow rate of 300 ml/min.

Measurement Uncertainty

The meters and sensors chosen for the calorimeter should have the best possible accuracy and repeatability. The final accuracy of the calorimeter is directly dependent on those of the constituent meters and sensors. The choice of instrumentation for a task has to be made after considering the weight or impact of the variable being measured on the final measurand, which in this case is the power-loss of the DUT.

Realistic Perturbation-Based Estimation (RPBE) which operates in the root sum squared sense, is best suited to estimate the uncertainty in measurement compared to the Worst Case Estimation method which overestimates the overall measurement inaccuracy. As per RPBE, the uncertainty in the measurement of the coolant power is expressed as,

$$u(P_{\text{water}}) = P_{\text{water}} \sqrt{\left(\frac{u(\Delta T)}{\Delta T}\right)^2 + \left(\frac{u(\dot{V})}{\dot{V}}\right)^2} \\ \text{where } u(\Delta T) = \sqrt{u(T_{\text{out}})^2 + u(T_{\text{in}})^2} \tag{5}$$

$u(Y)$ refers to the uncertainty in the measurement of Y. The actual measurements are assumed to be distributed uniformly. The best possible sensors and instrumentation was chosen for the experiment, and the absolute combined measurement uncertainty was found to be ±0.8 W (or 1.05 %) when measuring coolant power of 75 W. Expressing this at 95 % confidence level, the '*expanded uncertainty*' is 2.12 % at 75 W.

Measurement System

Since the power losses to be measured are low, instrument inaccuracy can fatally alter the results. The most important measurements in the system are those of water and wall temperatures, and the water volume flow-rate. The sensor data from the various Pt-100 temperature sensors deployed in the calorimeter was acquired with a HP DAQ 349970A Data Acquisition/Switch Unit and read on the PC with the Agilent VEE Pro graphical programming software. The electrical power supplied to the calorimeter was read at the connection terminals by Fluke Norma 4000 and read with the Agilent VEE Pro software as well. The table below lists all the measurement devices used in the calorimetric system.

Table 1: Measurement devices and controllers used.

Parameter	Device Type	Meter/Sensor	Manufacturer	Properties
Water flow-rate	Volume flow-controller	LFC 8718	Bürkert	Accuracy: 0.5% F.S., Repeatability: 0.5% F.S.
Water Temperature	Ceramic wire-wound RTD	Pt-100 1/10 Class B	SKS Group	4 wired. Accuracy: ±0.03 ℃
Air/Wall temperature	Ceramic wire-wound RTD	Pt-100 1/3 Class B	SKS Group	4 wired. Accuracy: ± 0.10 ℃
Air-water heat exchanger	Radiator	Airplex XT 360	Aqua Computer Gmbh	Brass casing, copper lamellae
Air-flow	DC Fans	-	Aqua Computer Gmbh	12 V, 5 fins
Water pressure	Pressure regulator	-	Gerhard Gotze & Co.	Max. inlet pressure 25 bar
Water preheater	Heating cables	Deviflex™	Devi	2 m long, 40 W heating capacity
Temperature control	Temperature controller	Model T16	Redlion	PID control
Power regulation	TRIAC	FC11AL/2	United Automation	Integral 26 A TRIAC

Control Scheme

To avoid measurement discrepancies, the temperature of the inlet water was controlled to remain fixed, at a constant flow-rate. Thus, the water temperature rise recorded will correspond exactly to the heat it absorbs in the calorimeter chamber. Although we can consider the temperature of the water in the calorimeter cooling channels to be more or less uniform, the same cannot be said about the public water supply, whose supply temperature is prone to fluctuations. This can affect the measurement accuracy and stability of the calorimeter and can adversely influence its settling time. Hence the solution would be to heat the water from the supply to a fixed level before supplying it to the measurement system. This control loop consists of a PID controller and TRIAC, along with a water heater and heater cables. This system performs well, but lower flow rates can be challenging.

Alternatively, another control scheme for maintaining a constant water temperature for different power-levels can be implemented. This can be done by varying the water flow-rate according to the water temperature feedback. Both these schemes can be coupled as well.

