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# Temperature Uniformity of the Glass Panel Heated in the Infrared Heating Chamber

**Kong Hoon Lee*, Ook Joong Kim**
*Energy System Research Center, Korea Institute of Machinery and Materials, 171 Jang-dong, Yuseong-gu, Daejeon 305-343, Korea*

An analysis has been carried out to investigate the effect of the reflectivity on the temperature distribution of a glass panel by infrared radiant heating. Halogen lamps are used to heat the panel, located near the top and bottom of the rectangular chamber. The thermal energy is transferred from the lamps to the panel only by radiation and it is considered by using view factor. The conductive transfer is limited inside the panel. The results show that the uniformity of the temperature distribution of the panel is improved and, at the same time, the time for heating increases as the wall reflectivity increases. The temperature difference between the center and the corner reaches a maximum in the early stage of the heating process and then decreases until it reaches a uniform steady-state value.

**Key Words:** Infrared Heating, Temperature Uniformity, Plasma Display Panel (PDP)

## Nomenclature

$A$ : Area of a radiating surface ($m^2$)
$\mathbf{A}$ : Vector form of areas ($m^2$)
$c_p$ : Specific heat (J/kgK)
diag : Diagonal matrix
$\mathbf{E}$ : Vector form of emissive powers ($W/m^2$)
$F_{ij}$ : View factor between two surface elements $A_i$ and $A_j$
$\mathbf{F}$ : Matrix form of view factors
$G$ : irradiation ($W/m^2$)
$\mathbf{G}$ : Vector form of irradiations ($W/m^2$)
$i, j$ : Indices indicating surface elements
$\mathbf{I}$ : Unit matrix
$J$ : Radiosity ($W/m^2$)
$\mathbf{J}$ : Vector form of radiosities ($W/m^2$)
$q$ : Heat transfer rate (W)
$\mathbf{q}$ : Vector form of heat transfer rates (W)
$T$ : Temperature (K or ℃)
$\mathbf{T}$ : Vector composed of temperatures (K)
$V$ : Volume ($m^3$)

**Greek Letters**

$\varepsilon$ : emissivity
$\boldsymbol{\varepsilon}$ : Vector composed of emissivities
$\rho$ : Density ($kg/m^3$), reflectivity
$\sigma$ : Stefan-Boltzmann constant ($\sigma = 5.6696 \times 10^{-8} W/m^2K^4$)

**Subscripts**

cond : conduction
rad : radiation

**Superscripts**

$n$ : Number of time steps

* Corresponding Author,
**E-mail** : konghoon@kimm.re.kr
**TEL** : +82-42-868-7291; **FAX** : +82-42-868-7335
Energy System Research Center, Korea Institute of Machinery and Materials, 171 Jang-dong, Yuseong-gu, Daejeon 305-343, Korea. (Manuscript **Received** April 1, 2005; **Revised** September 9, 2005)

## 1. Introduction

In the fabrication process of flat panel displays (FPD) such as LCD (Liquid Crystal Display) and PDP (Plasma Display Panel), a glass panel is exposed to several heat treatment process such as drying, baking for the coating dielectric and protective layers, and forming of electrode and barrier ribs. FPD is more expensive than CRT (Cathode Ray Tube) but has the merits of small thickness, light weight, large display area, low power consumption, etc. The performance of LCD and PDP is gradually improved and they will be the alternatives of CRT (Kiura, 2003).

The fabrication process of a PDP requires baking, vacuum pumping, and sealing under relatively high temperature in comparison to the LCD process. Improvement for such high temperature processes is necessary. Since heat treatment by the current convection oven is stable but needs long process time, it is very important to reduce the process time for the curtailment of the production cost (Ha et al., 2002).

In order to develop a technique to reduce the process time for the heat treatment, a few researches have been carried out to introduce the Rapid Thermal Processing (RTP) into the PDP process (Ha et al., 2002 ; Kim et al., 2001 ; 2002). The preferential problem that will be resolved to use the RTP in the PDP process is to improve the temperature uniformity of the heated glass panel since the large temperature difference occurring in the panel results in large thermal stress and fracture or deformation of the panel. Besides, uniform heating of the panel is needed to improve the performance of sealing and to remove the impurities as $H_2$, $O_2$, $CO$, $CO_2$ and $N_2$ contained inside the barrier ribs and phosphor layers by the vacuum pumping.

When a semitransparent material such as glass is heated by thermal radiation, heat transfer mechanism differs from that for an opaque material. Part of the radiation energy incident on the glass is absorbed and reflected on the surface, part is absorbed inside the glass, and the rest is transmitted through the glass layer (Viskanta and Anderson, 1975 ; Modest, 1993 ; Lee and Viskanta, 1998). For example, soda-lime glass is semitransparent to radiation in the range of wavelength less than 5 $\mu m$ but opaque in the other range (Viskanta and Anderson, 1975). In the present work, the glass panel is assumed to be opaque considering that the thickness of the panel is relatively thin in comparison to the size of the system and both barrier ribs and phosphor layers between the two sheets of the glass panel shield the radiation.

The present work has been carried out to develop a technique for uniform heating and temperature measurement as a part of the research to develop a vacuum sealing furnace for the PDP in the Korea Institute of Machinery and Materials (Kim et al., 2001 : 2002). The object is to investigate the characteristics for the radiant heating of the panel and the variation of the panel temperature. The primary parameter of analysis in this work is the wall reflectivity and its effect on the temperature distribution of the panel has been investigated.

## 2. Analysis

### 2.1 Model chamber

The model chamber is a cube of 340 mm length with wall thickness of 20 mm. The glass panel is composed of two sheets of soda-lime glass and is lying on the center of the chamber shown in Fig. 1. Each glass is 200 mm square and 2.8 mm thick. Twelve halogen lamps are used to heat the panel as the radiant heaters are installed 40 mm away from the top and bottom of the chamber (six lamps on each wall). Length of each lamp is 300 mm and the tube diameter is 10 mm.

### 2.2 Heat transfer model

The thermal energy is assumed to be transferred only by radiation through the space between the

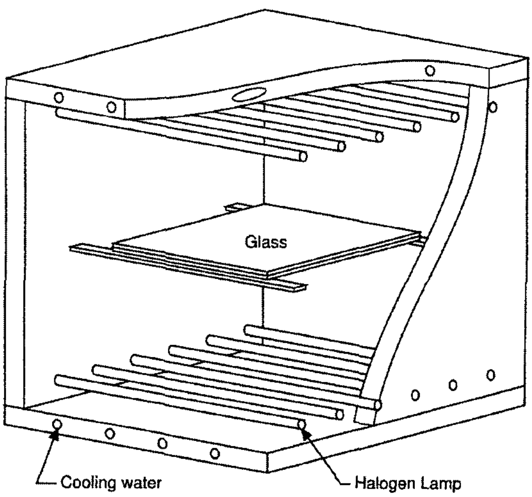


**Fig. 1** Schematic of the model chamber

heaters and the panel and only by conduction inside the panel. All the surfaces are assumed to be diffuse and gray and then the radiation exchange is considered by using view factor. With these assumptions, the radiation exchange can be evaluated with view factors, irradiation, and radiosity.

The heat transfer rate leaving the surface element $i$ is equal to the difference between the radiosity and irradiation and the energy balance on each surface can be written as

$$q_i + G_i A_i - J_i A_i = 0 \tag{1}$$

where the radiosity from the surface $i$ can be expressed as

$$J_i A_i = E_i A_i + \rho_i G_i A_i \tag{2}$$

The irradiation on the surface $i$ can be calculated from radiosities from all surfaces in the enclosure and view factors.

$$G_i A_i = \sum_{j=1}^{N} F_{ji} J_j A_j = A_i \sum_{j=1}^{N} F_{ij} j_j \tag{3}$$

The heat transfer rate, radiosity and irradiation can be expressed in terms of vectors and matrices for convenience of calculation.

$$\mathbf{q}_{\mathrm{rad}} = \mathrm{diag}(\mathbf{A})\,\mathbf{J} - \mathrm{diag}(\mathbf{A})\,\mathbf{G} \tag{4}$$

$$\mathrm{diag}(\mathbf{A})\,\mathbf{J} = \mathrm{diag}(\mathbf{A})\,\mathbf{E} - (\mathbf{I} - \mathrm{diag}(\boldsymbol{\varepsilon}))\,\mathbf{F}\,\mathrm{diag}(\mathbf{A})\,\mathbf{J} \tag{5}$$

$$\mathrm{diag}(\mathbf{A})\,\mathbf{G} = \mathbf{F}\,\mathrm{diag}(\mathbf{A})\,\mathbf{J} \tag{6}$$

The radiosity and irradiation can be expressed in terms of emissive power and view factor. Finally the heat transfer rate can be written as

$$\mathbf{q}_{\mathrm{rad}} = (\mathbf{I} - \mathbf{F})\,[\mathbf{I} - (\mathbf{I} - \mathrm{diag}(\boldsymbol{\varepsilon}))\,\mathbf{F}]^{-1}\mathrm{diag}(\mathbf{A}\boldsymbol{\varepsilon})\,\sigma \mathbf{T}^4 \tag{7}$$

Using Eq. (7), the heat transfer rate of gray diffuse surfaces can be calculated assuming the diffuse reflection at the surface and it is used as a boundary condition in the calculation. Considering the conduction in the glass panel, the energy equation can be written as

$$\rho c_p V \frac{\partial \mathbf{T}}{\partial t} = \nabla \cdot \mathbf{q}_{\mathrm{cond}} \tag{8}$$

This equation is discretized using the finite volume method for the spatial discretization and the explicit method for time marching to calculate the temperature variation of the glass panel heated in the radiant heating chamber.

$$\mathbf{T}^n = \mathbf{T}_n^{-1} + \mathrm{diag}(\mathbf{C})\,[\mathbf{K}\mathbf{T}^{n-1} - \mathbf{B}(\mathbf{T}^{n-1})^4] \tag{9}$$

In this equation, $\mathbf{C}$ denotes the vector composed of the time step ($\Delta t$), density ($\rho$), specific heat ($c_p$), and control volumes ($V_i$) and the matrix $\mathbf{K}$ consists of the conductivity, the area normal to the direction of the conductive transfer, and the distance between two nodes. $\mathbf{B}$ is obtained from the simplified form of Eq. (7), $\mathbf{q}_{\mathrm{rad}} = \mathbf{B}\mathbf{T}^4$.

$$\mathbf{B} = (\mathbf{I} - \mathbf{F})\,[\mathbf{I} - (\mathbf{I} - \mathrm{diag}(\boldsymbol{\varepsilon}))\,\mathbf{F}]^{-1}\mathrm{diag}(\mathbf{A}\boldsymbol{\varepsilon})\,\sigma \tag{10}$$

### 2.3 Solution method

The glass panel used in the present work consists of two sheets of soda-lime glass as mentioned before. The thermodynamic and radiative properties of the glass are assumed to be constant regardless of temperature and the values at room temperature are used. The density of 2500 kg/m$^3$, the conductivity of 1.4 W/mK, and the surface emissivity of 0.9 are used in the calculation (Rubin, 1985 ; Incropera and DeWitt, 1996). The variation of specific heat with temperature is relatively large and then the value at 200℃, 1035 J/kgK, is used (Sharp and Ginter, 1951).

For convenience of evaluation of the view factor, the shape of halogen lamp is assumed to be a thin strip instead of a cylinder since its projection area is relatively small in comparison to those of other surfaces. The view factors are obtained using the exact formulation between two rectangular surfaces which are lying in the parallel or perpendicular direction to each other (Gross et al., 1981). Reflectivity of the chamber wall is the primary parameter of the present work and the temperature of heaters varies between 1000 and 2000℃ so that the maximum temperature of the panel at the steady state reaches the desired values, 390℃. The radiant heater is assumed to be a gray body with the surface emissivity of 0.35. The temperature of chamber walls is set to be a constant value, 50℃, for simplification. Initial temperature of the panel is set to be 20℃. The calculation domain of each glass plate is divided into 40×40 grids, and the view factors of each cell to the radiant heaters and walls are evaluated.

The time step to obtain the variation of temperature is set to be 5 s.

## 3. Results and Discussion

Figure 2 shows the temperature variation with the wall reflectivity at the center point of the panel. The temperature measured by a pyrometer (Lee et al., 2003) is also shown in the figure for the comparison and the predicted results for the reflectivities of 0.88 and 0.8 are in good agreement with those measured for high and low reflectivities even though the prediction curve does not exact agree with that for the measurement. When the reflectivity of the chamber wall is high, the time required to reach a steady state is relatively long. In the contrary, when the reflectivity is low, it is clear that the temperature of the panel increases rather quickly and the time to a steady state becomes short.

Figure 3 shows the temperature variation at the corner of the panel with the wall reflectivity and it also indicates variation of the minimum temperature which occurs at the corner. When the wall reflectivity is high, the time required to reach a steady state becomes long but the temperature difference between the center and the corner is smaller since the corner region of the panel is heated to the higher temperature.

Figure 4 shows the temperature difference between the center and the corner when the reflectivity is 0.88 and the comparison with the data measured by pyrometer (Lee et al., 2003) at the corresponding positions. The temperature difference between the center and the corner is an important parameter since it is a measure of the uniformity of the temperature distribution of the panel. Figure 4 shows that the predicted temperature difference lies in good agreement with the prediction since the measured temperature difference is in the range of the predicted difference. In the figure, the coordinates (5 cm, 5 cm) indicates the position from the corner of the panel. The view port for the pyrometer was located at the bottom wall under (5 cm, 5 cm) from the corner of the panel (Lee et al., 2003). Since the temperature at the corner of the panel is lower than at the measuring position, the temperature difference to the center is larger. Figure 4 shows that the

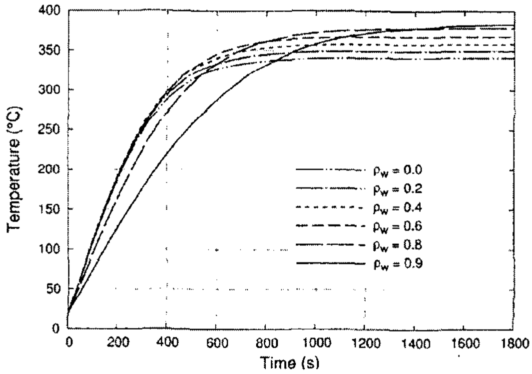


**Fig. 3** Temperature variation at the corner of the panel with wall reflectivity

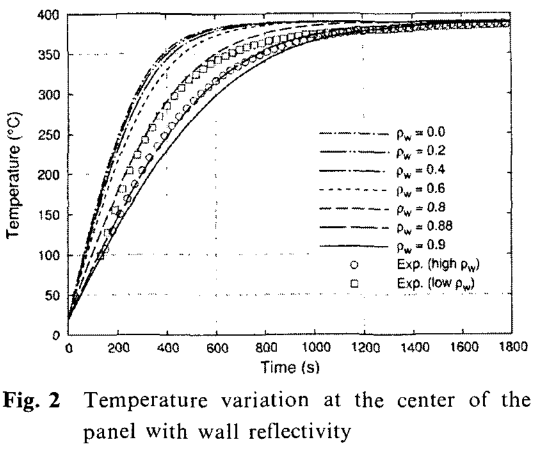


**Fig. 2** Temperature variation at the center of the panel with wall reflectivity

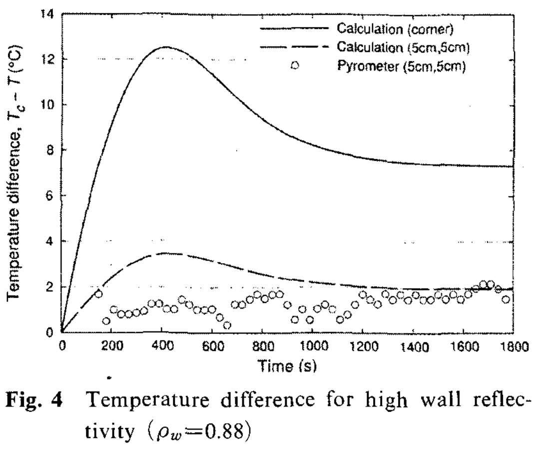


**Fig. 4** Temperature difference for high wall reflectivity ($\rho_w$=0.88)

difference quickly increases until about 420 s, then gradually decreases and finally becomes constant to reach the steady state.

Figure 5 illustrates the variation of temperature difference between the center and the corner in the panel with wall reflectivity. As explained in Fig. 4, the differences have their maximum values in the early stage of heating process, thereafter decrease, and then become constant to reach the steady states. When the reflectivity is 0, the maximum value is 67.4℃ obtained at 320 s after starting the heating process. As the reflectivity decreases, the difference increases and the time to reach the maximum value decreases. The maximum temperature difference might affect the real heating process even though the final difference is small enough because the large temperature difference in the process can cause fracture or deformation of the glass panel due to large thermal stress. In order to avoid such failure, initial temperature increase should be minimized and, therefore, the control of the electric power is necessary.

Temperature distributions on the panel surface show isotherms similar to concentric circles due to symmetrical heat transfer as shown in Fig. 6. However, since the temperature difference between the center and the corner is 40.7℃ for $\rho_w$=0.2 and 6.1℃ for $\rho_w$=0.9, it is clear that the temperature uniformity is improved when the reflectivity is large.

Figure 7 shows the temperature variation of the panel in the diagonal direction with wall reflectivity at the steady state ($t$=2400 s). This

