Finite Element Analysis for Temperature Compensation of ITO Conductive Film System

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Abstract: Indium tin oxide (ITO) heating film is primarily used as the defogging component of an instrument observation window. Conventionally, a constant current is used to heat the film. Through the feedback of the temperature sensing component, the output current is adjusted to achieve a set temperature. However, the temperature of the heating film is nonuniformly distributed, and determining the correct output current is time-consuming. This study adopted finite element heat transfer analysis to determine a heating method (such as heat power and heat flux) for an ITO conductive heating film system. The results of the analysis may serve as a reference for temperature compensation in ITO conductive heating films.

Key words: ITO film heater, heat transfer analysis, heat power, heat flux.

1. Introduction

Condensation may accumulate on the system observation windows of biomedical instrument testing systems because of temperature differences in and outside the system. Consequently, timed video recorders may be obscured by condensation and cannot take clear images. Chuang [1] used a thermal imager to observe the temperature increase process of heating film being heated to determine the power per unit area, system ambient temperature, and heat dissipation conditions of the heating film. The results serve as reference for determining appropriate locations for installing temperature-sensing components on the basis of temperature balance and distribution of heating films. Because Chuang's experiment was easily affected by environmental factors and because preparing for the experiment was time-consuming, the experiment was costly. Therefore, this study adopted finite element heat transfer analysis to determine a heating method (such as heat power and heat flux) for an indium tin oxide (ITO) conductive heating film.

The results were compared with those of the temperature balance identified in heating film experiments. Finally, an appropriate temperature compensation value for the temperature sensing element was established.

2. ITO Conductive Film

ITO is a mixed oxide of 90% In_2O_3 and 10% SnO_2. The most commonly used material has a composition of ca. In_4Sn. ITO thin film is a highly degenerate n-type semiconductor which has a low electrical resistivity of $2\sim4\times10^{-4}\,\Omega \cdot cm$. The low resistivity value of ITO films has relatively high electrical conductivity [2].

Conductive films with a high visible light transmittance are called transparent conductive films. The characteristics of these films are a transmittance of 60% or higher and a surface resistance of 10^{10} Ω·cm or lower [3]. Depending on the material, transparent conductive films consist of metal film, semiconductor oxide film [4, 5], nano line [6, 7], and graphene [8]. Among conductive films, the most widely applied are those made through ITO sputtering on PET film base material (ITO films) [9]. ITO films
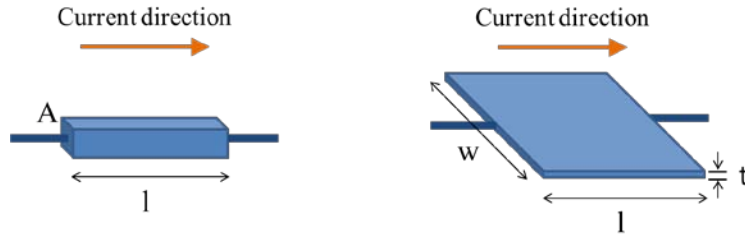
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Fig. 1   Calculating resistance [1].

have a transmittance of 80% or higher in the visible light range. They are applied in products such as windshields, optical lenses, and automotive electronics for heating and defogging. The followings introduce the characteristics of ITO films.

2.1 Resistance Characteristics of Conductive Film

Fig. 1 depicts a heating material component. Its resistance R is proportional to resistivity ρ and length l and is inversely proportional to cross-sectional area A, as presented in Eq. (1):

Resistance

$$R = \rho \frac{l}{A} \qquad (1)$$

$A = w \times t$, where w is width and t is thickness.

$$\text{resistance } R = \rho \frac{l}{A} = \rho \frac{l}{tw} \qquad (2)$$

When a material has uniform thickness, Eq. (2) can be rewritten as follows:

$$\text{resistance } R = \rho \frac{l}{tw} = R_s \frac{l}{w} \qquad (3)$$

where R_s is surface resistivity, whose unit is Ω/m^2. Length l is the distance between the positive and negative electrodes of the ITO heating film, and width w is the length of the electrode of the ITO heating film.

