MEASUREMENT UNCERTAINTY OF WINDING TEMPERATURE RISE ON WASHING MACHINE HEATING-TEST

KETIDAKPASTIAN PENGUKURAN KENAIKAN SUHU LILITAN KUMPARAN MOTOR PADA UJI PEMANASAN MESIN CUCI

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ABSTRACT

Evaluation of measurement uncertainty in safety tests is critical for a testing laboratory, especially if many aspects influence the test results, such as in the washing machine heating test. While performing the heating test, the temperature rise of the motor winding was determined to evaluate the safety level of a washing machine. The temperature rise is obtained by the resistance method, which measures the change of winding resistance to assess its temperature rise. In this work, the washing machine was loaded at maximum capacity and supplied with hot water. All factors contributing to the measurement uncertainty originating from both the measurement system and the testing method are evaluated. The expanded uncertainty of the temperature rise measurement obtained in this study is 1.4%. This uncertainty is mainly contributed by the variance of test water temperature (0.54%), calibration uncertainty of RCL meter (0.43%), and calibration uncertainty of temperature logging system (DLS) (0.31%). Therefore, the heating test requires a tight temperature controller, an improved calibration uncertainty of the resistance meter, and a better accuracy of the temperature logger to reduce the measurement uncertainty.

Keywords: motor winding, measurement uncertainty, washing machine, heating test

ABSTRAK

Evaluasi ketidakpastian pengukuran dalam uji keselamatan sangat penting untuk laboratorium pengujian, terutama jika banyak aspek yang memengaruhi hasil pengujian, seperti pada pengujian pemanasan mesin cuci. Saat melakukan uji pemanasan, kenaikan suhu lilitan motor diukur untuk mengevaluasi tingkat keselamatan penggunaan mesin cuci. Kenaikan suhu diperoleh dengan metode resistansi, yang mengukur perubahan resistansi lilitan untuk menilai kenaikan suhunya. Dalam makalah ini, mesin cuci dibebani maksimum dan disuplai dengan *air panas. Semua faktor yang berkontribusi terhadap ketidakpastian pengukuran dievaluasi baik yang berasal dari sistem pengukuran maupun metode pengujian. Ketidakpastian terentang dari pengukuran kenaikan suhu yang diperoleh dalam penelitian ini adalah 1,4%. Ketidakpastian ini sebagian besar disumbangkan oleh varians suhu air uji (0,54%), ketidakpastian kalibrasi RCL meter (0,43%), dan ketidakpastian kalibrasi sistem pencatatan suhu (DLS) (0,31%). Oleh karena itu, uji pemanasan memerlukan pengontrol suhu air yang ketat, peningkatan ketidakpastian kalibrasi alat ukur resistansi, dan akurasi pencatat suhu yang lebih baik untuk mengurangi ketidakpastian pengukuran.*

Kata kunci: *lilitan motor, ketidakpastian pengukuran, mesin cuci, uji pemanasan*

1. INTRODUCTION

A motor is an essential part of the washing machine used to perform a rotation in cleaning and drying clothes. On a long operation, the motor's temperature can increase and burn electrical insulation of the windings. The temperature rise is limited by the maximum capability of the motor windings insulation to withstand voltage from becoming short-circuited.

To ensure the safety level of washing machines from electric shock and fire hazards, their motor windings insulation should function adequately as an electrical insulator at the maximum motor winding temperature rise when the washing machines are operated normally. The limits of temperature rise and winding-temperature-rise measurement method are described in general terms on the safety standard of household appliances IEC 60335-1. The maximum standard temperature rise for class E winding insulation is 90 K (IEC, 2016a). The winding temperature rise is defined indirectly by measuring the change of winding resistance. As a result, a variety of factors influence the temperature rise accuracy. The heating test method specified in the standard can also contribute to measurement uncertainty.

