Mathematical Calculations Of Heat Transfer For The CNC Deposition Platform Based On Chemical Thermal Method

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Abstract. Chemical thermal deposition techniques are highly depending on deposition platform temperature as well as surface substrate temperatures, so in this research thermal distribution and heat transfer was calculated to optimize the deposition platform temperature distribution, determine the power required for the heating element, to improve thermal homogeneity. Furthermore, calculate the dissipated thermal power from the deposition platform. Moreover, the thermal imager (thermal camera) was used to estimate the thermal destitution in addition to, the temperature allocation over 400cm² heated plate area. In order to reach a plate temperature at 500 oC, a plate supported with an electrical heater of power (2000 W). Stainless steel plate of 12mm thickness was used as a heated plate and deposition platform and subjected to lab tests using element analyzer X-ray fluorescence system (XRF) to check its elemental composition and found the grade of stainless steel and found to be 316 L. The total heat losses calculated at this temperature was 612 W. Homemade heating element was used to heat the plate and can reach 450 oC with less than 15 min as recorded from the system as well as the temperatures recorded and monitored using Arduino/UNO microcontroller with cold-junction-compensated K-thermocouple-to-digital converter type MAX6675.

Keywords: Heat transfer, Deposition platform, CNC, Chemical Thermal Method.

1-Introduction
Heat Transfer is the study of the rates of thermal energy motion. There are three modes of Heat Transfer: Conduction, Convection, and Radiation [1]. Conduction is concerned with the transfer of thermal energy through a material without bulk motion of the material. Conduction is the diffusion of thermal energy, i.e., the movement of thermal energy from regions of higher temperature to regions of lower temperature. On a microscopic level, this occurs due to the passing energy through molecular vibrations [2]. Convection is the process of heat transfer by displacing the macroscopic elements of a medium (molar volumes) [3]. Radiation is the transfer of thermal energy between two objects through electromagnetic waves. Unlike conduction and convection, radiation does not require a medium. In general, gasses do not take part in radiation heat transfer [4].
One of the many chemical thermal deposition methods is the chemical thermal spray pyrolysis system which is contained the following parts, spray head, carrier gas, heating element, and temperature controller [5]. Thermal stability and uniformity of temperature distribution are very important in spray deposition process because of this method highly dependence on thermal decomposition. So in this work try to estimate the needed thermal power to achieve the required temperature with maximum stability and uniformity, as well as, design the heating element and temperature monitoring and controlling system.

2. Experimental
The nature and the surface of the substrates are extremely important because they greatly influence the properties of the films deposited onto them. Glass, quartz, and ceramics substrates are commonly used for polycrystalline films [6] [7]. In this work, the microscopic glass slides of (25.4mm x 76.2mm x 1.2mm) dimensions used as the substrate. There are some factors that effect on the film homogeneity, which are Substrate Temperature, deposition rate, spray time, distance, and air pressure. The substrate temperature has great importance in the preparing the homogeneous film, so we must choose the possible temperature to get the homogeneous film. We can measure the temperature of the substrate due to the thermocouple, which is connected to an electrical heater, and a large number of experiments did to get the possible temperature to get the homogeneous film.

The substrate heater (deposition platform) was an electrically controlled and monitored every 200 msec using Arduino UNO and analog to digital converter type MAX6675 with a K-type thermocouple. The controlling was done by a specially written instruction program code in C++, the latter facilitate the accurate real-time monitoring and controlling the deposition temperature during the process. The electric heater as illustrated in figure (1) is designed to equip the translated (X-Y) movable deposition platform with a thermal energy, which is suitable for the overall entire area of 400 cm². Furthermore, homemade gridded deposition platform plat was stainless steel type 306L according to the handheld X-ray fluorescence XRF type Skyray Instrument EDX-Pocket III report as shown in figure (2). It has also been used the thermal camera (Fluke thermography type Ti10) to evaluate the performance efficiency of the home-made electrical heater by thermal images of the heated plate and surface temperature of the substrate.

![Figure 1. Home-made electrical heater using tungsten wire and quartz tube.](image-url)
3. Calculation and Results

The basic heat transfer relationship for conduction is the Fourier equation:

\[ Q = \frac{KA\Delta T}{L} \]  

Where \( Q \) is the rate of heat transfer, \( K \) the thermal conductivity of the material in this case (1.28) for the firebrick that used as a thermal insulator in the bottom and sidewall of the carriage. The Stainless Steel adopted in this work was (grade 306L) according to the XRF measurement and results, \( L \) is the thicknesses of the platform, \( A \) is the area of the heat transfer as shown in figure (3), and \( \Delta T \) is the temperature difference of the heat transfer.
Then:

The heat transfer from the side of the carriage as illustrated in figure (4) in red color, assume that the outside temperature of the fiber brick is 75 °C. To calculate the thermal losses from the carriage wall.

\[
Q_{\text{cond.}} = \frac{KA\Delta T}{L}
\quad (2)
\]
\[ Q_1 = \frac{1.28 \times (0.012 \times 0.8)(500 - 75)}{0.006} \]

\[ Q_1 = 870.4 \text{ W} \]

To evaluate the heat transfer by conduction from the lower surface of the plate.

\[ Q_2 = \frac{1.28 \times (0.2 \times 0.2)(500 - 50)}{0.8} \]

\[ Q_2 = 28.8 \text{ W} \]

To evaluate the heat transfer from the upper surface of the plate (by convection) as shown in 'figure (5)'.

\[ Q_{conv} = hA(T_a - T_\infty) \quad (3) \]

Where: \( h \) is the heat transfer coefficient in (W/m.°C).

The Nusselt number \( Nu \) in natural convection is in the following equation (4):

\[ Nu = 0.54(Ra)^{\frac{1}{4}} \quad 10^4 < Ra < 10^7 \quad (4) \]

Figure 5. The upper-heated surface with projection of the X-Y movable deposition platform.
Where $R_a$ is the Rayleigh number, which is defined as the product of Grashof number and Prandtl number, as:

$$R_a = G_r \cdot P_r = \frac{g \cdot \beta (T_s - T_w) L^3}{\varrho^2}$$

(5)

Where:
- $g$: gravitational acceleration m/s$^2$
- $\beta$: Coefficient of volume expansion, 1/k
- $L$: Characteristic of geometry, m
- $\varrho$: Kinematics viscosity of fluid, m/s$^2$

Then, suppose the plate heated for 500°C and exposed to atmospheric air at 20°C we first determine the film temperature as:

$$T_f = \frac{T_s + T_w}{2}$$

(6)

$$T_f = \frac{500 + 20}{2} = 260 \degree C = 533 k$$

The Properties of air at $T_f$:

$$\beta = \frac{1}{533} = 1.87 \times 10^{-3} K^{-1}$$

$$K = 4.39 \times 10^2 \frac{W}{m.k}$$

$$\varrho = 2.88 \times 10^{-5} N \frac{s}{m^2}$$

$$P_r = 0.68$$

$$g = 9.81 \frac{m}{s^2}$$

Then Rayleigh number can be found using equation (7):

$$R_a = G_r \cdot P_r$$

(7)

$$= 2.150606 \times 10^5$$

According to the equation (4) can calculate Nusselt number $Nu$.

$$Nu = 0.54 \left(2.150606\right)^{\frac{1}{5}}$$
\[ Nu = 11.6 \]
\[ h = 16.5 \frac{W}{m^2 \cdot ^\circ C} \]

Then the heat transfer by convection is:

\[ Q_{\text{conv}} = hA(T_s - T_\infty) \]
\[ = 16.5 (0.2 \times 0.2)(500 - 50) \]
\[ Q_{\text{conv}} = 297 W \]

Now to evaluate the heat transfer from the upper surface of the plate by radiation as shown in figure (6) using equation (8)

\[ Q_r = \sigma f A (T_s^4 - T_\infty^4) \]  
\[ Q_r = 5.67 \times 10^{-8} \times 0.78 \times 1 \times (0.0 \times 0.2) [(733)^4 - (298)^4] \]
\[ Q_{\text{conv}} = 617 W \]
Then the total heat transfer calculated and needed to safely reach 500 °C is:

\[ Q_T = Q_{\text{conv}} + Q_{\text{cond}} + Q_{\text{rad}} \]  \hspace{1cm} (9)

\[ Q_T = 1864.4 \text{ W} \]

While the electric heater designed to supply power according to the equation.

\[ Q_{\text{in}} = 11 \text{ Amp} \times 220 \text{ volt} = 2420 \text{ W} \]

Therefore, the inlet energy is quite enough to heat the plate more than 500 °C safely. The experimentally result results approved the uniform thermal distribution and temperature over all the examined area (400 cm²) as shown in figure (7), the latter explain the thermal energy detect and distributed as a function of temperature in histogram view, whereas the inset figure showed the uniformity of thermal energy and temperature distribution as well as the heat loss in the sidewall of the carriage.

**Figure 7.** Histogram showed the thermal energy distributed overall the image, inset figure is the thermal image exhibited thermal and temperature distribution overall deposition area.
4. Conclusion

The theoretical calculations of heat transfer showed that the total heat loss of all kinds is less than the
designed capacity of the home-made electric heater that manufacturer, and therefore the heater has the
ability to equip the deposition platform plate with uniform thermal energy and uniform temperature overall
its area equally.

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