Water Temperature Measurement

The temperatures of water are measured at its points of entry and exit to the calorimeter. The water flows through small sections of insulated copper piping, whose copper surface temperature is measured by Pt-100 RTD's to yield the water temperature. The measurement data from four different locations on the pipe surface is averaged to obtain the water temperature. The control schematic of the calorimeter is presented in Figure 2.

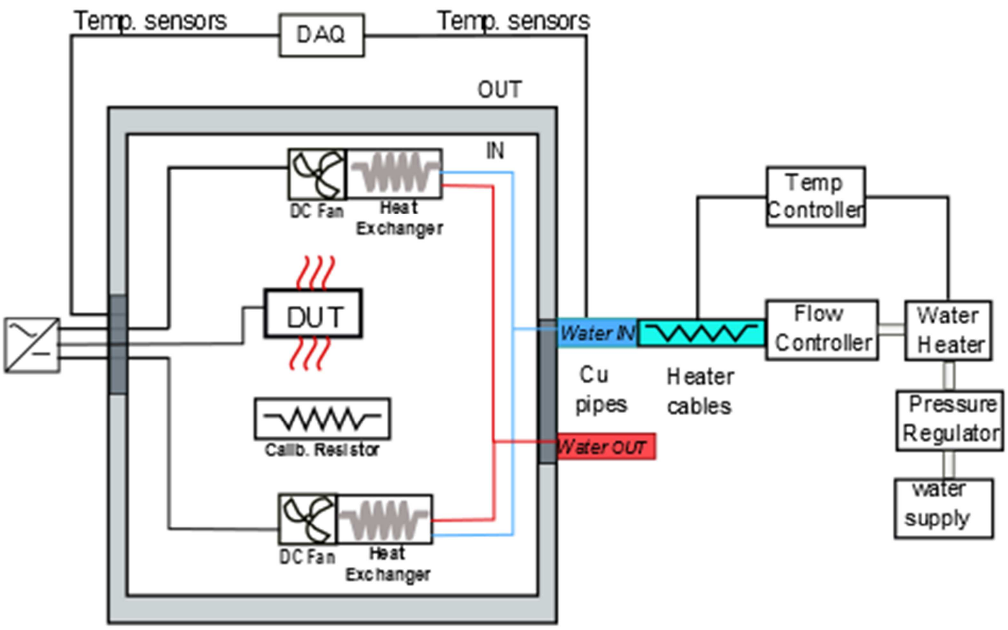

Figure 2: The calorimeter and control schematic.

Experimental Results

Balance Test

The balance test was carried out at a fixed flow-rate of 200 ml/min, with a 15.6 Ω resistor supplied by a regulated DC power supply to dissipate powers from 25-125 W. The steady-state analysis of the measurement system was done in accordance with the standard IEC 34-2A 1972 (the tests presented in this paper were carried out in late 2012 [11], before IEC 60034-2-3 and EN 50598-2 standards were published). It states that stable conditions are achieved when "measurements of rise in temperature and volume flow rate of cooling medium indicate that losses are constant to within ±1 % over a period of two hours or when the temperature rise of the cooling medium does not vary by more than ±1 % in one hour, the volume rate of flow being constant."

Both these steady-state requirements were considered simultaneously to check the stability of the measurements. The setting times varied from 4-12 hours, in inverse proportion to the power measured. Once the steady-state was reached, the thermal power and wall-leakage calculations were carried out from the recorded sensor measurement data.

As per the least-squares method, a curve was fitted to the measurement points to obtain the calibration curve. The wall leakages were calculated and compensated to obtain the calibration curve shown in Figure 3. The linear relationship between electrical and coolant thermal power is,

$$P_{water} = 0.924 P_{loss} + 0.216 \quad \text{W} \tag{6}$$

It represents the relationship between the total electrical power dissipated inside the calorimeter and the coolant thermal power, and will be the reference for actual test with the DUT. The electrical power lost by the DUT (P_{loss}) and the coolant power are related as:

$$P_{loss} = P_{water} + P_{wall} \pm P_{Cu} - P_{fan} + P_{stray}, \tag{7}$$

where P_{wall} is the heat-leakage through insulation, P_{Cu} is the heat leakage through the copper conductors in the electrical connections in the test chamber, P_{fan} is the heat generated by the fans and P_{stray} refers to the other non-quantifiable loss. The electrical power dissipated as heat in the calorimeter is the sum of the DUT losses, copper wiring's possible heat contribution and the fan power.

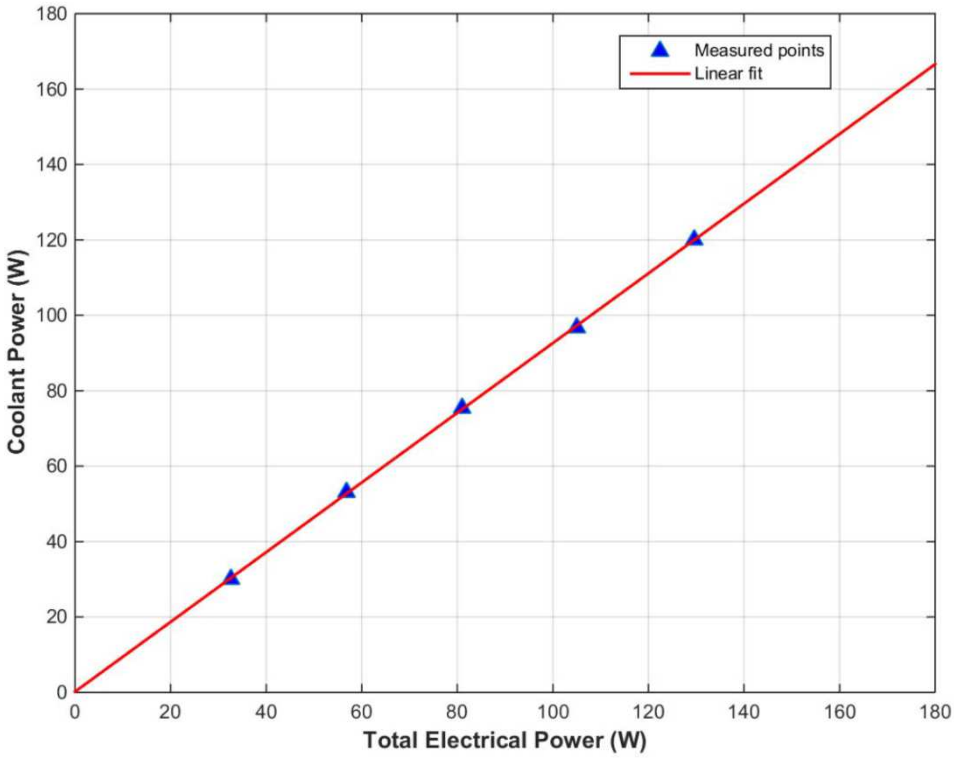

Figure 3: The calibration curve at 200ml/min.

Actual Test

Following the calibration of the calorimeter, an ABB frequency converter ACS 350-01E-04A7-2 was tested in the calorimeter. The converter was supplied 230 V at 50 Hz and loaded with a 3-phase resistor. Only the DUT is enclosed within the calorimeter. The thermal power was calculated as per equation (1). The wall leakages were determined from the inner and outer wall temperature measurements. The measurement results are shown in Figure 4.

With wall-leakages compensation, the average power lost by the frequency converter was around 21.35 W. Separate electrical measurements indicated that the power input to the DUT was 0.75 kW, and the output was 0.727 kW, indicating the power loss to total 23 W. The heat conducted from test chamber to ambient by current carrying copper conductors was measured to be negligible. Thus, the electrically measured power loss fits closely with the coolant power measured by the calorimeter. The calorimetric experiment was thus able to successfully verify that converter's efficiency to be 97 %.