The measurement results are not complete without the estimation of measurement uncertainty. A great deal of effort has been made to identify the influence of the resistance method on temperature rise measurement of water pump motor winding. Beige found that the extrapolation curve gives the largest contribution to the total measurement uncertainty. He analyzed the uncertainty using 14 resistance data of one winding in the first 40 seconds after switching off the motor but did not calculate the sensitivity coefficient from each uncertainty source (Beges, 2011). Gnacinski investigated the effect of distorted voltage in temperature rise measurement using the resistance method on induction motor (Gnacinski, 2008). The uncertainty of measurement depends not only on the measurement method but also on the surrounding condition and testing procedure. The sensitivity coefficient is also necessary to be calculated because it describes how output value varies with the changes in the input values (Kirkup & Frenkel, 2006). Although the method of determining the temperature rise of the motor windings has been studied before, to the best of the author's knowledge, the measurement uncertainty analysis of that in the washing machine heating test based on IEC 60335-1 and IEC 60335-2-7 has never been done. Therefore, this paper discusses aspects that affect the measurement result and their uncertainty contribution to the measurement, especially type B uncertainties.

2. MATERIALS AND METHODS

2.1. Estimation of Measurement Uncertainty

The testing laboratory is required to have and implement a procedure for estimating the uncertainty of measurement (ISO, 2005). The laboratory should identify all the components that can contribute to the uncertainty of the measurement results and make a reasonable estimate of uncertainty. The uncertainty estimation method that has been agreed in general is based on the ISO Guide to the Expression of Uncertainty in Measurement (ISO GUM). ISO GUM provides a standard methodology in estimating the uncertainty, including determining the measuring scale models, identifying sources of uncertainty, quantification of the value of each uncertainty source, including standard uncertainty u_i, degrees of freedom v_i, and the sensitivity coefficient c_i. The following steps are calculating combined standard uncertainty, effective degrees of freedom, coverage factor, and expanded uncertainty (ISO, 2008). The parameters that can affect the uncertainty of the measurement results can be numerous. It depends on the complexity of the testing method, environmental influences, measuring equipment, and personnel.

The uncertainty contribution of each parameter on the measurement result has a different level. The influence level can be minimized by limiting the variability of parameters during testing. In the scope of electrical testing, the laboratory which is incorporated in the IECEE CB scheme shall use a voltage source with a variation of voltage of 2%, frequency of 0.5%, and max total harmonic distortion (THD) of 3% to minimize the contribution of the uncertainty of measurement from input voltage factor (IEC, 2007). Besides the voltage parameters, other parameters that could affect the measurement results also need to be controlled during the testing process.

The accuracy of measuring equipment is also confined to suppress uncertainty. Temperature measuring devices that work in the measurement range below 100° C are required to have an accuracy of 2° C, while the resistance measuring instrument by a measuring range 100 mΩ up to 1 MΩ must have an accuracy of 3% (IECEE, 2003)

Uncertainty can arise from the measurement method, for example, from the extrapolation process. The extra-polation of the regression equation determines the value of the target. The uncertainty of this source is estimated from the range of several extrapolation results (Beges, 2011).

2.2. Resistance Method for Measuring Temperature Rise

Temperature measurement can be per-formed using several methods, such as a thermocouple, infrared sensor, RTD, and resistance method. Since the windings are usually encased in a protective shell made of metal, it isn't easy to access the windings to attach the temperature sensor. Therefore, the resistance method is more appropriate to apply in the measurement of winding temperature rise. As an indirect measurement method, it gives a more complex measurement uncertainty. Beges have researched methods for measuring the resistance of the winding temperature rise. He concluded that extrapolation polynomial fit is used to measure temperature rise if the first measurement takes less than 20 seconds after the voltage is disconnected, with the measurement interval of 4 seconds and 40 measurement data (Beges, 2011). In comparison, Bakti stated that each winding resistance measurement in the induction motor produces a more accurate temperature rise value than the results of resistance measurements of a combination of both (Bakti & Firdaus, 2014).

