Accurate Heat Loss Evaluation of Water-Cooled Electric Motors Using a Differential Ultrasonic Calorimeter

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***Abstract*—Measuring thermal losses of electric motors is important for their design, optimization, and correct pricing after manufacture. This measurement can be conducted by checking the temperature difference of the motor coolant (usually water) between the coolant inlet and outlet. High speed measurement facilitates testing various load scenarios and manufacture throughput; high measurement accuracy and resolution is required for drawing the correct conclusions on the efficiency of design alterations.**

Ultrasonic temperature sensors can quickly sense temperature with high resolution and accuracy across the entire ultrasonic pathway. However, conventional high resolution ultrasonic sensors are expensive. By contrast, oscillating ultrasonic temperature sensors can be implemented using mass produced transducers and electronic parts at a fraction of the price of conventional high resolution ultrasonic measurement equipment.

The presented ongoing research focuses on the development of a differential ultrasonic oscillating temperature sensor for evaluation of power losses in electric motors. Computer simulations, electronic and firmware design, and experimental results are presented and discussed.

Keywords—temperature sensing differential temperature measurement; ultrasonic oscillating sensor; ultrasonic instrumentation; ultrasonic NDE; thermal power loss evaluation; differential calorimetry

I. INTRODUCTION

Over the past few decades, temperature sensors have become one of the most purchased types of electronic sensors [1]. The market share of temperature sensors is forecasted to increase by 4.8% between 2016 and 2022 reaching £5.2 billion [2]. Temperature sensors come in various types, the most common of which are thermistors, resistance temperature detectors, thermocouples, and infrared temperature sensors. The list of temperature sensor applications is extensive; it includes numerous applications in medicine, science, technology, engineering and various industries (energy generation, automotive, food, etc.).

Many conventional temperature sensors are inexpensive, accurate, and reliable to some extent. However, one of their drawbacks is the substantial cost increases that come about when accurate temperature readings with high resolution are required. For example, DS18B20 sensors can easily achieve a resolution of ±0.2 K at a price as low as a few pounds. On the other hand, sensors with resolution lower than ±0.05 K can cost from a few hundred up to a few thousands of pounds.

Ultrasonic temperature measurements have proven their capability of overcoming a number of limitations inherent to conventional temperature sensors [3]. Conventional sensors can only sense temperature at their particular location, which can be costly when the average temperature over some vessel needs to be determined. Ultrasonic sensors, however, can sense the average temperature across a complete ultrasonic path. In addition, most conventional sensors must achieve thermal equilibrium between the sensor and the surrounding environment. This equilibrium can take a few seconds after a temperature change before the sensor starts to produce correct readings [4, 5]. In contrast, the response of ultrasonic thermometers is nearly instantaneous. Finally, ultrasonic sensors were reported to achieve much higher resolution than conventional temperature sensors [5].

Ultrasonic transducers and instrumentation vary in cost depending on many factors such as operating frequency, bandwidth, accuracy, sensitivity, the targeted application, and/or the underlying technology. For example, medical ultrasound systems are prohibitively expensive when compared to conventional thermometers, yet in that field a medical ultrasonic scanner costing £20k may be considered to be a low cost instrument [6].

One of the reasons for this is the required manufacturing precision. For example, a typical 5 MHz transducer requires a piezoelectric element of a thickness of around 0.3 mm. In addition, high frequency ultrasonic systems require expensive hardware. Cost reductions can potentially be achieved by using low-frequency, low-intensity, inexpensive ultrasonic transducers, which are commercially available for ranging and proximity applications. A pair of narrow-band 40 kHz air ultrasonic transducers, such as the Prowave 400ER18S, can cost under £6 per pair. However, these sensors exhibit some undesired features such as low reproducibility and hysteresis. Fig. 1 presents a comparison of accuracy, price and operational range for various types of conventional and ultrasonic temperature measurement devices.

