Effect of palm oil temperature on thermal losses of PTC sensor designed for overfill protection using current-voltage characteristic

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Abstract. Characteristic of positive temperature coefficient (PTC) sensor can be described using current-voltage curve which depends on thermal properties of medium. The PTC sensor for overfilling protection designed for palm oil (CPO) container cannot identify the medium liquid with high temperature and high viscosity due to the overlapping of current voltage curve. For this case, a signal of worst-case alarm is generated. This paper presents the effect of CPO temperature on thermal losses of the PTC sensor represented by thermal resistance factor between the sensor and the medium surrounding it. A type of EPCOS B59050D1100 PTC sensor was characterized in two mediums; CPO and still air, to simulate “full” and “empty” status. The sensor response was then observed through the current-voltage curve at different temperature from 300 K to 360 K. The thermal resistance were then obtained from the modeling of current voltage curve, resulting the values of 125 K/W for CPO and 343 K/W for still air with 63.5% in difference between both mediums. Using proposed two points method, the effect of medium temperature on thermal resistance can be eliminated and reduced, where the Rw variation is less than 3.15% for palm oil and 4.5% for still air. This result is within the normal operation tolerance below 5% and can be used safely to determine the status whether the sensor is in still air or in palm oil medium.

1. Introduction
The palm plantations in Indonesia are mostly 70% located on the island of Sumatra and result the large number of oil palm factories operating in the region. Fresh processed Crude Palm Oil (CPO) has high temperatures and is stored in giant containers before shipping. Level sensor for CPO detection system in the tank is needed to determine contain of the tank and also to prevent the overfilling of CPO in the process of filling, which causes environmental pollution. Level measurements control the filling process using the pump automatically, where the measured material can be gaseous, liquid or solid.

The method for level measurement of liquids in the tank can be divided into continuous and non-continuous monitoring. Santhosh [1] and Reverter [2] have developed a continuous level measurement system of liquid in the tank based on capacitive sensor. Two electrodes are installed in the tank so that the liquid level can be detected based on the capacitance value of the material between the two electrodes. Techniques like these are very expensive and have low responses [3]. A wide-range sensor levels using fiber-optic Fabry-Perot interferometers that allow for high sensitivity measurements was developed using Bragg fiber-optic lattices with fluid variations [4, 5]. These measurements provide
very precise results for continuous fluid measurements but have a high price [6]. The research presented by Zixiao et al. [7] has designed sensors that work using a single mode laser ring in determining fluid levels while Vismanath et al. [8] used ultrasonic method.

Thermistor sensor with Positive Temperature Coefficients (PTC) is designed as safety industrial instrument for overfilling protection of the CPO in tanks to prevent from overfilling. The detection is evaluated by the altering of power dissipation with respect to the changes of the thermal losses of the medium surrounding it. An encapsulated sensor at the bottom of the probe detect the liquid surface, an actuator is closed which switches off the pump and stops the filling process.

Current PTC sensor for overfilling protection tank measures their resistance as a function of the medium temperature. In self-heated mode, the properties of an electrically loaded PTC sensor are well described by the current-voltage model which depends on thermal losses between the sensor and the medium surrounding it. Previous work in [9] reported that the sensor status "immersed" and "not immersed" in liquid with high temperature cannot be properly recognized status; two incorrect states are encountered: false alarm and worst case.

Crude palm oil has high viscosity and temperature; therefore it can shift significantly the current-voltage characteristic of PTC sensor with conventional method. This problem is solved through modeling of the current-voltage (I-U) characteristic and direct measurement of the thermal losses represented by thermal resistance independent of the medium temperature. In this paper we presented the effect of CPO temperature on the stability of the thermal resistance using modeling of I(U)-curve and new method based on two points measurement to eliminate the effect of temperature.

2. Experimental Methods

2.1. Overfill Protection Sensor for Palm Oil Container

The palm oil processing produce vegetable oil in the form of crude palm oil (CPO), obtained from the results of fruit meat extraction (Mesocarp). Palm oil is semi solid, this is because the oil has a high melting point of 25°C to 60°C [10]. Temperature 25°C is the standard temperature measurement method that also describes the condition of room temperature, while the temperature 60°C is the temperature of the tank filling process and the drainage of CPO in the pipe [11, 12]. Chemical composition, structure, moisture content and binding of the water, temperature and thermal history of the material are the key factors affecting thermo-physical properties of food materials. The application of overflow sensor for palm oil is shown in figure 1.