The R_s of ITO film is primarily related to the sputtering process and material thickness. The R_s of ITO films from the same processing batch are a constant. In addition, ITO heating films made with materials of the same specifications have a resistivity that is directly proportional to the length-width ratio of a cut ITO film.

2.2 Temperature Increase Characteristics of Conductive Film

To increase the temperature of ITO heating film, a fixed electric power source is supplied to the film. After a period of time, the temperature of the heated film reaches equilibrium. The temperature equilibrium of an ITO film heater is affected by the unit area power of the film, the ambient temperature of the system, and the heat dissipation conditions. A higher unit area power of the heating film leads to higher temperature equilibrium of the system. Likewise, a high system ambient temperature or poor heat dissipation conditions results in higher the temperature equilibrium.

$$\text{unit area power} = \frac{\text{electric power}}{\text{area of the ITO conductive film}} \qquad (4)$$

3. Finite Element Analysis

This study adopted the finite element analysis software Solid Works Simulation to conduct ITO film structure heat transmission analysis. The following sections introduce the design of the ITO film finite element analysis.

3.1 Conductive Film Model

The structural geometric model of the ITO conductive film comprises two components, namely (a) ITO film unit and (b) the ITO film system (glass on top of ITO film; Fig. 2). Material characteristics and thermal parameters are listed in Table 1.

3.2 Condition Settings for Thermal Conduction Simulation of Conductive Film

When simulating the heating methods for the ITO

conductive heating film system, the heat source input was divided into heat power (W) and heat flux (W/cm^2) on the bottom of the ITO conductive film. The ITO conductive film was cooled to room temperature. The natural convection coefficient of the remaining surfaces to the air was set to 5-25 W/(m$^2\times$K). The temperature of the testing environment was set to 27 °C (Fig. 3).

(a) ITO filmunit   (b) ITO film system
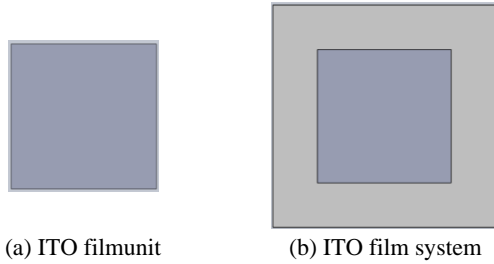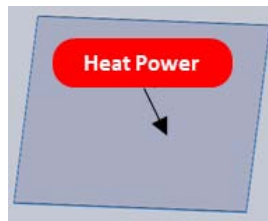
Fig. 2   Geometric model of ITO film components.

Table 1   ITO film and glass material parameters.

Material Name	PET	Glass
Density (kg/m^3)	1,420	2,458
Thermal conductivity (W/m·K)	0.261	0.749
Specific heat (J/kg·K)	1,140	834.6
Specifications(L/W/H, mm)	120×120×0.4	160×160×2.0

(a) Heat source input

(b) Natural convection coefficient

Fig. 3   Settings for the thermal conduction simulation.

4. Results and Discussion

Analysis of the thermal conduction of the ITO film was conducted by examining the methods for setting the heat flux and heat power of the single ITO film and the ITO film system.

4.1 ITO Thin Film Temperature Measurement Results

Chuang [1] used fixed current as the power source for an ITO heating film system (l = 120 mm, w = 120 mm). The resistivity of the current system was 41.35 Ω, and the working current was 0.5 A. Therefore, the electric power was 10.34 W. A fixed current was provided by the heating system as the power source, and the temperature of the heating film increased from room temperature until reaching an equilibrium. During the heating process, an FLIR C3 thermal imager was used to record the temperature of the heating film. In the experiment, the heating film temperature was sampled at 49 points. The samples were numbered, as presented in Fig. 4. Temperature data 5 mm from the edge were used for comparison during finite element analysis. Tables 2 and 3 indicate that the temperature measurement scope of the single ITO film and the ITO film system were 55-56 °C and 49-50 °C, respectively.
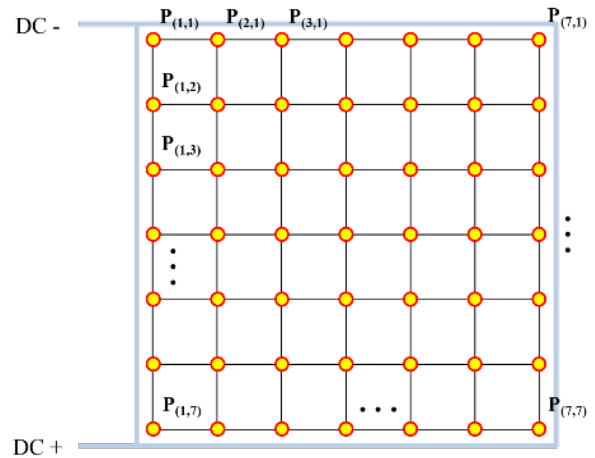