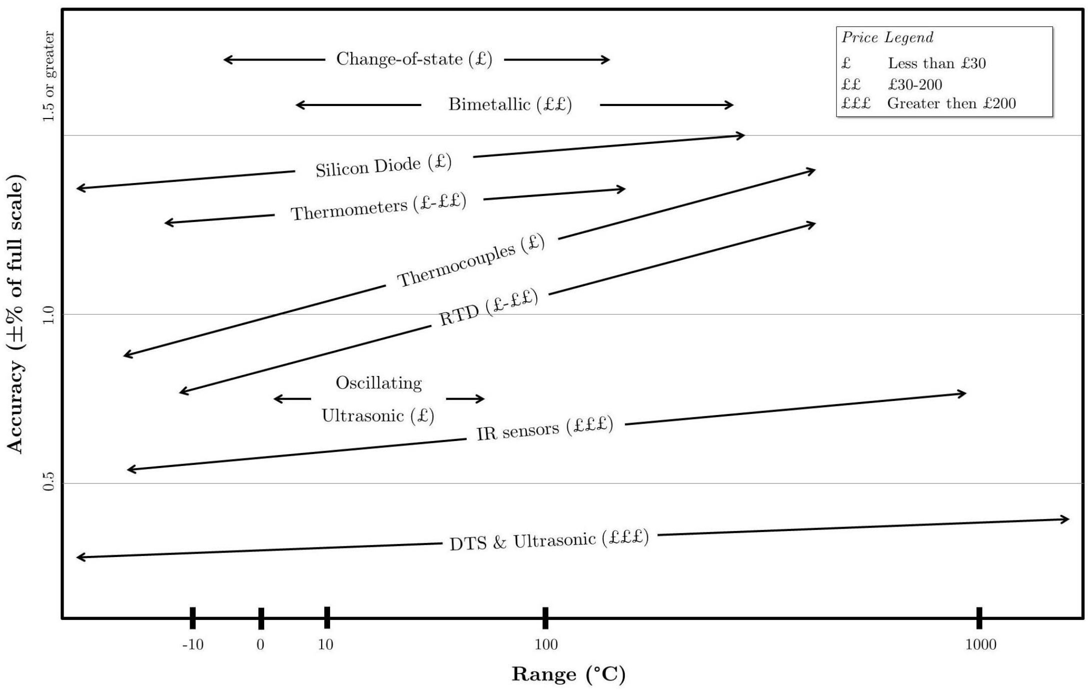

Fig. 1. Comparison of various types of temperature sensors.

II. Determining power losses by differential temperature measurement and simulating the required accuracy

A. Relation between power losses and coolant temperature differential

Power losses in electric motors are converted to thermal energy which can be characterized in order to assess the power loss. By measuring the temperature difference at the inlet and outlet of a water-cooled electric motor, the amount of power loss within the motor can be found. The power loss of a cooled electric motor P_L depends on the difference in coolant temperature between the inlet and outlet ΔT, its flow rate f and specific heat capacity c as follows:

$$PL = cf\Delta T \tag{1}$$

Measuring these variables accurately with high resolution at high speed enables better performance analysis and design optimization of electric motors during their design stage.

B. Simulating the influence of temperature measurement resolution and accuracy on the evaluated power loss

Accurately determining power loss is essential for electric motor standardization. Manufactured motors are normally rated by their efficiency and priced accordingly, because higher-efficiency motors bring about savings in running cost. There are various national and international standards regarding motor efficiency; some of the most common ratings are presented in Table I.

TABLE I. International Motor Efficiency Rating Standards

Efficiency	***IEC 60034-30***	***Europe (CEMEP)***	***United States***
Super premium	IE4		
Premium	IE3		NEMA Premium
High	IE2	EFF1	Epact
Standard	IE1	EFF2	

We conducted numerical simulations for various temperature measurement accuracies/resolutions in order to establish acceptable values for the correct classification of common motor types. The simulations were based on information for 26 commercially available electric motors, collected from their data sheets, including their rated power P_{ds}, efficiency η_{ds}, and suggested temperature difference of the cooling water at the inlet and outlet ΔT_{ds}. The required coolant flow rate f_r was calculated from the rearranged equation (1) as follows

