

Short Papers

Design of a 300-kW Calorimeter for Electrical Motor Loss Measurement

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Abstract—This paper describes the design of a calorimeter that is suitable for measuring power losses in electrical motors of up to 300 kW (402 hp). Refined from the two previous generations, this calorimeter is of air-cooled open type. Accurate control of the air flow rate and temperature gradients between the inside and outside walls of the calorimeter ensures that a repeatable and durable measurement environment is achieved. During the design stage, attention is focused on heat leakage prevention and reduction in the length of the testing procedures. Heat leakage is mitigated by appropriate insulation and active temperature control over all walls and connection ports. In selecting the materials for the structure, lightweight aluminum and polystyrene are used in sandwich form to reduce the thermal time constant and, thus, the operational time for the calorimeter to reach its equilibrium. After the calorimeter is commissioned, further reduction in the lengthy test procedures is realized by boosting the initial power loss value of the motor under test. That is, some additional resistive heaters are installed inside the calorimeter and operate in conjunction with the test motor. This push-pull technique can guarantee a constant combined power loss during operation, which is assumed to be the final value of motor loss. By predefining a suitable motor loss and a tolerance, it is possible to dynamically control the input power to the dc heaters from the start and to shut down the heaters once the motor loss value enters the tolerance selected. Calibration results confirm the effectiveness and accuracy of the calorimeter.

Index Terms—Calorimetry, electric machines, heat transfer, loss measurement, power loss.

I. INTRODUCTION

With the increase in energy awareness, energy efficiency has become a key criterion in the design, manufacture, marketing, and operation of electrical motors. This trend has been reinforced by legislation in the U.S. [1] and by voluntary codes in the European Union [2]. In the industry, medium-sized electrical motors, which are rated between 1 and 500 hp (373 kW), account for the majority of electricity consumption. Consequent improved energy efficiency within this group of motors offers considerable promise in terms of energy savings and environmental benefits. However, accurate determination of efficiency using traditional input-output methods becomes increasingly difficult as the motor size exceeds 150 kW.

If the motor is not highly efficient and the measurement accuracy is not highly demanding, motor efficiency can reasonably be estimated to an accuracy in the range of 1%–2% using traditional methods [3]. However, if accurate knowledge of motor losses is needed, input-output methods may have difficulty with high-efficiency motors

since their accuracy depends on the motor rating [4]. In such situations, calorimetry offers an effective alternative [5].

Calorimeters directly measure the effect of power loss and thus eliminate the inaccuracies that are inherent in subtracting two similar-sized power figures to calculate the total loss, as in the case of input-output methods [3], [5]. In the literature, various calorimeters have been proposed [6]–[16]. In general, these have been low-power facilities with measurement capabilities of below 1 kW. It is obvious that the real advantage of calorimetry lies in the accurate evaluation of large or highly efficient motors, where other methods become inadequate. For this reason, the calorimeter design in this paper targets medium motors rated at 30–300 kW (40–402 hp).

II. PREVIOUS DESIGNS

Two generations of calorimeters have previously been developed by the authors' research team [17], [18]. They were of similar physical sizes and suitable for electrical motors of up to 30 kW. Both used air as the coolant because of its convenience and cheapness. Using a conditioning system, air can easily be cooled down to a controlled level prior to its supply to the calorimeter. In this way, the test motor was not operated at excessively high temperature, as was the case in some previously reported designs [15].

A. First-Generation Calorimeter

The first-generation calorimeter was of balanced type, which required two similar tests to be conducted in sequence and the power loss of the motor under test to be compared with that of a known power source, such as a heater. In the first test, the electrical motor was tested under normal conditions, and the temperature rise of the coolant was recorded when thermal equilibrium was achieved. In the subsequent test, the test motor was replaced by a resistive heater. By careful trial-and-error control of the power to the heater, it is possible for the calorimeter to reproduce the results of the previous motor test. Thus, assuming that the air flow rate, temperature rise, and heat leakage were all repeated, the power input to the heater could be assumed to be the power loss of the motor. However, the facility suffered from lengthy operating procedures and high levels of heat leakage through the calorimeter boundaries and connection ports. Even after careful calibrations, an overall measurement accuracy of approximately 0.5% was the best that could be achieved.

B. Second-Generation Calorimeter

For the second-generation calorimeter, a direct-type, and not a balance-type, calorimeter was used. This can at least, in theory, halve the testing duration. The cost is the necessity for accurate determination of air's properties for energy calculation purposes. Clearly, this leads to some experimental difficulties since air's density, vapor contents, and specific heat are all dependent on temperature, pressure, and humidity. Furthermore, most air flow devices measure volume flow rather than mass flow. Nevertheless, these difficulties may largely be overcome by the use of high-precision instruments and temperature equalizers in the ducts [18].

