Heat Distribution Analysis of a Thick Film Transcutaneous Gas Sensor

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Abstract: - The partial pressure of oxygen and carbon dioxide in the arterial blood is an important factor for doctors to determine the respiratory conditions of patients. Transcutaneous blood gas monitoring is a popular non-invasive measurement technique for obtaining fast and relatively accurate responses. In this investigation, thick film technology was employed to develop a blood gas system based on an amperometric sensor which consists of a heating module to elevate the temperature at the skin surface to transcutaneous levels. The heating module included a heating element and its temperature was regulated by a temperature control circuit. Using an infrared camera, the transient and steady-state temperature distribution of the heating element was analyzed. A three-dimensional theoretical model was also established to evaluate the temperature response of the sensor and subsequently compared with the results of the practical prototype. Based on the analysis and development, future heating modules for transcutaneous sensors could be generated more easily, hence effectively improving the design stages.

Key-Words: - Thick film, transcutaneous, blood gas, sensor, heating element, temperature distribution, transient, steady-state

1 Introduction

Healthcare and medical services have always played important roles in part and parcel of daily lives. In order to understand and determine the medical status of patients, different parameters throughout the human body were measured and analyzed. On such important medical parameter is the measurement of blood gas levels in the arterial blood. This is essential for doctors to monitor the respiratory conditions of patients, in particular the preterm neonates who are undergoing surgery or experiencing respiratory difficulties.

Transcutaneous blood gas measurement, introduced in the early 1970s [1] is a popular, non-invasive technique that allows on-going, continuous monitoring features. For this measurement, the surface of the skin must be in the specific temperature range within the sensing area [2]. This temperature must be high enough to obtain recordable results, but at the same time it has to be sufficiently low so as not to burn or damage the skin. This critical temperature, at which the skin will be damaged, varies for different individuals and it also depends on the position at which the sensor is placed on the human body. In general, this critical temperature is found to be approximately 46°C [3].

Thick film technology [4] is one technique that allows high volumes of production with high repeatability and at low cost. The manufacture of sensors using this technology is found suitable and is adopted commonly in many industries. Hence, thick film technology was employed to develop the transcutaneous blood gas sensor. In this paper, the focus is concentrated on the temperature distribution on the surface of the sensor in order to determine its effects on the overall performance. The main objective is to study the heat distribution on the sensor substrate. A temperature control circuit was designed in order to provide the required controlled temperature for the transcutaneous measurement.

A theoretical simulation of the heat distribution was performed using the ANSYS software based on finite element method (FEM). The results were then compared to the experimental observations for a more comprehensive investigation. The results could be used in future prototypes to achieve low cost sensor design solutions.

2 Sensor Design

The complete blood gas sensor consisted of two main parts, namely the heater and gas sensor modules [5, 6]. In this paper, the heater module is the main topic of investigation.

To fabricate the heater module, terminal pads for soldering connection were made from silver-palladium (AgPd) ink while the heating element was made of platinum (Pt) ink. Pt exhibits interesting characteristics such as high temperature coefficient of resistance (TCR). It is also a stable material which can be exposed to a variety of environments
at high temperatures without degradation. The temperature characteristic of Cermet Pt used is linear within required temperature range with TCR of 3500 ± 200 ppm/K [7].

The thick film process began by printing each layer using a unique screen that contained the desired template layout. This was followed by the drying and firing processes to bind the ink onto the substrate which in this case was alumina (96% Al₂O₃). The heating element meander area is shown in Fig. 1.

3 Experiment

3.1 Equipment and Procedure
Experiments were carried out with the infrared (IR) camera DeltaTherm and supporting software DeltaVision. The DeltaTherm camera is mainly used for thermal stress analysis but can be also applied in other applications [8]. It contains a 128 by 128 array of indium-antimony (InSb) detecting elements.

The temperature distribution was measured on both sides of the substrate, the front and the back. The front was defined as the side where the heating element was printed and therefore it was supposed that the overall maximum temperature should be found on this side. The temperature distribution of each side of the substrate was measured on separate occasions under the same operating conditions in order to obtain comparable results.

3.2 Experimental Results
Fig. 2 shows the temperature distribution over the heated area after one minute of operation. It is noted that each change of shade in the contour plots represents a temperature change of 0.5 °C within the region. As shown in Fig. 2, the area of the heater is indicated by the white rectangular outline (8.8mm by 8mm) and a grid is included for better graphical comparison of the images. The highest temperature occurred approximately at the middle part of the heating element along the x-axis. The back of the substrate also indicated a more uniform concentric distribution of the heated region. The overall temperature range for both the front and back of the substrates were the same. It was also important to note that heat was transferred through the alumina substrate readily at the transient stage of operation.