$$f = \eta_{ds}P_{ds}/(c\Delta T_{ds}),$$

and then rounded to a 6 L/min resolution in order to represent a range of pumps with a fixed flow rate. The resulting exact temperature difference ΔT_0 was determined from the rounded required flow rate f_{rr}; then the range of ΔT measured by two similar temperature sensors with the same accuracy/resolution ε was calculated as $\Delta T = \Delta T_0 \pm 2\varepsilon$. Evaluated power loss P was determined for the worst case maximum and minimum values of ΔT. Finally, the estimated motor efficiency η_x can be calculated for both the worst cases separately as follows:

$$\eta_x = cf_n\Delta T/P_{ds} \tag{2}$$

Fig. 2 shows the range of estimated motor efficiencies for 2, 4 and 6-pole electric motors with 15 kW rated power versus accuracy/resolution of the temperature measurement sensor. The simulations were conducted for differently priced standard, high and premium efficiency motors.

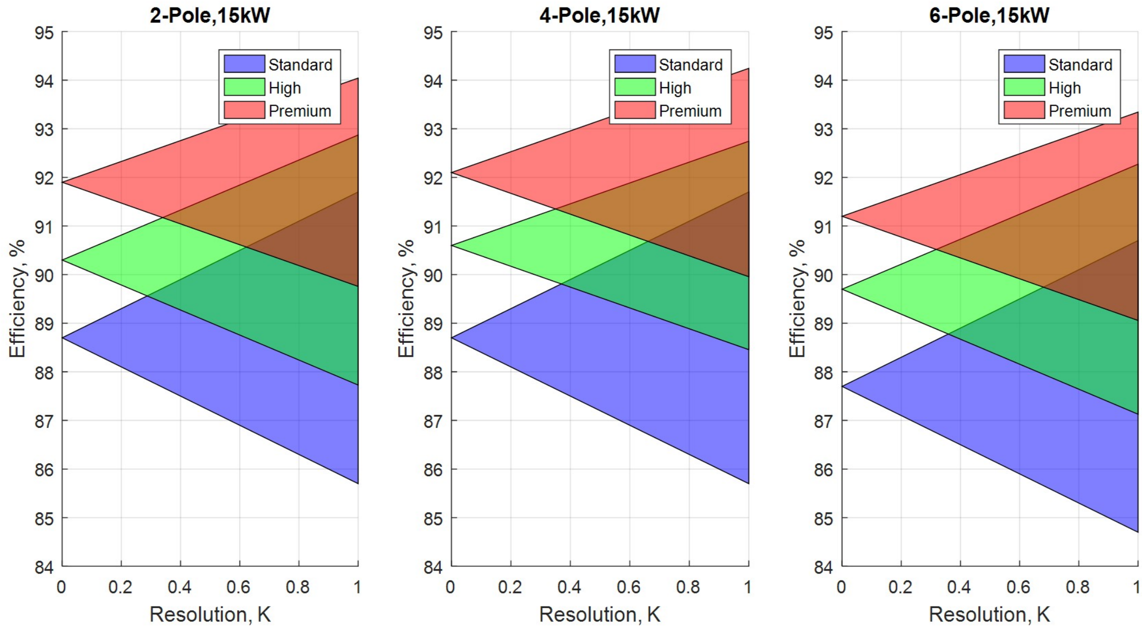

Fig. 2. Simulated results of evaluated motor efficiency versus accuracy/resolution of the temperature sensors for various 15 kW electric motors.

As can be seen from Fig. 2, it can be challenging to classify a motor into a correct efficiency class using temperature sensors with accuracy below ±0.2 K. The efficiency class, hence the selling price, of a given motor can be incorrectly determined in cases where the accuracy of the employed temperature measurement system is greater than 0.5 K (± 0.25 K). This is clearly shown in the areas of Fig. 2 where the differently colored regions overlap. Therefore, ultrasonic oscillating temperature sensors can potentially be useful to quickly and correctly rate the motor efficiency at their manufacturing site.

III. Electronic Developments for Ultrasonic Oscillating Sensors

A. Oscillating ultrasonic architecture

An oscillating ultrasonic architecture was chosen over other ultrasonic sensor architectures due to its relative simplicity. Using a single amplifier can sustain oscillation across a closed loop which includes a pair of ultrasonic transducers; however, an amplifier provides only a very limited control over the sensor operation. In addition, inexpensive ultrasonic transducers feature several resonances at various frequencies. For this reason a single amplifier system, when powered up, can start oscillating at several different frequencies depending on the initial conditions.