Heat leakage through the calorimeter's boundaries was minimized by careful arrangement of insulation and, in particular, by active

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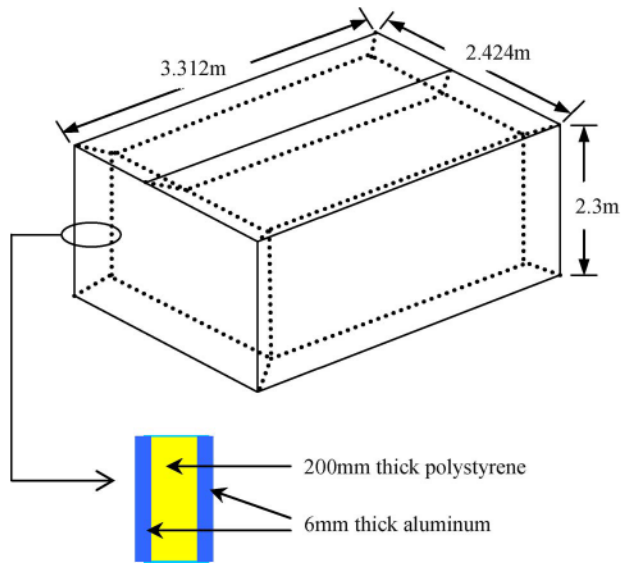


Fig. 1. Structure of the 300-kW calorimeter.

temperature control [18] on the walls, supporting legs, and motor shaft linkages.

This calorimeter provided substantial improvements and achieved accuracies of better than 0.2%.

III. DESIGN OF THE 300-kW CALORIMETER

Based on the successful development of the two previous generations of calorimeter, a 300-kW facility was designed for the testing of medium-sized motors. This was not simply a case of scaling up the 30-kW design. First, by increasing the diameter of the airflow ducts from 100 to 200 mm, the nonuniformity of the air temperature across these ducts became significant. Second, test durations were substantially prolonged. The thermal time constant of the 300-kW calorimeter was in excess of 90 min, therefore requiring test durations of at least 9 h for each test point. While all calorimeters suffer from tedious test procedures, this calorimeter would be prohibitively time consuming and costly if there were no special mitigation measures in place.

A. Structure

The calorimeter is designed to be airtight and of low thermal conductivity across the walls. The panels are fabricated in a sandwich construction, which consists of a layer of 200-mm-thick expanded polystyrene between two layers of 6-mm-thick aluminum sheet. As shown in Fig. 1, this calorimeter has external dimensions of 3.312 m \times 2.424 m \times 2.3 m ($L \times W \times H$) to accommodate medium motors rated at 30–300 kW. To gain easy access to the calorimeter for installing the test motor, the top panel comprises two removable pieces. A maximum temperature rise of 20 °C is designed to give a power rating of 18 kW at a mass flow rate of 0.8 kg/s of dry air, corresponding to a maximum 300-kW motor with the lowest efficiency at 94%. For the purpose of reducing ambient temperature variations, the well-insulated calorimeter is further installed in an insulated chamber with inner dimensions of 4.5 m \times 3.7 m \times 2.8 m. Within this chamber, four stirring fans, as well as an adjustable cooling/heating system, are employed to stabilize the ambient temperature.

The calorimeter box has several exits to external connections, including the inlet and outlet ducts for flow circulation, steel supporting legs on the ground, shaft connection to the loading system, and elec-

trical cable exits for the supply and transducer signal linkage. These represent major paths for heat leakage in addition to the panel walls.

B. Air Energy Calculations

Previously, it was commonly assumed that the specific heat of the coolant at the entry and exit ports of the calorimeters was uniform [9]–[13]. Consequently, the difference in power losses measured at the inlet and outlet ports was assumed to be proportional to the temperature rise of the coolant. Therefore, the calculation for air energy was simplified to measuring the temperature rise. The correlation factor between power and temperature rise can conveniently be obtained via a full calibration. However, this assumption gave rise to significant measurement errors. For example, in water-cooled calorimeters, the specific heat varies by 4%, and density varies by 5% in the working temperature range (15 °C–35 °C), whereas, for gas-cooled systems, these variations can be as much as 10%.

To eliminate this problem, the assumption is removed, and a set of accurate formulas is employed to calculate the exact energy of the air at the entry and exit ports, based on accurate measurements of air's properties.

C. Test Duration

In principle, the time required for a calorimeter to reach its thermal balance is infinite. In practice, however, it is a function of the desired measurement accuracy that the tester wishes to achieve. For instance, if the power loss is to be measured to an accuracy of 0.2%, the operational duration for a test point should be at least 6.2 times the thermal time constant. In addition to their economic benefits, this partially explains the use of lightweight materials, such as aluminum and polystyrene in the calorimeter construction. After the calorimeter is commissioned, it is unlikely to further minimize this thermal time constant.

However, the test duration depends on not only the time constant but also the initial value. Therefore, the use of boost heaters is proposed in this paper to push the initial heat loss to be near the final value of the motor. Boost heaters are situated in the calorimeter and operate alongside the test motor from the start. When the motor loss increases, the heater loss decreases to have a fixed summation of power losses released by the heaters and the motor. This can be done by a dynamic H-bridge voltage control of the dc heaters. If the motor loss reaches a threshold (e.g., 90%–110% of the predefined loss value), the heaters would stop, and the motor would act as the solo heat source until thermal equilibrium is achieved.

By reducing the thermal time constant at the design stage and boosting the initial value on operation, the duration for achieving thermal equilibrium can significantly be shortened (in this case, from 9 h to approximately 5 h). This latter duration is similar to that for the 30-kW calorimeter.

IV. CALIBRATION

Periodic calibrations are generally used to check the precision of the calorimetric system and also identify any errors or drifts that may have occurred over time.

Initial calibrations are performed using the boost heaters inside the calorimeter, which are supplied by a half-controlled single-phase rectifier. The currents and voltages are measured by Hall-effect transducers, so that the power to the heater can be measured to an accuracy of better than 0.1%. By feeding a known power to the resistive heaters and waiting sufficient time for the calorimeter to reach thermal balance, a power reading via a LabView interface is obtained. Then, a series of

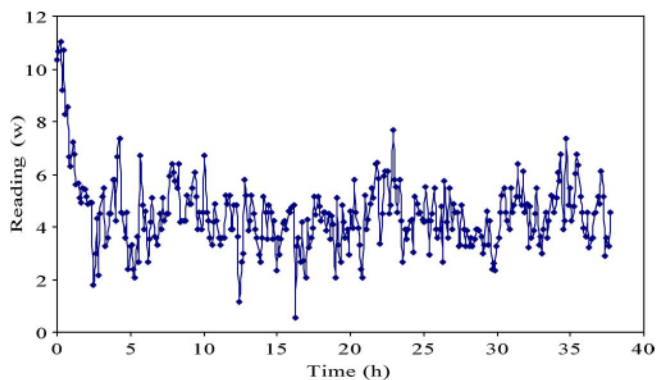


Fig. 2. Calibration of the zero power point.

calibration tests are conducted by controlling the input dc powers from 0 to 10 kW. The measured power losses from the calorimeter are all within a 0.2% accuracy. The experimental results for the zero point are shown in Fig. 2. Through analysis of these results, it can be observed that the calorimeter has a zero-point drift of approximately 5 W with a standard deviation of approximately 2 W.

The measurement errors identified in calibration tests have been input to the control program of LabView and will be compensated in the subsequent motor tests.

V. CONCLUSION

Calorimetry has long been acknowledged as an accurate tool for the measurement of power loss. Unfortunately, the previous calorimeters in the literature were all low-power facilities and achieved only limited success.

This paper has described the design of a 300-kW high-precision calorimeter. Refined from the two previous generations, this calorimeter is of air-cooled open type with improvements on heat leakage prevention and reduction in the test duration. This facility is capable of measuring power loss in electrical machines rated up to 300 kW with an overall accuracy of 0.2%. The power loss results from initial calibrations have confirmed the effectiveness and accuracy of the calorimeter.

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Near-Field Millimeter-Wave Imaging of Exposed and Covered Fatigue Cracks

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Abstract—In this paper, the efficacy of near-field millimeter-wave nondestructive techniques, using open-ended flange-mounted rectangular waveguide probes, for extracting information of 3-D crack area deformation (i.e., in-plane and out-of-plane deformation) is demonstrated. It is shown that this information can be obtained from indications of unique interference patterns that are generated between the probe and the metal surface during the raster scan of a surface-breaking exposed and covered fatigue crack using a phase-sensitive reflectometer.

Index Terms—Crack, imaging, interference pattern, millimeter waves, near field, nondestructive, reflectometer.

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