Winding temperature rise can be calculated using equation [1].

$$\Delta t = \frac{R_2 - R_1}{R_1}(k + t_1) - (t_2 - t_1) \text{ .... [1]}$$

where Δt is the temperature rise of the winding (K), R_1 is the winding resistance at the beginning of the test (Ω), R_2 is the winding resistance at the end of the test (Ω), t_1 is the ambient temperature at the beginning of the test (°C), t_2 is the ambient temperature at the end of the test (°C), k = 234.5 for copper (°C), and k = 225 for aluminum (°C) (IEC, 2016a)

2.3. Heating Test Method

The heating test simulates the worst conditions during the normal operation of the washing machine. The heating test refers to the standard IEC 60335-1: 2016: Household and similar electrical appliances: Safety Part 1: General requirements and IEC 60335-2-7: 2016: Household and similar electrical appliances - Safety Part 2: Particular requirements for washing machines. The test sample used is a single tube washing machine with a washing capacity of 7.5 kg and without any heating system. The nominal voltage of the washing machine is (220-240) V, and nominal power is 350 W. Heating test is performed by operating the washing machine in normal operation as described below (IEC, 2016a; IEC, 2016b):

1. The temperature of the testing room is controlled at a temperature range (20 ± 5) °C. The washing machine is placed on a wooden board with a thickness of 20 mm.
2. The washing machine is supplied by a voltage that causes overheating the washing machine that is 254.4 V or 1.06 times the rated voltage.
3. Test clothes load the washing machine with a dry mass equal to the nominal capacity stated in the instructions and then filled with water thoroughly. For washing machines without heating elements, the temperature test water used in the test is (65 ± 5) °C.
4. Washing machines are run for three cycles using a program that produces the highest temperature rise, with four-minute rest intervals in between. For single tube washing machines that serve washing and water extraction, each cycle consists of washing operation followed by water extraction.
5. Winding temperature rise is determined by the resistance method at the end of the last cycle before the control system stops the motor.

3. RESULTS AND DISCUSSION

Each step in the procedure may contribute to the measurement uncertainty of motor windings' temperature rise. Components of measurement uncertainty can be identified through the analysis of the test procedure and the measurement models.

3.1. The Initial Temperature of Test Room (t_1)

Room temperature was measured by a K-type thermocouple connected to a data logging system DLS Fluke 2686A. The thermocouple is placed inside a plastic tube with a diameter of 5 cm and 25 cm long with holes at both ends to avoid any momentary temperature fluctuations due to convection hot air coming from the hot water system or cool air from the air conditioner. When the initial room temperature was measured, the measurement uncertainty could arise from the calibration uncertainty of the Data Logging System (DLS). The calibration certificate stated that the calibration uncertainty of DLS for temperature measurement in the range of (0-200) °C is 0.2 °C with a 95% confidence level. Besides the calibration certificate, uncertainty could arise from the readability of the DLS. DLS has a 0.1 °C digital resolution. Therefore, it contributes uncertainty of 0.05 °C.

The sensitivity coefficient for the uncertainty from initial temperature measurement is obtained from the first differential equation [1] partially to t_1 as equation [2].

$$c_{t_1} = \frac{\partial \Delta t}{\partial t_1} = \frac{R_2}{R_1} \quad \text{.........................} \quad [2]$$

3.2. Measurement of Initial Resistance (R_1)

The main motor windings resistance was measured using a Fluke RCL meter PM6306 with measurement circuit is shown in Fig 1. The drain motor only has one winding.

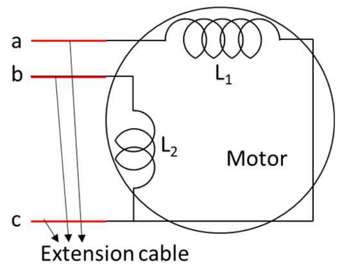


Figure 1. The initial resistance measurement circuit for winding L1 and L2

L1 initial resistance winding was measured at a point a-c while winding L2 at point b-c by using an extension cable. The extension cable was added to make easier access to the measurement points. The extension cable's resistance was subtracted from the initial resistance measured to get the corrected result.