Fig. 4   Location distribution of temperature sampling points.

Table 2   ITO film temperature measurement results [1].

				0.5A			
	MAX	MIN	MAX - MIN		AVG_insid	AVG_all	
	58.9	47.3	11.5		57.1	55.4	
	A1	A2	A3	A4	A5	A6	A7
B1	47.3	49.7	51.1	51.9	51.8	51.7	50.4
B2	51.5	54.7	55.6	56.9	57.8	58.2	55.8
B3	51.8	55.0	55.7	57.2	58.2	58.9	56.3
B4	52.2	55.5	56.3	57.4	58.3	58.1	55.9
B5	53.3	56.5	57.0	57.1	58.0	58.0	55.3
B6	53.8	57.5	57.8	57.4	57.6	57.8	55.1
B7	52.6	56.7	57.0	56.8	57.3	57.6	54.6

Table 3 ITO film system temperature measurement results [1].

|	A1	A2	A3	A4	A5	A6	A7
	0.5A						
	MAX	MIN	MAX - MIN		AVG_insid	AVG_all	
	55.88354	39.76657	16.1		53.17231	50.33578	
B1	39.8	44.3	45.6	46.8	47.5	47.4	44.0
B2	44.1	49.6	51.5	53.1	53.9	53.6	49.2
B3	45.1	50.3	52.2	54.6	55.7	55.9	50.5
B4	45.5	50.2	51.8	54.1	55.2	55.2	50.7
B5	46.1	50.9	52.1	53.4	54.4	54.4	50.5
B6	46.6	52.0	53.1	53.5	54.0	54.4	50.4
B7	43.6	48.8	50.2	50.5	51.0	51.5	47.5

4.2 Heat Power Analysis Results

Fig. 5 presents the results of the heat power analysis of the ITO film with a heat power of 10 W and a natural convection coefficient of 6 W/(m²×K). Fig. 5a indicates that the temperatures at the center and edge of the single ITO film were 165 °C and 597 °C, respectively. The temperature distribution was inconsistent with the actual measured temperatures. In the ITO film system, the temperatures at the center and edge of the glass were 75 °C and 72 °C, respectively, which were also inconsistent with the actual measured temperatures (Fig. 5b). With this heat flux setting method, excessive thermal energy was input in the ITO film,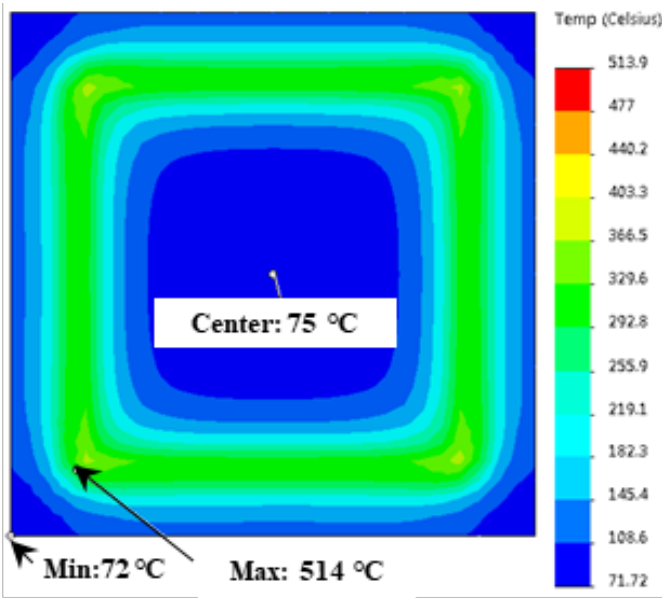 resulting in an excessively high temperature and an unreasonable distribution. Subsequently, heat flux was used to analyze the ITO film thermal input.