To overcome these uncertainties, a more robust design of electronic driver must include an electronic band pass filter (BPF) that limits operation of the oscillating sensor to a particular frequency range. Additionally, submerged operation of ultrasonic transducers is usually subjected to external electromagnetic interference and noise [7]. The BPF specification should be chosen carefully, as the consistency of the results is very sensitive to the BPF bandwidth. Automated BPF tuning can be provided using low-cost microcontrollers, because bandwidths which give the best results differ across frequency regions.

Theoretically, the sensor is designed to oscillate at a frequency where the amplitude of the frequency response of the open loop system exceeds unity and the phase response goes to zero. These conditions cannot always be satisfied unless a phase shift is inserted into the system [8].

B. Electronic devices for oscillating ultrasonic temperature sensors

Electronic drivers, designed for nonlinear ultrasonic oscillating temperature sensors, should be capable of being easily assembled in various configurations. For this reason we developed a modular electronic system that can be assembled in a number of ways and deployed in various combinations. Each module in such a system is responsible for performing a certain function of the electronic driver and data acquisition systems.

Control commands for different modules need to be broadcasted to all the modules simultaneously, but only an appropriate module should perform a certain required action. Most of the modules in the developed system were designed around programmable system-on-chip (PSoC) microcontrollers and had an ability to be programmed in circuit [7]. An example of an assembled modular system, shown in Fig. 3, features two boards for multiplexing input and output signals from the ultrasonic sensors (a and c respectively), an ultrasonic driver board (b) and a TCXO-based frequency meter module (d).

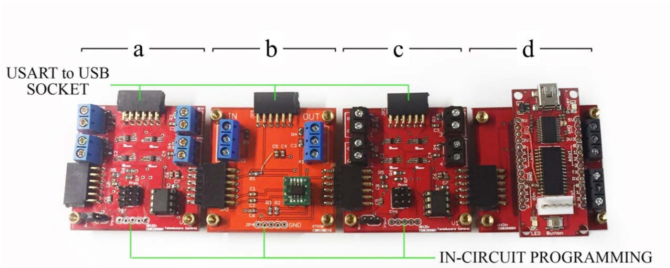

Fig. 3. An example of assembled modular system that features (a, c) signal multiplexers, (b) ultrasonic driver and (d) frequency meter [7].

The overall bill of materials for the developed fully functional modular system stands at under £20, including the cost of PCBs, relevant electronic parts, and microcontrollers [9].

IV. Experimental Differential Ultrasonic Temperature Measurements

A. *Experimental setup*

The experiments were conducting using a pair of ultrasonic oscillating temperature sensors, placed at the inlet and outlet of a water heater, which simulated the heat losses of an electric motor. Heat produced by the heater was taken away by cooling water that circulated in a closed-loop system via a submersible electric pump as shown in Fig. 4.

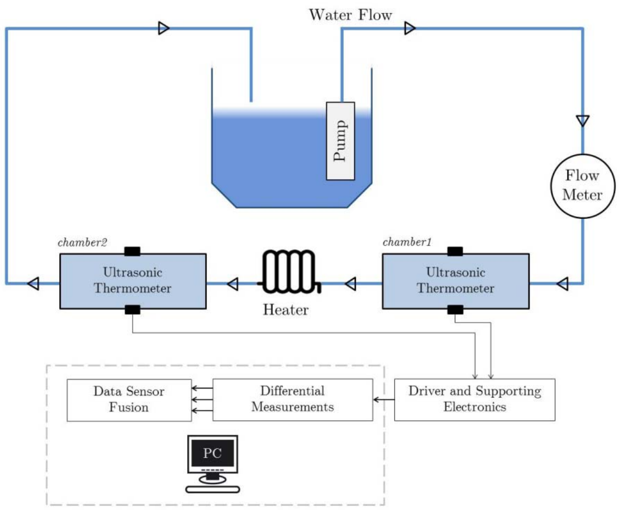

Fig. 4. Experimental setup for measuring temperature differential using ultrasonic oscillating sensors.

A separate flowmeter was used to measure the water flow. After passing chamber 1 with an oscillating temperature sensor to measure the inlet temperature, water was heated by around 10 K. (Such a figure for the temperature difference between the motor inlet and outlet is recommended by the motor manufacturer [10].) The chambers were designed to operate at flow rates of up to 10 L/min, which is sufficient to take away heat losses of modern electric motors with standard efficiency, rated up to 73 kW. Chamber 2 was used for measuring the temperature of the heated coolant at the heater outlet. Both chambers were equipped with conventional temperature sensors providing the reference data. The full experimental setup with included equipment is pictured in Fig. 5.

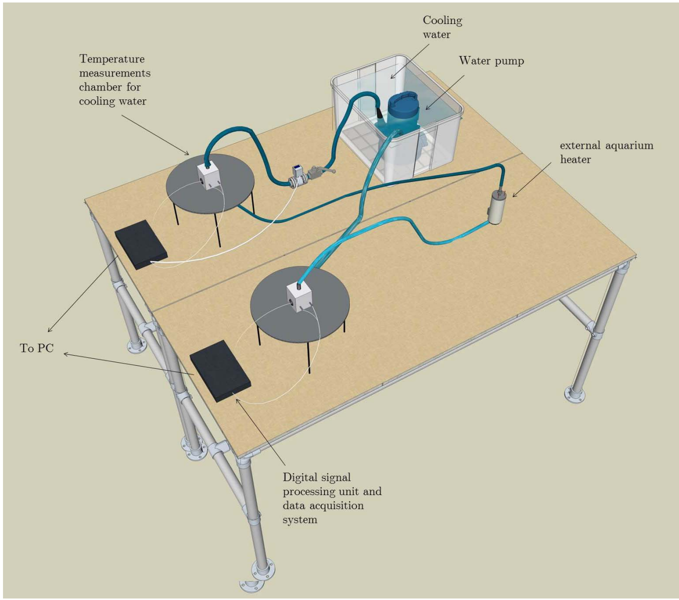

Fig. 5. Experimental setup and equipment for measuring temperature differential using ultrasonic oscillating sensors.

B. *Experimental results and discussion*

The results presented in Fig. 6 show that the output frequency of the ultrasonic temperature sensors followed the temperature profile, as measured by the conventional temperature sensors. By plotting the frequency graph of temperature vs. the ultrasonic sensor output, it was found that frequency-temperature hysteresis in the presence of water flow was minimal.

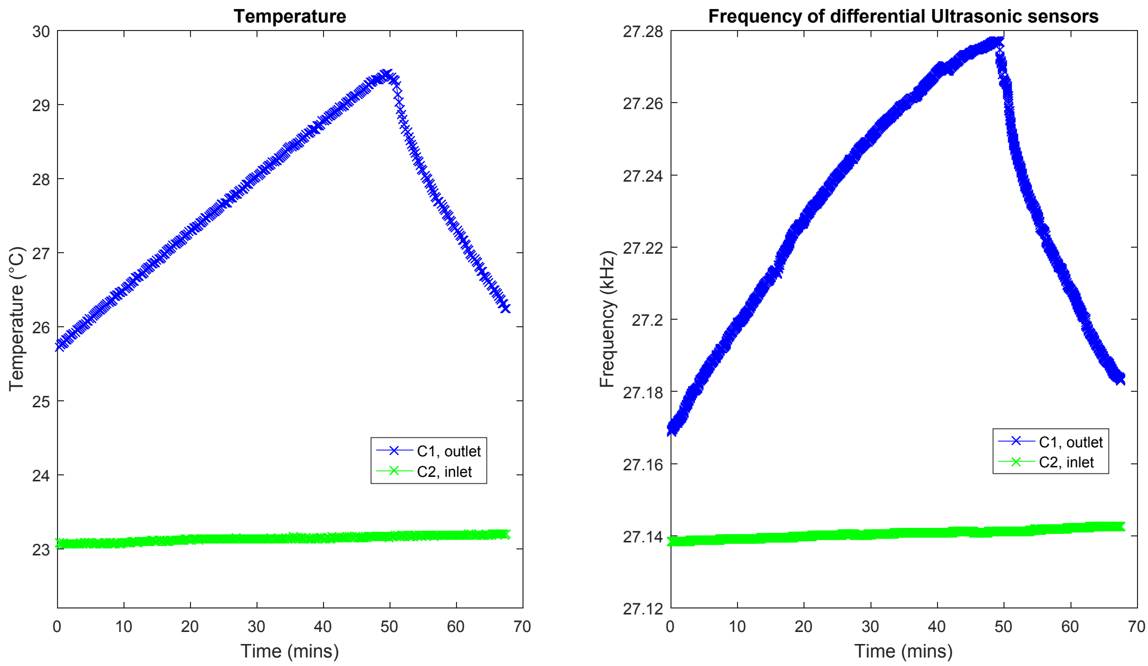

Fig. 6. Temperatures at the inlet (green) and outlet (blue) of the water heater, recorded using conventional temperature sensors (left) and corresponding output frequencies of oscillating ultrasonic sensors (right).

As can be seen from Fig. 6, the ultrasonic frequency recorded using the oscillating ultrasonic sensor closely followed the temperature measurements from the conventional sensor without any noticeable output frequency jumps for any of the chambers. The heater produced a temperature differential of about 4 K during the experiment; at the same time the output frequency changed by about 110 Hz, giving a sensitivity of about 27.5 Hz/K. As the coolant was not cooled to the environmental temperature, the water temperature, measured in chamber 1, increased by 0.15 K, resulting in the corresponding change of output frequency of the ultrasonic sensor of about 4 Hz, giving a similar sensitivity of 27 Hz/K.

Differential data were calculated by subtracting readings obtained in chamber 1 from those obtained in chamber 2 (Fig. 7).

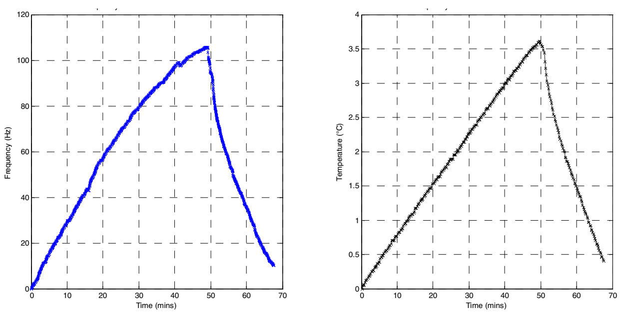

Fig. 7. Differential temperature using conventional sensors (left) and frequency responses versus time (right)

To measure power loss of a water-cooled electric motor, it was assumed that two motors have different responses. The first case P_1 was at the start of the experiment (t = 0 mins) where temperature is lowest and the second point P_2 where temperature is at the highest level (t = 50 mins). The power loss was calculated using (1). For the motor at the first point, the power loss can be calculated as:

$$P_1 = 4.181 \times 6 \times 2.64 = 66.2\ W$$

The power loss for the second motor (at the highest temperature) can be calculated as:

$$P_2 = 4.181 \times 6 \times 6.25 = 156.8\ W$$

C. Limitations of the ultrasonic oscillating sensor

A number of limitations were observed when operating the system with ultrasonic oscillating sensor architecture. One major limitation is frequency-temperature hysteresis which exists across piezoelectric materials. Previous research found that piezoelectric hysteresis is strongly linked to contamination redistribution, strain change, change in quartz, twinning, and oscillator circuit hysteresis [11, 12]. Some of these mechanisms are well understood and have been significantly reduced or eliminated.

There are some options that can be implemented to reduce hysteresis effect. These include employing data sensor fusion algorithms where readings from calibrated conventional temperature sensors correct ultrasonic frequency.

V. Conclusion

Ultrasonic frequency was successfully used to evaluate temperature difference with a resolution down to fractions of a kelvin—with significant improvements compared to evaluating temperature using conventional sensors. At the same time, this development was able to quickly and accurately determine average temperature across a complete ultrasonic pathway.

One potential application of this development is classification of water-cooled electric motors to specific international standards at the time of their manufacture. Further research will focus on correcting frequency-temperature hysteresis which occurs due to the peculiar nature of piezoelectric elements.

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