The uncertainty of the initial resistance measurement primarily originated from the calibration certificate and the resolution of the RCL meter. The calibration uncertainty provided standard uncertainty of 0.11% of reading, and the readability added standard uncertainty of 0.0005 Ω derived from 0.001 Ω resolution.

As described in Fig. 1, the use of extension cable also generated uncertainty due to the changes in ambient temperature. The effect of temperature on the cable resistance can be analyzed by employing the equation $R = R_0 (1 + \alpha \Delta t)$, with R_0 was the resistance of the cable on the initial temperature t_1, α was a constant resistivity copper material, which is 3.93×10^{-3}/ °C, and Δt was the difference between the initial and final temperatures (Waygood, 2013).

Correction for the measurement of the cable resistance R_2 is equal to 0.390× (1 +3.93×10^{-3}×1.53) = 0.392 Ω. The difference between cable resistance correction values at the beginning and the end is (0392 - 0390) = 0.002 Ω. Changes in ambient temperature and the contact resistance between the RCL-meter probes and the extension cable might generate uncertainty in extension cable resistance. Contact resistance was minimized by clamping on the probe tip to the cable. Semi-range of estimated error considered as uncertainty contribution that was 0.001 Ω. Because the extension cable contributes a small portion to the measurement uncertainty, therefore, it is negligible.

The sensitivity coefficient for the initial resistance uncertainty (R_1) is acquired from the first differential equation [1] partially to R_1 as Equation [3].

$$c_{R_1} = \frac{\partial \Delta t}{\partial R_1} = -\frac{R_2}{R_1^2}(k + t_1) \text{ .... [3]}$$

3.3.Final Resistance Measurement (R_2)

Many aspects need to be considered to estimate the uncertainty of determining R_2, including the test method. The washing machine should be run for three cycles under normal operating conditions before the motor winding resistance was measured. The test input voltage was 254.5 V, which is the most unfavorable voltage that may significantly influence the winding temperature rise. A voltage regulator supplied the voltage to maintain voltage stability not more than 0.2%. Uncertainty derived from the voltage fluctuations is ignored due to less than 2%.

In the normal operation cycle, the washing machine is loaded with standard clothes and hot water. The water temperature should be maintained between 60 °C to 70 °C. To provide the hot water, the heating system was set to 65 °C and varied by ±5 °C. The variability of water temperature potentially contributed to the uncertainty of measurement of final resistance R_2 because the hot water might influence the air temperature surrounding the motor. Test the water temperature would heat the room inside the washing machine. An increase in air temperature in the motor chamber will increase the motor temperature by convection. The rise of motor temperature had indirectly increased the winding resistance. Special experiments were prepared to investigate errors from *t* water temperature. The washing machine was loaded with cloth and hot water at different temperatures of 60 ºC and 70 ºC. The change in winding resistance during the experiment was recorded. Water with a temperature of 60 °C was added to the tube together with the test clothes. During this loading, the winding temperature was monitored until it reached a steady-state condition. The same procedure was repeated but with a water temperature of 70°C. The measurement results of the water temperature test are shown in Table 1.

Uncertainty of test water temperature was estimated from the difference between winding resistances with 70 °C water temperature and 60 °C. Table 1 indicates that the maximum test resistance difference between both is 0.1362 Ω. Therefore, half of the error range, i.e., 0.068 Ω, was regarded as an uncertainty contribution from the test water temperature. Error distribution assumed for this error was following the rectangular distribution.

Table 1. Comparison of winding resistance for the two different water temperature

No	Winding resistance , *R* (Ω)		
	With water temp 60 °C a	With water temp. 70 °C b	Resistance Difference b–a
1	29.645	29.781	0.136
2	29.642	29.781	0.139
3	29.646	29.782	0.136
4	29.647	29.783	0.136
5	29.654	29.789	0.135
6	29.649	29.785	0.136
7	29.658	29.791	0.133
8	29.642	29.781	0.139
9	29.644	29.779	0.135
10	29.651	29.788	0.137
$\bar{R}$	29.648	29.784	0.136

At the last operating cycle of the washing machine and before it changed into standby condition (i.e., before the extraction operation was completed), the connection of the voltage source was released, and resistance measurement was conducted immediately. Final resistance measurements for all windings were taken alternatively with the same instrument.

When the voltage source was released, the timer was started. Time measurement was done by a calibrated stopwatch. Ideally, the resistance measurement was done when the motor was still working. However, the existing measurement system could only be utilized when there was no voltage, thus winding resistance measurements were carried out as soon as possible after the voltage connection to the washing machine was disconnected. Three windings shall be measured at the end of the test simultaneously, namely the drain motor winding and two windings of the washer/extractor motor (main motor). An essential step before starting the measurement is to transfer the initially connected circuit to a voltage source to be connected to the measurement system. Due to manual operation, the transfer process required 35 seconds to complete. This condition simulated the actual testing process. The resistance measurement began 36 seconds after disconnecting from the supply. The resistance measurement was done by turns between the three winding with an average switching time interval of 7 seconds. This time interval included the transfer time of the probe one to another position and the waiting time of the automatic scale selection of the LCR meter.

Resistance data of each winding plotted against time to obtain a deriving function in resistance against time. The desired resistance value was the resistance at t = 0. So, the resistance value was determined using a regression equation for extrapolating the result. The regression equation was formed using the least-squares method. Inserting t = 0 into the regression equation yielded the final resistance value. Extrapolation errors were estimated by two approaches. The first is by calculating the difference between predicted outcomes of some regression equations at t = 0. The second is by computing the standard error of regression when used to extrapolate a value that was estimated from its residual standard deviation of regression. The residual standard deviation can be evaluated by equation [4] (Stone, 2013).

$$S_E = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{\nu}} \qquad \text{[4]}$$

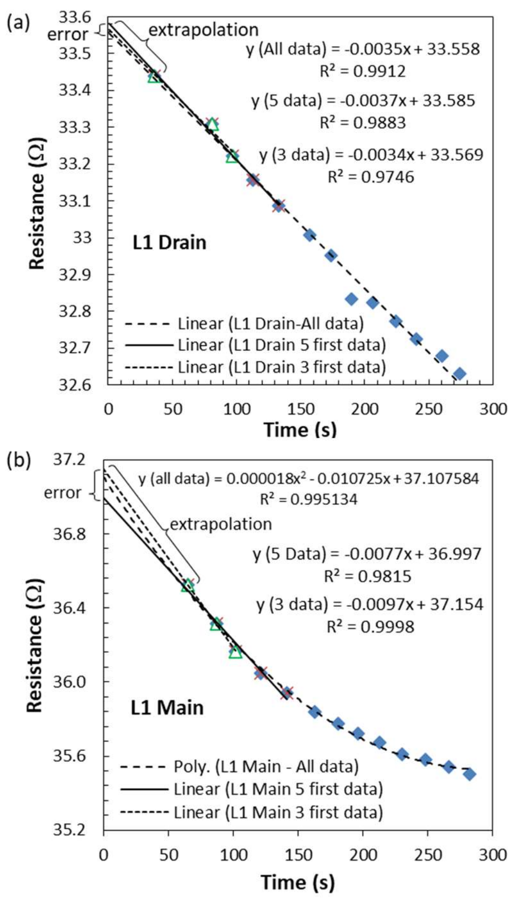
y_i : actual measurement data of resistance

$\hat{y}_i$: true value of resistance estimated from the regression equation

ν : degree of freedom = $n - k$, with n number of data, and k number of parameters estimated from the regression equation.

The extrapolation error was firstly estimated from the distribution of the resistances at zero seconds predicted by several possible extrapolation-lines (Beges, 2011). The extrapolation lines were extended from three regression lines generated from all of the measurement data, the first five measurement data, and the first three measurement data. The extrapolation lines were drawn in Figure 2 for each winding. Every extrapolation line predicted a different R_2 value. A collection of entire R_2 values produces an error range as indicated in Figure 2. The deviation of the error range contributes to measurement uncertainty due to extrapolation. Fig.2 (a) shows that the winding resistance of the drain motor changes linearly while those of the main motor, in Fig. 2 (b) and Fig. 2 (c) quadratically changes because they have different winding enclosure design. Unlike the main motor that has a ventilated winding enclosure, the drain motor winding is entirely enclosed in the metal enclosure that prevents air from directly influencing the change in winding temperature. Furthermore, the drain motor operates only for a short period compared to the main motor resulting in a smaller increase in winding resistance. The ventilated enclosure in the main motor is intended to prevent the motor from burning due to heat accumulation (Lu, et al., 2016).

R_2 final resistance was obtained by inserting x = 0 in the equation regression equation. R_2 resistance calculation results are presented in Table 2. The measurement uncertainty was estimated from the experimental standard deviation of final resistance R_2 obtained from the extrapolation. The probability distribution function for the extrapolation error was assumed to be a rectangular shape. Another possible source of measurement uncertainty caused by extrapolation is derived from the curve fitting technique.



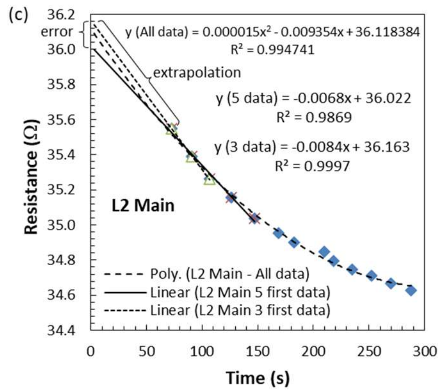


Figure 2. Prediction of the final resistance by extrapolation of the three different regression curves. Error at t=0 contributes a measurement uncertainty due to extrapolation for (a) drain motor winding, (b) first winding of main motor (L1), and (c) second winding of main motor (L2). The equation indicates in each figure corresponds to the regression equation generated from the measurement data.

Table 2. Comparison of final resistance R_2 obtained from several extrapolations.

Extrapolated from	Final Resistance R_2 (Ω) of		
	Drain motor winding	Main motor winding L1	Main motor winding L2
Regression of all data	33.558	37.108	36.118
Regression of the first 5 data	33.585	36.997	36.022
Regression of the first 3 data	33.569	37.154	36.163
Standard deviation	0.0136	0.0807	0.0720
Measurement uncertainty	0.0078	0.047	0.042

The measurement uncertainty can be estimated by calculating the residual standard deviation using equation [4]. The calculation results are shown in Table 3.

The final resistance R_2 changed with time after the motor was disconnected from the mains supply. We recorded the time corresponding to the decrease in resistance. The measurement of time may confer R_2 measurement uncertainty. The uncertainty can be estimated from calibration uncertainty and different time between the termination of the voltage source and the starting of the stopwatch.

The uncertainty of the calibration certificate was 0.62 seconds, and the uncertainty of the delay of start measuring the winding resistance was estimated at 1 second. The sensitivity coefficient for the uncertainty component derived from the time measurement c_T is determined by multiplying the rate of change in resistance with time $c_{T\text{-}R2}$ and the sensitivity coefficient of R_2. It was estimated from the first derivative of the regression function based on the first 5 data of R_2 resistance measurements. The rate of change $c_{T\text{-}R2}$ obtained for drain motor winding, L1 of main motor winding, L2 of main motor winding are –0.0037, –0.0097, and –0.0084 respectively, corresponding to sensitivity coefficient of –0.033, –0.085, and –0.076.

Based on the testing steps above, the source of measurement uncertainty R_2 can be derived from the calibration certificate of the RCL meter, RCL meter reading, extrapolation errors, and time recording. The sensitivity coefficient for the final resistance (R_2) was obtained from the first differential of equation [1] partially to R_2 as equation [5].

$$c_{R_2} = \frac{\partial \Delta t}{\partial R_2} = \frac{1}{R_1}(\mathrm{k} + t_1) \quad \text{................. [5]}$$

3.4.The Final Room Temperature (t_2)

During the test, the test room temperature was monitored and controlled. Temperature recording is done automatically using the Data Logging System Fluke 2686A DLS. The room temperature to be used in the winding temperature rise calculation was the temperature when the final resistance measurement began. Uncertainty of the final room temperature measurement came from DLS calibration certificate and DLS readability. Both were the same as the uncertainty of initial temperature measurement.