4.3 Heat Flux Analysis Results

For ITO film thermal input, a heat flux of 345 W/m² and a natural convection coefficient of 6 W/(m²×K) was selected, the results of which are presented in Fig. 6. Fig. 6a indicates that the temperatures observed at the single ITO film observation points were between 55 and 56 °C, which was consistent with the experimental temperature. The surface temperatures at the center and edge of the ITO film were 59 °C and 42 °C, respectively. In addition, the temperatures at the ITO film system observation points were 49 °C, which was the same as the temperature measured during the experiment. The temperature of the glass center was approximately 56 °C, whereas the temperature at the edge decreased to 28-29 °C (Fig. 6b). Therefore, using heat flux as the ITO film thermal input could produce a more reasonable temperature distribution result, which may serve as reference for future temperature compensation experiments.
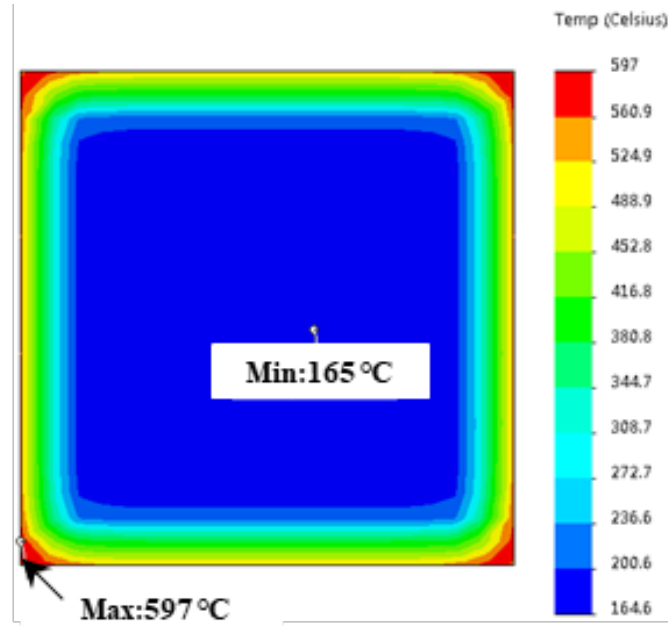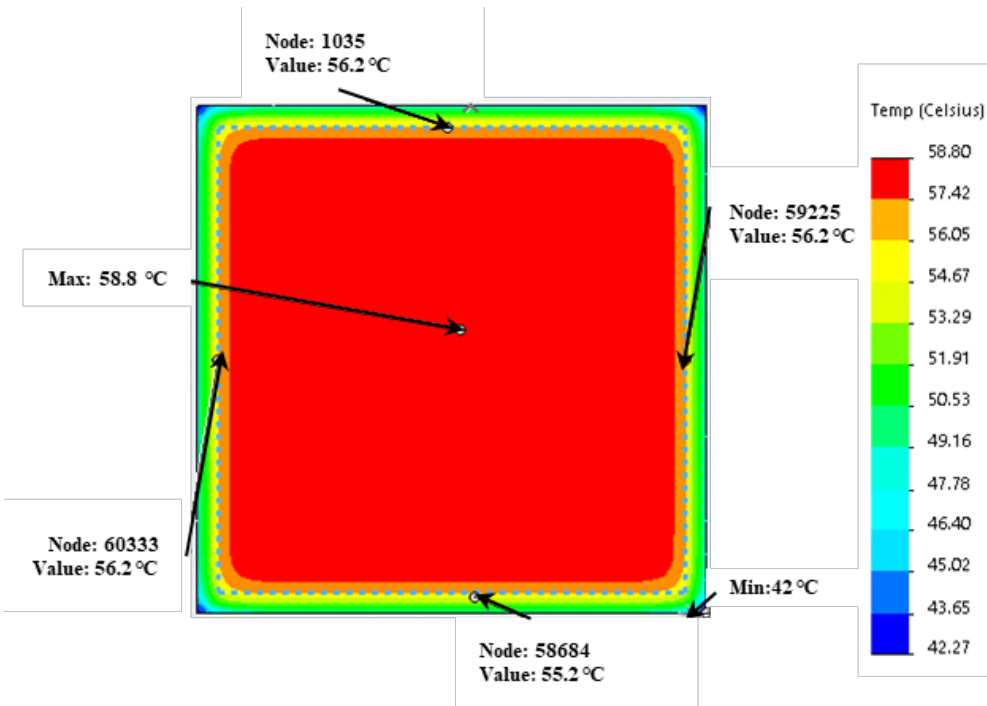