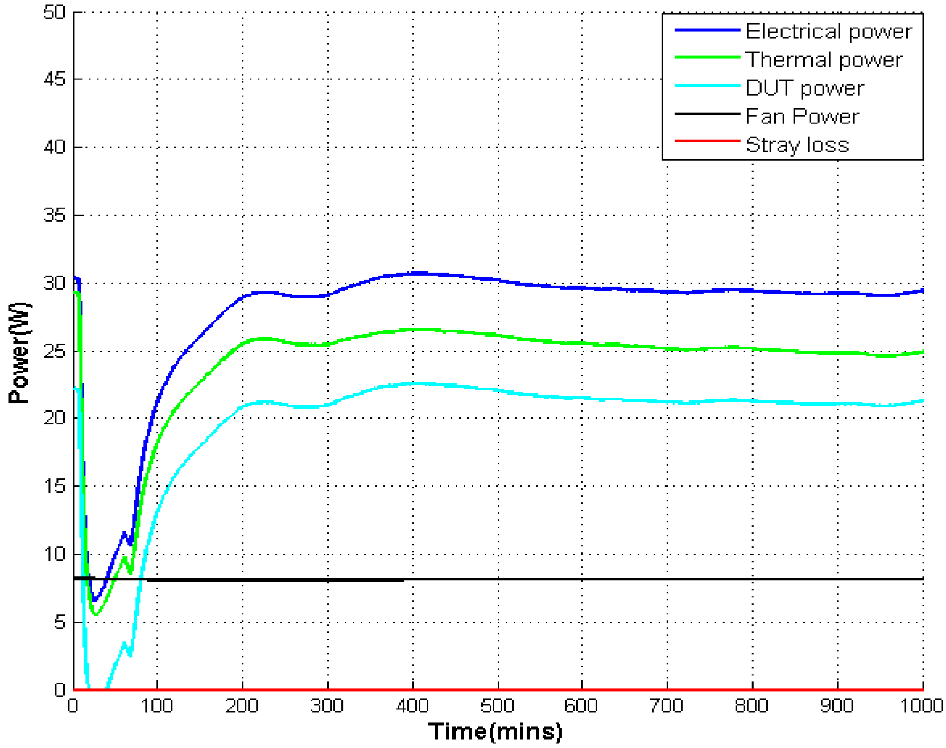

Figure 4: Measured powers from the DUT's calorimetric test at 200 ml/min.

Discussion

The attempt at building a wide range, simple, water cooled calorimeter was fairly successful. While the inlet water temperature control scheme efficiently prevented oscillations in the coolant circuit, wall leakage prevention by double insulation was inefficient. The novel construction may have resulted in the stray losses without which the calorimeter calibration would be much better. These unaccountable losses may be the result of possible leakages through the contact gaps in the inner and outer insulation boxes and also through the wiring channels.

Also, although the thermal resistance offered to various heat paths was high, the overall thermal resistance of the calorimeter remained low. Apparently, the heat conductivity of the insulation slabs was higher than expected. Higher the power measured, higher was the leakage. However, it was possible to determine these leakages quite well through wall temperature measurements. Copper conductors were not found to leak any heat to outside, at least at the power levels measured. At higher powers though, this may be a problem, which can be mitigated by using suitably dimensioned conductors. The higher settling times observed in the experiment may be due to fluctuating ambient temperature, which also influences the wall heat leakages.

Conclusion

As targeted, a water-cooled calorimeter, with larger measurement range and versatility was implemented. The highly accurate temperature sensors and flow controller enable it to measure 25-520 W of power with fairly good accuracy. For 25 W of power measured, the extended uncertainty in measurement is approximately 0.5 % at 200 ml/min flow rate. Above 75 W of losses measured, the extended uncertainty is at least 2 %. The max range of the flow-controller is 300 ml/min.

As far as calorimetric measurement of low (<10 or 20 W) or fractional powers are concerned, the parameter of vital importance is the calorimeter heat exchange volume. If the calorimeter is too large and the coolant temperature rise is low, then the system will take much longer to stabilize. Lowering the flow rate correspondingly is not an option though, as it engenders another issue of uneven fluid mixing. Even the choice of calorimetric method might need to be reassessed, and specialized calorimeters like the one reported in [12] might be required. The considerations of test duration and coolant temperature rise are valid even for higher power measurements (>100 W). But of higher importance here are the heat leakages, which can considerably compromise the calorimetric measurement's efficiency.

Although this double walled calorimeter is less effective than the DJC in countering the wall leakages, an extensive design optimization (with respect to dimensioning, insulation) and professional construction can improve its accuracy. The design process should only proceed once the dimensions of the heat exchanger, balance resistor and DUT are known in advance. Also, the water temperature rise control schema can be implemented and compared with the inlet-water temperature control scheme for its effectiveness. Conducting the test in a closed space can ensure a near-constant ambient temperature, which shall prevent rogue measurement errors. A good addition to the calorimetric system would be a cooling system which recirculates water and thus avoid unnecessary wastage.

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