Table 3. Calculation of residual standard deviation (S_E) to estimate measurement uncertainty due to the curve fitting

Winding	Number of Data	Regression Equation	Sum Square of Residual	Degree of freedom	S_E (Ω)
Drain	13	$R_2 = -0.003485t + 33.557911$	0.0069	11	0.084
L1 Main	13	$R_2 = 0.000018t^2 - 0.010725t + 37.107584$	0.0059	10	0.026
L2 Main	13	$R_2 = 0.000015t^2 - 0.009354t + 36.118384$	0.0053	10	0.025

The sensitivity coefficient for the uncertainty of final room temperature (t_2) was obtained from the first differential Equation [1] partially to t_2 as equation [6].

$$c_{R_2} = \frac{\partial \Delta t}{\partial t_2} = -1 \quad \text{..........................[6]}$$

The method of determining degrees of freedom (v) differs depending on the type of uncertainty. For the B type uncertainty, scientific judgment based on a pool of available data is used to determine the degree of freedom. One can define the degree of freedom of the calibration certificate from the information of coverage factor and the confidence level. Statistically, assuming that the t-student distribution approach is applied at the 95% confidence level, the degrees of freedom for the coverage factor of 1.96, 1.98, and 2.0 are ~ (infinity), 120, and 60. The degrees of freedom of the equipment readability, extrapolation method, and water temperature variation are estimated from equation [7] (ISO, 2008).

$$v_i = 0.5 \times u_{rel}^{-2} \quad \text{............... [7]}$$

where u_{rel} is the relative uncertainty of type B components. The evaluators determine the u_{rel} value based on their experience and knowledge about the equipment's reliability and the method's accuracy. Digital equipment used in this research, such as the RCL meter and the Data Logging System, are considered reliable and have a 0% probability of going out of the semi-range error, thus from equation [7], the degrees of freedom of the equipment readability are infinite. In the same way, the degree of freedom of the extrapolation and the water variation's uncertainties are 50 because the uncertainties were judged to be reliable only 90% or have 10% relative uncertainty. Components of measurement uncertainty are summarized in the uncertainty budget, as shown in Table 4.

Table 4 shows that the expanded uncertainty of this measurement is 0.9 K. Temperature rise measured Δt_{rep}, for the drain winding, was 64.3 K so that the relative uncertainty is 0.9/64.3 = 0.014 or

Table 4. Uncertainty budget of winding temperature rise of washing machine motor (drain motor) for heating test

Index	Component	Unit	Probability Distribution	Error Estimation	Divisor	v_i	c_i	u_i
	Initial room temperature t_1							
uB1	Cal. certificate DLS 2686A	°C	Normal	0.2	1.98	120	1.1	0.10
uB2	Readability DLS 2686A	°C	Rectangular	0.05	1.73	~	1.1	0.029
	Final room temperature t_2							
uB3	Cal. certificate DLS 2686A	°C	Normal	0.2	1.98	120	-1.0	0.10
uB4	Readability DLS 2686A	°C	Rectangular	0.05	1.73	~	-1.0	0.029
	Initial winding resistance R_1							
uB5	Cal. certificate RCL Meter	Ω	Normal	0.032	2	60	-10	0.016
uB6	Readability RCL Meter	Ω	Rectangular	0.00005	1.73	~	-10	0.000029
uB7	Extension cable resistance	Ω	Rectangular	0.001	1.73	~	-10	0.00058
	Final winding resistance R_2							
uB8	Cal. certificate RCL Meter	Ω	Normal	0.027	2	60	8.8	0.013
uB9	Readability RCL Meter	Ω	Rectangular	0.00005	1.73	~	8.8	0.000029
uB10a	Extrapolation error	Ω	Rectangular	0.02	1.73	50	8.8	0.012
uB10b	Residual standard deviation due to curve fitting	Ω	Rectangular	0.0069	11	11	8.8	0.00054
uB11	Variation of water test temperature	Ω	Rectangular	0.068	1.73	50	8.8	0.039
uB12	Extension cable resistance	Ω	Rectangular	0.001	1.73	~	8.8	0.00058
uB13	Cal. certificate Stopwatch	s	Normal	0.62	2	~	−0.033	0.31
uB14	Delay time to start measuring	s	Rectangular	0.0	1.73	60	−0.033	0.58
	Combined standard uncertainty, u_c, in K						0.44	
	Effective degree of freedom, v_{eff}						125	
	Coverage factor with v_{eff} & CL 95%, k						1.98	
	Expanded uncertainty, $U = k.u_c$, in K						0.9	

1.4 %. Based on the equipment accuracy limit, temperature measurement shall have accuracy of 2 °C or 3% in this case (Bakti & Firdaus, 2014). This means that the method meets the requirement. The uncertainty contribution, $u_{ratio,}$ is the ratio between the total $u_i c_i$ and the reported temperature rise in percent units. For example, "Time measurement" consists of two uncertainty components, uB13 and uB14 (see Table 4). The sum of the $u_i c_i$ of both is 0.00115 + 0.00214 = 00329.

If the value of the reported temperature increase, Δt_{rep}, is 64.3 K, then the u_{ratio} is calculated by applying equation [8]:

$$u_{ratio} = \Sigma u_i c_i / \Delta t_{rep} \text{ x } 100\% \text{ ....[8]}$$

From equation [8], u_{ratio} of time measurement becomes 0.0329/64.3×100% = 0.01%. Calculation results of uncertainty contribution for all influential factors are summarized in Table 5.

Table 5. Comparison of uncertainty contribution

Influenced Factor	Component	$\Sigma u_i c_i$	Uncertainty contribution ($\Sigma u_i c_i / \Delta t_{rep}$ x 100%)
Readability RCL meter	uB6, uB9	0.0005	0.00
Time measurement	uB13, uB14	0.0033	0.01
Cable extension resistance	uB7, uB12	0.0109	0.02
Readability DLS	uB2, uB4	0.0577	0.09
Extrapolation	uB10	0.1018	0.16
Cal. certificate DLS	uB1, uB3	0.2000	0.31
Cal. certificate RCL meter	uB5, uB8	0.2780	0.43
Water temperature variance	uB11	0.3460	0.54

Beges, in his study about winding temperature rise measurement, concluded that the most significant factor in total measurement uncertainty came from the extrapolation process (Beges, 2011). In contrast, based on our study as described in Table 4 and Table 5, extrapolation is not the dominant factor in the uncertainty of temperature rise measurement on the washing machine heating test. We found that three factors affect the uncertainty significantly; first, the variation of water temperature; second, calibration uncertainty of RCL meter; third, calibration uncertainty of DLS. We use longer time to collect data (for 300 s) than the previous study, which used only 40 seconds. The longer duration to record data, the more accurate temperature characteristic can be obtained.

4. CONCLUSION

This paper describes in detail about uncertainty analysis of temperature rise measurement on the motor winding when conducting a heating test for washing machines based on IEC 60335-1 and IEC 6035-2-7. The expanded uncertainty obtained from the measurement is 0.9 K which equivalent to a relative uncertainty of 1.4 %, representing the measurement system's accuracy. The factors that predominately influence the measurement uncertainty are the variation of the test water temperature, the calibration certificate of the RCL meter, and the accuracy of the ambient temperature recorder with relative uncertainty contribution of 0.54%, 0.43%, and 0.41%, respectively. Therefore, we must pay more attention to control the variation of water temperature during the heating test to improve the measurement uncertainty. Furthermore, using better accuracy of temperature logging system to measure the ambient temperature will also considerably reduce the combined uncertainty of the temperature rise measurement. It should be concluded that the resistance method can be implemented to measure the temperature rise of three windings simultaneously with an accuracy below the maximum accuracy limit for this case.

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