A REVIEW OF CALORIMETRIC APPLICATION FOR ACCURATE POWER LOSS MEASUREMENT

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ABSTRACT

This paper reviews the technological developments in calorimetry for accurate power loss measurement. The various topologies and features of calorimeters are described with special attention given to their merits and shortcomings. It is hoped to provide a guideline and quick reference for developing a calorimetric system.

INTRODUCTION

Recent years have seen a growing application of calorimetry in determining power losses in electrical machines and power electronic devices. The system efficiency and thermal performance of these devices are of extreme importance to the designers, manufacturers and end users. Only when accurate power loss results are available can device design and manufacturing quality control follow to improve overall performance.

Taking electrical machines for example, the conventional input-output method [1] is widely accepted but is prone to measurement uncertainty with increasing machine efficiency or power rating. The back-to-back method [2] requires that two identical machines are mechanically connected to form a generator-motor set, which is not always readily available.

In contrast, the calorimetric approach directly evaluates the heat loss by a machine under test so that it removes the inherent uncertainty in input-output methods. Therefore, calorimetry can potentially achieve a high level of measurement accuracy despite the power rating and supply distortion of the machine.

ORINGIN OF CALORIMETERS

The embryonic form of calorimeter may be traced back to the eighteenth century. In 1760, the earliest reported calorimeter was developed by Black [3] and was employed to measure the specific heat capacity of a test sample. Calorimetric experiments were performed by putting the tested sample in a hollow ice container and covering it with a slab of ice on the top. Provided that the sample and ice are thermally isolated from the surrounding environment, the heat dissipated in the sample would gradually melt the ice and the water would drain down. When thermal balance is attained, the drained water could be measured to find the specific heat capacity of the sample.

Nearly three decades later in 1789, the "calorimeter" was formally coined by Lavoisier in his book "Elements on chemistry" [4]. A calorimeter was described as a multiple-layer container with ice being the insulator in between layers. Similar to the earlier version, the thermal content of the tested sample was obtained from assessing molten water after thermal balance was reached.

Having been explored extensively for more than 200 years, calorimetry now has become an effective method of evaluating losses in any heat dissipater. Its diverse applications include assessing heat losses in high energy particle collisions [5] and chemical reactions [6], electrostatic discharges [7], high-power devices [8], lasers [9] and optical fibres [10], magnetic materials [11], capacitors [12], superconductors [13], mapping deflection coils [14], power transformers [15], power electronic components and inverters [16], electrical machines and drives [17-25].

PRINCIPLE OF CALORIMETERS

The objective of a calorimeter is to directly measure the power loss in a test object by installing the object in an airtight enclosed container (calorimeter). A cooling system is arranged to flow in and out the calorimeter so as to convey the heat dissipated by the object when it is in an operational condition. After thermal balance is attained, the energy extracted from the enclosure is balanced exactly by the loss released by the test object. The power loss in this steady state is expressed by the equation:

$$P_{loss} = V \times (C_{p2} \times \rho_2 \times T_2 - C_{p1} \times \rho_1 \times T_1) \qquad (1)$$

Where C_p is the specific heat in J/kg°C, ρ the density of coolant in kg/m^3, V the volumetric flow rate in m^3/sec, and T the temperature in °C. The subscripts 1 and 2 denote the entry and exit across the calorimeter, respectively.

If the density and specific heat of a coolant at the inlet and outlet are steady, equation 1 can then be simplified as,

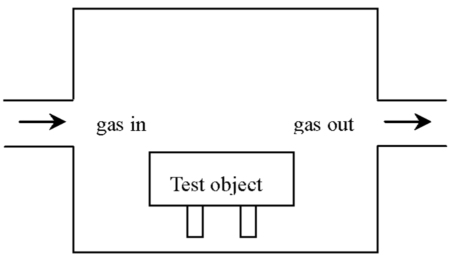
$$P_{loss} = C_p \times V\rho \times \Delta T \qquad (2)$$

Where the term $V\rho$ represents the mass flow rate of the coolant in kg/sec. As long as this parameter is controlled constant for a calorimeter, the observed power would be proportional to the temperature rise. Such a ratio may be derived through a calibration against a known heat loss (e.g. heater).

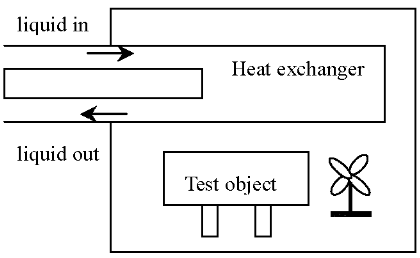
However, the assumption that the specific heat and density of the coolant are uniform across the entry and exit ports brings about measurement uncertainty, especially for gas-cooled systems.

CLASSIFICATION OF CALORIMETERS

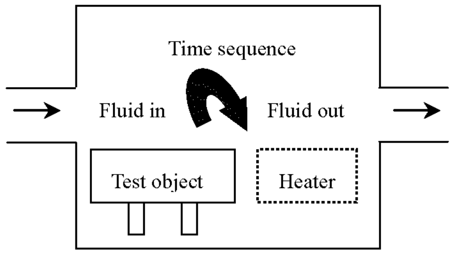
In the literature, various types of calorimeters have been reported. According to their ways of heat exchange, calorimeters generally fall into two categories. The first is the direct calorimeters, which assess the power loss in the test object directly [17,18]. Indirect calorimeters, on the other hand, introduce a reference heater. The power output of this heater is then adjusted so that the test conditions for the reference heater match that for the test object [10,19-21,26]. In terms of fluid selection, gas-cooled and liquid-cooled systems have different arrangements for heat transfer. Gas can penetrate through the test object without causing any damage or hazard but liquid requires additional mediums (heat exchanger and fan) for the same purpose. Combined with coolant selections, the direct calorimeters can be further divided into two types: the open calorimeter for gas coolant [17] and the closed calorimeter for liquid coolant [18]. Based on the different testing procedures employed, indirect calorimeters can also be divided into two types: the balanced calorimeter, which uses a single chamber in the way the test and reference objects are tested one after another in time sequence [19,21], and the series calorimeter, which uses a two-chamber arrangement [10,20]. The four variants are illustrated in Figure 1.



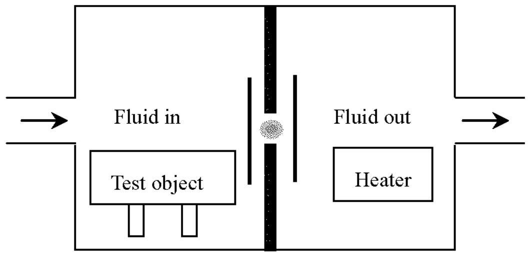
Direct: open calorimeter



Direct: closed calorimeter



Indirect: balanced calorimeter



Indirect: series calorimeter

Figure 1 Classification of Calorimeters

A. Open Calorimeter

The open calorimeter uses gas as a coolant, generally air. Among all types of calorimeters, this is the simplest in structure and installation. Obviously, the heat generated from the test object could be directly transferred to the coolant gas, giving the calorimeter a quick response time.

Nonetheless, air suffers from low heat capacity and changeable properties which equation 2 is not applied. These features make the system large in volume and accurate measurement of the gas contents critical.

The accuracy of such calorimeter is quoted as 5.6 W on the scale of 3.2 kW [27].

B. Closed Calorimeter

As opposed to the open type calorimeter, the closed calorimeter uses liquid as a coolant, commonly water. The coolant liquid is circulated in a closed loop across the calorimeter and heated up inside the calorimeter. In essence, the heat released by the test object is first transmitted to the air, then to the coolant fluid via the heat exchanger and auxiliary fan.

Even so, the closed calorimeter still has a higher efficiency of heat transfer than its open-type counterpart because liquid normally has a higher density, heat capacity and thermal conductivity than gas, primarily increasing measurement accuracy of coolant proprieties. For instance, the value of C_p for water is more than 4 times greater than air. Moreover, C_p for water varies less (0.07%) than air (0.5%) with temperature and humidity within the working range. This latter feature eases the requirement for loss measurement so that simplified equation 2 becomes applicable.

But the presence of the heat exchanger will lead to a non uniform internal temperature distribution across the walls and a time delay between sensing changes in temperature and feedback control to follow them. In addition, it limits the calorimeter's flexibility to accommodate large test objects. The power required by the cooling fan can also be a significant part of the total power loss, consequently reducing overall accuracy.

The accuracies of such calorimeters are reported to be 3.8% for a power loss of approximately 1.2 kW in [18] and 0.2% for 600 W in [28] and 0.2% for 1.5 kW in [29], respectively.

C. Balanced Calorimeter

The balanced calorimeter is designed to eliminate the necessity of accurate measurement of coolant properties by using a reference heater to mimic the test object in heat production. This method requires two similar experiments being undertaken in time sequence. The first one is to perform a normal experiment when the test object is installed in the calorimeter whilst the second employs an ohmic heater acting as the heat source to repeat the experiment. By the means of careful trial-and-error control of heater power, it is likely for the calorimeter to return to the previous thermal equilibrium (equal temperature rise). Given repeatability of air flow rate and heat leakage, the power to the heater in the second experiment can be reasonably assumed to be the loss in the first.

Compared with the direct calorimeters, the apparent advantage of this method is the removal of the measurement of the fluid properties which proves to be very difficult. Instead, a stable power supply to the heater and accurate measurement of the heater power can be readily achieved. There is no doubt that conducting such a complete calorimetric test would be very lengthy and tedious. As well known, one of the major limitations of the calorimetric approach lies in its time-consuming procedures. In this regard, the balanced calorimeter has gone from bad to worse. Furthermore, the presumption that fluid parameters and heat leakage do not change between two consecutive tests does not hold true. The heater may have less surface area than the test object and thus produce a higher operating temperature, leading to an altered thermal distribution inside the enclosure and a different temperature gradient between the two tests. This is particular true if the internal wall surface of the calorimeter is not thermally conducting.

The accuracies of these calorimeters are quoted as 1.45% on full load losses of 1 kW [28] and 4.7% on no load losses for a 5.5 kW test machine [19], and 1% on a full scale of about 1 kW [30].

D. Series Calorimeter

The series calorimeter is proposed as a refinement of the balanced method. It is also called the double chamber calorimeter [20]. In this method two identical inter-connected chambers are constructed, one for the test object and another for the reference heater. During a calorimetric experiment, the test object and heater are operating simultaneously in the chambers. The coolant fluid firstly flows into the test chamber and then the heater chamber. Through controlling the power to the heater, it is possible to achieve the same temperature rise in both chambers. In a steady state, the heater power loss is presumed to be the same as that in the test object.

Just as with the balanced type, this calorimeter does not need accurate measurement of the coolant's properties to obtain the energy figure. It also improves the balanced calorimeter by reducing the length of experimental time. Yet, the introduction of an additional chamber will increase the cost and space requirements. Additionally, to maintain the fluid flowing through two chambers in the same condition is never realised since the specific heat of a fluid depends on its temperature. This is particularly the case for air being the coolant. In order to maintain the same temperature rise, the coolant outlet temperature in the second chamber would be twice as big as in the first, creating different temperature gradients to the ambient environment. As a consequence, the heat leakage through the enclosure boundaries in the second chamber would be much greater, giving a falsely higher power loss. It may be thought that to double the thermal insulation capacity for the second chamber would equalise heat leakage between the two [20]. However, this assessment is only valid when: i) at each and every corresponding point between the two chambers, the second chamber always has a doubled temperature gradient to the ambient than the first; and ii) the heat contents of the coolant fluid are independent of temperature. Clearly these assumptions are hardly guaranteed because the tests are conducted by employing two different heat sources under two different thermal conditions.

The accuracies of these calorimeters are reported to be 0.18% for loss measurement of 1 mW and 0.45% for 10 μW in [10], and 1.5% for power loss of 1 kW in [20].

SPECIAL CONSIDERATIONS

In designing a calorimetric system, the type of the calorimeter, the dimension and capacity, the fluid coolant and heat transfer arrangements are among first things to consider. Furthermore, issues including heat leakage, temperature measurement and operational time are of importance to achieve the measurement requirement within a reasonable period of time.

A. Heat Leakage

The heat leakage error is largely evoked by conductive connections. In the case of testing electrical machines, the leakage paths establish through walls, mounting bedplate, shaft linkage and other connecting ports to the surroundings. These problems can be overcome by applying external temperature compensations (active temperature control) to achieve as closely as possible to an isothermal condition across the boundaries, in conjunction with good insulation arrangements. In this respect, a sandwich structure is suggested which consists of two thin layers of high-conductivity metal (e.g. aluminium) and a thick layer of insulation material (e.g. polystyrene) in between. An additional advantage of using metals to cover the surface of the structure is to reduce the non-uniform distribution error in temperature profile across the surface of each wall.

B. Temperature Measurement

Ideally, the temperature of the coolant at the measurement points should be single valued. In reality, there would be temperature gradients on the cross section plate of the inlet/outlet ducts. It is apparent that using a single temperature sensor to measure the mean fluid temperature will unavoidably give rise to measurement uncertainty, which can easily exceed the accuracy required. This error is often overlooked. In practice, there are two solutions available to this problem. One is adopting multiple temperature sensors in a grid to find a mean temperature [20], and the other is using temperature equaliser to average the fluid temperature at the temperature measurement point [27]. This equaliser serves two purposes: i) to divide the main air flow into many sub-flows so that the difference across the cross-section of the duct is considerably reduced; and ii) to equalise the temperature difference by conduction using high conductivity tubes and wires.

C. The Length of Test Procedures

In principle, the settling time for a calorimetric system to reach its thermal balance is infinite due to its exponential tendency. Practically this is a compromise between measurement accuracy and operational time. If the power loss is to be measured to an accuracy of 0.2%, the operational time for a single test point should be at least 6.2 times the thermal time constant. At the design stage, this thermal time constant can be minimised by selecting light weighted materials for the structure, such as aluminum and polystyrene.

In theory, the settling time depends on both the thermal time constant and the initial value. After the calorimeter is commissioned, it is not convenient to further reduce the time constant. But the length of test procedure can still be mitigated by boosting the initial loss value [28]. A simple implementation might be to employ a DC boost heater working along with the test object within the calorimeter. Through control of the supply voltage to the heater, the sum of power losses released by the object and the heater can be dynamically maintained to a predefined value. Once the observed power value reaches a certain range, the heater would be turned off and the test object then would work alone to reach its equilibrium.

SUMMARY

This paper provides a review of calorimetric application in heat loss measurement. Calorimetry has been gaining in popularity because it inherently removes the need of measuring two large quantities (input and output) to find the power loss in a test device. Therefore it offers much promise in accurate loss measurement where other techniques may find difficulty.

The calorimeters reported previously can be divided into four types. The open calorimeter provides simple construction and installation but it is necessary to measure the gas contents with precision, which poses difficulties. The closed calorimeter has a higher efficiency of heat transfer which may reduce the size of the calorimeter. Nonetheless, it requires an additional heat exchanger, resulting in a shifted internal temperature distribution inside the calorimeter and a time delay between sensing changes in temperature and feedback control. The balanced calorimeter eases the requirements of measuring the coolant flow rate and properties but introduces a heater to repeat the calorimetric test consecutively, resulting in much lengthy testing procedures. In addition, it is unlikely to return the same measurement condition in the two experiments since the heater has different surface area and temperature profile to the test object. The series calorimeter uses two chambers in the structure and thus a doubled space. This approach is refined from the balanced calorimeter and significantly reduces the operational time. However, the second chamber always has a higher but not exactly doubled heat leakage to the ambient, as compared to the first chamber.

In summary, for any type of calorimeters to work effectively, nothing has been more significant than maintaining steady mass flow rate, preventing heat leakage through the boundaries, and accurately measuring the fluid temperature.

It should be pointed out that a key stumbling-block of calorimeters is still their time-consuming procedures. This may be mitigated by reducing the thermal time constant in selecting structural materials and/or enhancing the initial loss value with an ancillary heater.

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