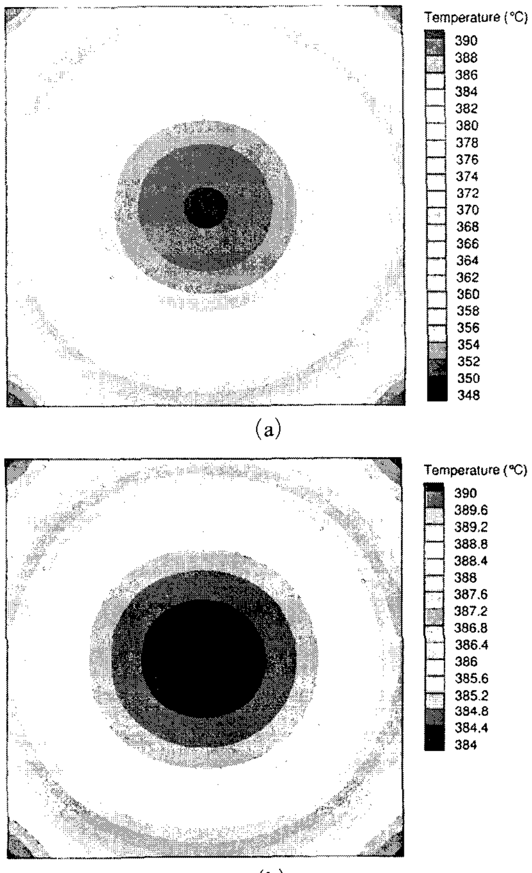


**Fig. 6** Temperature distributions at the steady state for (a) $\rho_w$=0.2 and (b) $\rho_w$=0.9

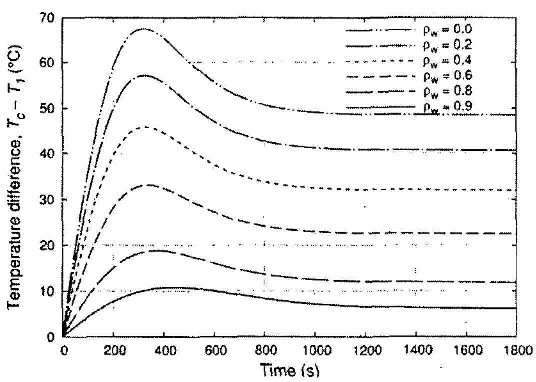


**Fig. 5** Temperature difference between the center and the corner in the panel

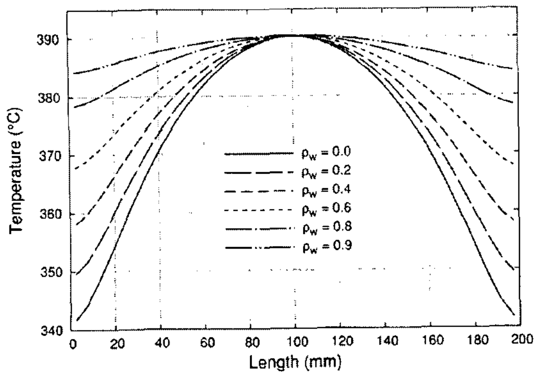


**Fig. 7** Temperature distribution along the diagonal of the panel at the steady state

figure shows that the temperature difference between the center and the corner is the largest and the difference decreases as the reflectivity increases. Thus uniformity of the temperature distribution can be improved only with high reflectivity if the change of the geometry is not considered.

Figure 8 summarizes the predicted results in the present work and shows both the maximum and steady-state temperature differences and the time required to heat the panel. As seen in the figure, the maximum temperature difference ($\Delta T_{max}$) occurrs in the early stage of the heating process and the steady-state temperature difference is small when the reflectivity is large. It is clear that the differences increase as the reflectivity decreases. When the reflectivity is large, the part of the radiation energy emitted from the heaters is reflected on the chamber wall and the reflected energy is used to heat the panel together with the energy directly incident on the panel. In particular, the reflected energy plays an important role to improve the uniformity of the temperature distribution of the panel. Since a low reflectivity means that the high emission or absorption, the radiation energy incident on the wall from the heaters is absorbed more than reflected on the wall, which causes the heat loss through the chamber wall to increase. Therefore, in order to heat the panel to the same temperature, more electric power is required for a low reflectivity to compensate for the heat loss. As the electric power increases, the heating time decreases and the rapid heating of the panel is possible.

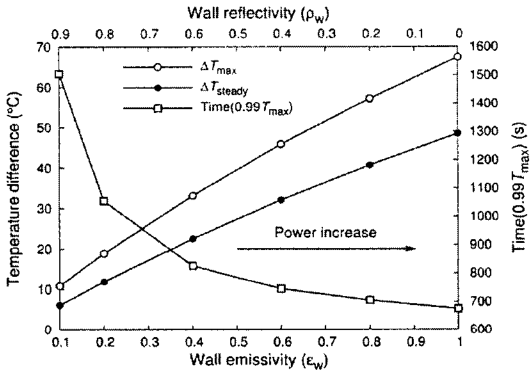


**Fig. 8** Temperature variation at the center of the panel with wall reflectivity

## 4. Conclusions

The effect of the reflectivity on the temperature distribution of the glass panel by infrared radiant heating has been investigated and the following conclusions have been conducted.

(1) As the wall reflectivity increases, the uniformity of the temperature distribution of the glass panel is improved but the time required to reach the steady state becomes long. To the contrary, when it is small, it is possible to quickly heat the panel with a loss of the temperature uniformity.

(2) The temperature difference of the panel reaches a maximum in the early stage of the heating process, thereafter decreases gradually, and then becomes constant to reach the steady state.

(3) As the reflectivity decreases, the electric power increases to heat the panel to the desired temperature since the heat loss through the chamber wall increases.

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