(a) ITO film

(b) ITO film system

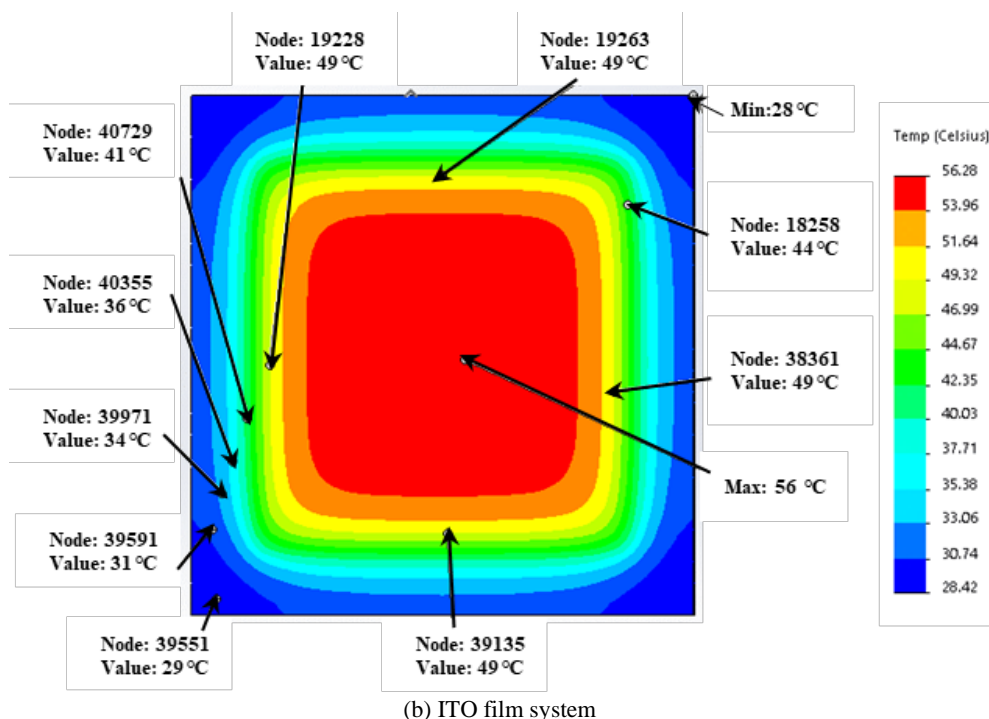**Fig. 5 Heat power analysis results.**

(a) ITO film

(b) ITO film system

Fig. 6   Heat flux analysis results.

5. Conclusion

This study used finite element thermal conduction analysis to determine an effective method for heating ITO conductive heating films (i.e., heat power or heat flux). The results revealed that when using heat power to analyze ITO film thermal input, excessive thermal energy was input, resulting in an excessively high temperature and an unreasonable temperature distribution. By contrast, using heat flux as the thermal input source for ITO film resulted in relatively reasonable overall temperature distribution. Compared with experimental temperature measurements, the temperature distribution measurements of the current study were the same. On the basis of these results, an effective temperature compensation analysis method for ITO conductive heating film was established.

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