![Figure 1. Overfill protection sensor with PTC sensor for CPO container.](image)

Due to self-heating mode, the sensor temperature ($T_S$) is much higher than CPO temperature ($T_M$), so that the heat transfer to the environment is depend on thermal losses between sensor element and filling medium, represented by thermal resistance ($R_W$). In practical applications, the sensor characteristic can be explained by the equation (1) [13, 14].
\[ R = R_{T0}e^{B\left(\frac{T_c-T_s}{T_s}\right)} + R_0 \]  

(1)

where \( R_{T0} \) is the sensor resistance at temperature \( T_0 \), \( R_0 \) is the unloaded resistance, \( T_c \) is Curie temperature, \( T_s \) is temperature sensor and \( B \) is the temperature coefficient of the sensor.

Heat transfer from the PTC sensor to the surrounding medium can be explained by mechanism of heat conduction and convection. For conduction, the relationship between a heat transfer, spatial temperature gradient \( \frac{\partial \vartheta}{\partial n} \) in a spatial direction \( n \) of time frame \( \Delta t \) is described by the Fourier Law of Heat Transport [15].

\[ \dot{j}_q = -\lambda \frac{\partial \vartheta}{\partial n} = -\lambda \cdot \text{grad} \vartheta \]  

(2)

The constant \( \lambda \) is the material-dependent proportionality constant of Fourier's law whereby the density of the energy-transferring molecules in still air remain low so that the thermal conductivity is particularly low. If the sensor is considered as a cylinder with single layers, then the heat transport of the sensor is expressed as equation (3).

\[ \dot{Q} = \frac{2\pi \cdot L \cdot \lambda}{\ln \left(\frac{r_2}{r_1}\right)} \cdot (T_1 - T_2) \]  

(3)

The relationship between the thermal resistance \( R_w \) of the sensor in the measuring substance that depends on the value of the thermal conductivity and the heat transfer coefficient \( \alpha_w \), the surface area \( A \) of the sensor can be explained in (4) [16].

\[ R_w = \frac{1}{\alpha_w \cdot A} \]  

(4)

Various filling substances with different heat transfer coefficient have specific \( R_w \), which can be used as the sensor status within medium.

2.2. Sensor Characterization

Characterization sequence of the PTC sensor has been integrated using microcontroller based circuit with a preprogrammed digital to analog converter (DAC) served constant current, as shown in figure 2. An EPCOS B59050D1100 PTC sensor immersed in CPO samples was then tested in self-heating mode by providing a programmable voltage ranging from 0 V to 30 V. Effect of CPO temperature variation was measured by heating the palm oil sample in the Heraus Oven T6060 to keep the sample temperature stable.

**Figure 2.** Data acquisition circuit for sensor characterization consist of digital to analog converter, signal processing circuit and analog to digital converter.

When current flows through the PTC-thermistor, the sensor will heat up and transfer the thermal energy to the medium. Heat transfer mechanism depends not only on the load applied, but also on the
thermal losses between sensor and medium, represented by $R_W$ factor. The condition of equilibrium state of the electrical power and the delivered thermal output can be written as equation (5) [9].

$$U_T^2 \cdot \left[ R_{T0} e^\left( \frac{T - T_C}{R_T} \right) + R_0 \right]^{-1} = (T - T_M) \cdot R_W^{-1} \tag{5}$$

In the experiment, the EPCOS sensor with dimensions of 25mm long and 2.8mm diameter was modified with an encapsulated housing made of brass served as mounting to the tank wall. Figure 3 shows the sensors dimension and the housing.

**Figure 3.** Sensor housing and mounting.

### 2.3. Modeling of I(U) Curve and Two-Points Method

Sensor parameters $R_{T0}$, $R_T$, $T_C$, $B$, $T_S$ and thermal resistance $R_W$ in equation (5) are obtained simultaneously by modeling I(U)-curve using Jacobi Matrix method, where the determinant function must not be equal to zero [11].

$$FD( x_1, x_2, \ldots, x_n ) = \begin{vmatrix} \frac{\partial g_1}{\partial x_1} & \ldots & \frac{\partial g_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_n}{\partial x_1} & \ldots & \frac{\partial g_n}{\partial x_n} \end{vmatrix} \neq 0 \tag{6}$$

The estimated values are selected as initial values for the unknown sensor parameters and also thermal resistance, changed iteratively until an optimum of the quality function is completed. The calculation process use least-square-method, where the result is an estimate of the unknown coefficients of the model.

$$S = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{7}$$

where $n$ is the number of data points.

Since $R_W$ is obviously used for the sensor status “immersed” or “not immersed” in liquid, it is expected to be constant and not affected by CPO temperature. An algorithm was developed to eliminate the medium temperature using two-points measurements on the I(U)-curve, $(U_1; I_1)$, $(U_2; I_2)$ resulting $R_1$ and $R_2$, respectively. Using this data and predetermined sensor parameters, the $R_W$ can be calculated directly derived from equations (5-7).

$$R_W = (T_{S1} - T_{S2}) \left[ \left( \frac{U_1^2}{R_1} \right) + \left( \frac{U_2^2}{R_2} \right) \right]^{-1} \tag{8}$$
where

\[ T_{S1} = \frac{T_C}{\ln \left( \frac{R_1 - R_0}{R_{T0}} \right)} \quad \text{and} \quad T_{S2} = \frac{T_C}{\ln \left( \frac{R_2 - R_0}{R_{T0}} \right)} \]  

(9)

\( T_{S1} \) and \( T_{S2} \) are refers to the sensor temperatures at the measured points, as shown in figure 4.

**Figure 4.** Isotherm curve with 2-points method for direct \( R_w \) determination.

3. Results and Discussion

Figure 5(a) shows \( I(U) \) characteristic of the EPCOS PTC sensors immersed in CPO with medium temperatures varying from 300 K to 360 K. At the initial applied voltage up to 5 V, the curve step increase linearly in an ohmic region and reach maximum at the Curie point, followed by a decrease exponentially of current consumption. High temperature of CPO will decrease current consumption, since the sensor does not require much power to attain the thermal equilibrium.

**Figure 5.** The variation of \( I(U) \) curve of the PTC sensor influenced by CPO temperature from 303 K to 357 K in (a) and the \( R_w \) value changes about 35% from initial temperature at 300 K (b).

Table 1 shows the results of the \( I(U) \) modeling which described the nature of the sensor for a long period of operation. The obtained sensor parameters are then stored as history and used for two-point
algorithm to determine the thermal resistance value without having to measure the overall curve \( I(U) \) and independent of the medium temperature.

**Table 1.** Sensor parameters obtained from modeling of the \( I(U) \)-curve.

| No  | Sensor Parameters | \( R_{T_0} \) | 23.0\( \Omega \) |
|-----|-------------------|--------------|----------------|
| 1   | Sensor resistance at temperature \( T_0 \) | \( R_{T_0} \) | 23.0\( \Omega \) |
| 2   | Unloaded resistance | \( R_0 \) | 18.0\( \Omega \) |
| 3   | Temperature coefficient | \( B \) | 80.0 |
| 4   | Curie temperature | \( T_C \) | 380.2K |
| 5   | Medium temperature | \( T_M \) | 300K to 360K |

From figure 5(b) and table 1 is shown that the CPO has a good conductance properties. When the oil temperature rise, the heated palm oil will degrade into polar material and the chemical property varies during heating. As a consequence, the heat properties will change in the form of \( R_W \) parameter. Heating mechanism will also encourage a reaction of free fatty acids and lead to the formation of a new substance that will change the thermal properties of the CPO [17]. Calculated \( R_W \) as shown in figure 5(b) was unstable due to CPO temperatures and results decreasing of \( R_W \) from 110.2 K/W to 72.1 K/W or about 34.65%. This result cannot be accepted to determine the sensor status, since the thermal resistance range is out of normal tolerance within 5%.

To overcome this problem, the application of the two-points method is proposed to minimize the changing of \( R_W \) value due to medium temperature. Figure 6 shows the results using two-point measurement method.

![Figure 6. Two points method for thermal resistance measurement results a tolerance below 5% for each filling mediums and 63.5% difference between CPO and still air.](image)

**Figure 6.** Two points method for thermal resistance measurement results a tolerance below 5% for each filling mediums and 63.5% difference between CPO and still air.

Detection algorithm can be used to reject the temperature influence on the measurement. Results showed only a small deviation of the \( R_W \) observed for each medium; for CPO, \( R_W \) varies from 127 K/W to 123 K/W with 3.15% and for still air, from 351 K/W to 335 K/W or 4.5% deviation. Since the calculated thermal resistance between the mediums was relative high about 63.5% in the difference, this range is able to avoid the overlapping status “full” or “empty”.

From this results, the sensors can decide filling medium within normal tolerance below 5%, and about 63.5% between both CPO and still air. This can be programmed in the microcontroller for the application and to determine the status whether the sensor is in still air or in palm oil.
4. Conclusion
Thermal resistance of PTC sensor used for level sensor application shows the unstable parameter due to high medium temperature. This $R_W$ and sensor parameters are obtained from modeling of $I(U)$ curve simultaneously and shows 34.65% difference in accordance with CPO temperature variation. Using two-points method of $I(U)$ curve measurement, a relatively stable $R_W$ value with low instabilities about 3.15% for CPO and 4.5% for still air was produced, whereas the difference between CPO and air can be achieved up to 63.5%. This stable parameter can be safely used as a determinant of status sensors for the filling process of the CPO containers.

Acknowledgement
The research was funded by the University's Research Funded UR 2017.

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