It was found from further experiments of the measurements with IR camera, the state after five minutes could be depicted as a stable response given that the temperature control circuit was set to regulate at an unchanged temperature. This generalization was acceptable as the images taken after ten or twenty minutes later remained relatively unchanged as compared to the five minutes effect, seen in Fig. 3. Similar observations were found on both the transient and steady-state distributions. A slight imbalance of non-symmetry in Fig. 3(a) could be caused by low-speed airflow from the left side during the measurement. Despite these inaccuracies, it can be assumed that the temperature distribution was similar on both sides of the substrate in the stable state.
4 Theoretical Model

4.1 Definition

In general, there are three heat transfer mechanisms that describe heat flow away from a heat source across a certain structure: conduction, convection and radiation.

Heat conduction is defined as the transfer of the heat through a solid when a temperature difference exists across the solid. Fourier’s law of heat conduction states that the heat flux is proportional to the temperature gradient in the specified direction \( n \).

The law is given by

\[
q_n = k \cdot \frac{\partial T}{\partial n}
\]

where \( q_n \) is the magnitude of the heat flux in the \( n \) direction (W/m²), \( k \) is thermal conductivity of material (W/m·K) and \( T \) is the temperature (K).

Heat convection is the transfer of energy in the form of heat from a bounding surface to a fluid and defines the heat exchange conditions at the boundary of the solid body. Depending upon the cause of the fluid motion, a distinction is made between a free or natural convection and a forced convection [9]. Newton’s law of cooling expressed the heat flux from solid surface to a fluid by

\[
q = h \cdot A \cdot (T_w - T_a)
\]

where \( q \) is heat transfer rate (W), \( h \) is the film coefficient (W/m²·K), \( T_w \) is wall temperature (K) and \( T_a \) is the free stream temperature (K).

Radiation is the transfer of thermal energy by electromagnetic waves. The wavelengths of radiated waves can range from the long infrared to short ultraviolet, depending on the temperature of the body [10]. Stefan-Boltzmann law of radiation describes this heat flow transfer as

\[
q_i = \sigma \cdot A_i \cdot (T_i^4 - T_j^4)
\]

where \( q_i \) is the heat transfer rate from surface \( i \) (W), \( \sigma \) is the Stefan-Boltzmann constant (W/m²·K⁴), \( \epsilon_i \) is the effective emissivity, \( A_i \) is the area of surface \( i \) (m²) and \( T_i, T_j \) are absolute temperatures at surface \( i \) and surface \( j \), respectively (K).

Using Eqns 2 and 3 as well as suitable coefficient values, the heat transfer rates were calculated for the investigated samples. It was found that heat transfer rate for convection was approximately ten times larger than that for radiation. In this investigation, heat radiation was neglected because the effect on the temperature within the heated area at 45 °C was considerably small. Thus, it was acceptable to assume that the heat transfer was dominated by conduction and convection.

4.2 Numerical Model

Numerical solution in ANSYS heat flow analysis is based on the first law of thermodynamics [11]. This law is used for describing the heat conduction and convection with different boundary conditions applied during the evaluation. The formulation of natural convection equations follows the same basic principles that govern general fluid motion. Further simplifications must be done to provide the solution [12] which results in the governing equation for isotropic material in terms of rectangular coordinates

\[
\rho \cdot C_p \left( \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = q_{gen} + k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

where \( v \) is velocity of mass transport of the heat, \( \rho \) is the density of the solid, \( C_p \) is the specific heat, \( q_{gen} \) is
heat generation rate per unit volume, \( k \) is thermal conductivity, \( T \) is temperature and \( t \) is time.

The ANSYS model was meshed before applying any load. This is an important step in analysis as finer meshing results in more accurate solutions, but it demands more computational time for the solution. The meshed model of the heated area is shown in Fig. 4.

![Fig.4 Meshed Model](image)

A heat generation load was applied to the heating element model. The initial load was obtained from using the resultant values evaluated from the power measured in prior experiments as shown in Fig. 5. It was important to assume that the effective volume of the heating element was the same as that of the model.

![Fig.5 Measured Power to Heating Element for First Minute](image)

The second stage of applying loads on the model was the heat convection from the substrate to the surrounding air. Heat convection was characterized by the film coefficient and the bulk temperature of ambient air. The film coefficient depends on the physical geometry and the fluid thermo-physical properties. Typical values for air natural flow are in the range of 2 to 30 W/m\(^2\).K [12]. Due to numerous random variables which influenced convection, it was essential to simplify the considerations. With that, several film coefficient values were used in the model. It was found that the most suitable value for the film coefficient was 15 W/m\(^2\).K. The bulk temperature of ambient air in the model was set at the average room temperature of 22 °C.

### 4.3 Theoretical Results

The transient analysis showed the heat transfer over the sensor with respect to time. It was necessary to perform this analysis to verify that the critical temperature of the model was not exceeded on the substrate upon the stabilization of the heat distribution. The maximum temperature was stabilized approximately after the first minute and therefore it was adequate to carry out the modeling for this period.

![Fig.6 Transient Analysis after (a) 5 s, (b) 30 s](image)

Applying the initial heat generation load as determined from Fig. 5, the transient responses after 5 s and 30 s of operation are illustrated in Fig. 6. It can be seen that the maximum temperature of 44.955 °C begins at the middle region of the heating element (in the x-axis direction). The change in shade generally depicts 1 °C change in temperature. After 30 s, the area around the heating element reached required transcutaneous levels.

![Fig.7 Steady-state Analysis](image)
The steady-state analysis was also carried out. A constant supply of power load was applied to the heating element. The value of 0.272 W was determined from averaging the experimental results. Hence, the corresponding heat generation of 1.045x10^9 W/m^3 was applied. The graphical result of the steady-state analysis is presented in Fig. 7.

5 Discussion

5.1 Compare Experimental and Theoretical Results

Several heaters were fabricated and measured with the IR camera. The experimental results were compared with the theoretical mathematical model of the sensor. The aim was to validate the model of temperature distribution and to establish the kind of ANSYS analysis that would be ideal for comparison between theoretical design and practical application.

The transient analysis is shown in Fig. 8 with each shade representing a variation of 0.5 °C and 1 °C for the experimental and theoretical results respectively. It was noted that the temperature distribution in the designated sensing area was uneven although the heating element pattern was relatively uniform. The rate of the temperature change was lowest in the area on the upper edge of the heating element. Further away from the heated area near the contact pads, the rate of temperature change increased and this suggested that the area would not be suitable for blood gas measurements which required a stable transcutaneous temperature.

As seen from the images in Fig. 9, the steady-state temperature distribution obtained from the modeling and experiments are similar. The temperature distributions were also comparable to that of the transient analysis (in Fig. 8). Although there were distinct differences in the magnitude of temperatures denoted by the different shades, the characteristic of the temperature distributions followed similar trends. Therefore, the ANSYS analysis can be employed effectively for the modeling of the temperature distribution and analysis of the temperature uniformity on the substrate.

5.2 Analysis of the Results

The modeled substrate was designed with the same dimensions as that of the real substrate. The properties of the material used were practical values from the manufacturer’s specifications. However, due to estimations and simplifications, differences between the mathematical model and the real sensor, such as the film coefficient values, were present. Several assumptions had to be made during the design process of the model. Firstly, as illustrated in Fig. 10, the cross-section of the thick film heating element is not a basic geometrical shape, apparently to some extend it is hemispherical.

The thickness of the element was not constant and it was difficult to achieve the actual model of its shape. Hence, a simple rectangle was used instead as shown in Fig. 11. This simplification could have caused the differences between the theoretical and theoretical results. The inaccuracies in the heat generation would subsequently emerge.
The effect of overlapping contacts design between two thick film lines was another important assumption, as described in Fig. 12. For the thermal representation, it was possible to estimate that the area with two overlying layers has almost the same properties for heat transfer as that of a single layer at the same position. All assumptions have been used in order to simplify the design of the model. Subsequently, a faster and simpler mathematical solution was reached.

6 Conclusion

The transient and steady-state temperature distributions of the heater module of the transcutaneous gas sensor were evaluated experimentally and theoretically.

From the experiments, it was found that the distribution was not uniform in the middle of the heating element. The optimum position for transcutaneous measurement was at the top edge of the heating element. The maximum temperature on the substrate was measured and evaluated to be approximately 46 °C. The theoretical temperature distribution obtained from the model gave relatively good representation of the actual physical heating element. Although different maximum temperatures were observed, the distribution trends were comparable for both the experimental result and model. Simplifications had been carried out during the development of the model. Supported with the measurements made from the IR camera, the errors due to assumptions were minimized for the ANSYS model. Therefore in conclusion, the model proved to be useful for creating new heater designs.

References: