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Change Laws of Flake's Temperature during Making a Diamond Film by DC-PJ

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Abstract: When making a diamond film by direct current plasma jet, a kind piece of flake is used as a base body which the film can be attached to. The flake's temperature is unstable. Therefore, some experiments and constructed mathematical models, which were solved by computer, were done. The results show that the flake's temperature is influenced by many factors and the mains are plasma jet power and vacuum pressure. Through adjusting the two parameters, the flake's temperature can be accurately controlled, furthermore, diamond films' quality would be improved. Lowering sediment platform's temperature has a little effect to the flake's temperature at present technology conditions.

Key words: CVD (Chemical Vapor Deposition); plasma; impact heat transfer

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Making diamond film by direct current plasma jet is one of high technologies. Development trend of the technology is to get a large area film with good quality by an equipment with high power direct current plasma jet at present [1]. However, during the film growing, its base body has variable temperature, which has directly a bad effect on good film growing and causes experimental study not to be well carried on [1,2]. Influence factors and change laws of the temperature must be investigated in order to get good diamond films .

1 Structure of Apparatus

Structure of the apparatus is shown in **figure 1**. Argon, hydrogen and hydrocarbon (here is methane) supplied by a gas source are transferred into a component named plasma jet, which is composed of a stick cathode and a tube-shaped anode. Afterward, gas molecules are changed into plasma and its volume expands sharply, so the plasma runs out from a little hole in the lower part of the anode at a high speed. The plasma is cooled rapidly after arriving in the surface of a flake on a sediment platform. At the same time, a chemical action happens and a diamond film generates on the flake. Inner of the sediment cavity is vacuum. The sediment platform and the walls of the apparatus are cooled by water [1,2].

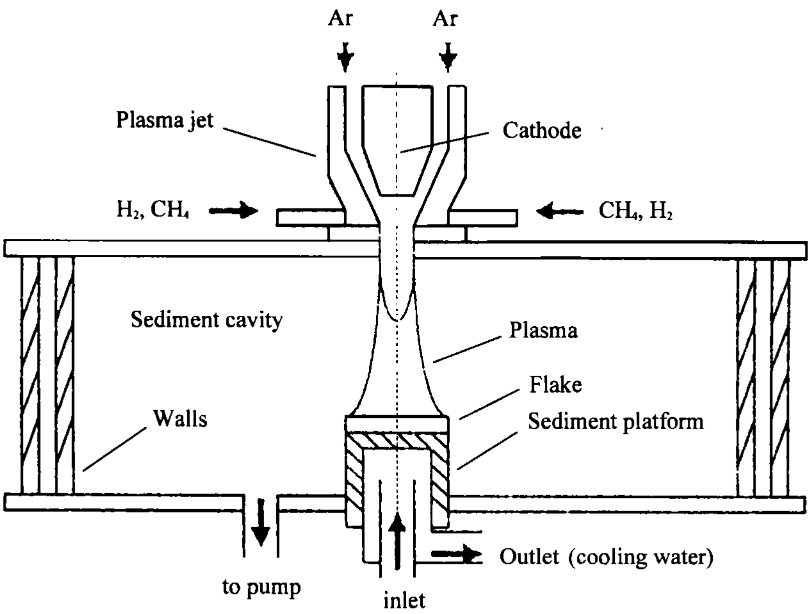

Figure 1 Structure of apparatus named DC-PJ.

2 Construction of Mathematical Models

2.1 Mathematical model of plasma jet

In process of plasma jet's work, chemical and physical actions happen inside. Firstly, plasma discharges arise between cathode and anode by action of DC voltage. Then it causes gas to be ionized and changed into plasma. At same time, its volume expands quickly, and the plasma runs out of the spout at a high speed by driving of flowing Ar. Thus, a plasma jet with high temperature forms. The plasma jet can be looked as an open system of specific heat and temperature of plasma. The speed and temperature at the spout can be worked out by solving the model as follows:

$$\begin{cases} h_p = \dfrac{UI\eta}{\sum\limits_{i=1}^{3} \rho_i G_i} + \sum\limits_{i=1}^{3} w_i \left(h_i + \dfrac{v_i^2}{2} + g_z \right) - \dfrac{v_p^2}{2} - g_z \\ \rho_p = \dfrac{p_p}{T(2w_1 R_1 + w_2 R_2)} \\ v_p = \dfrac{\sum\limits_{i=1}^{3} \rho_i G_i}{\rho_p A_p} \\ T_p = f^{-1}(h_p) \end{cases} \tag{1}$$

where $i = 1, 2, 3$ representing Ar, H_2 and CH_4 respectively; h_p — inner energy per unit of plasma; U — term of source; I — direct current; η — efficiency of plasma jet; ρ_i — density of gas; G_i — volume flow of gas; w_i — mass fraction; h_i — inner energy per unit; $\frac{v_i^2}{2}$ — movement per unit; g_z — location energy; $\frac{v_p^2}{2}$ — movement per unit of plasma; g_z — location energy of plasma; ρ_p —density of plasma; p_p — pressure in the cavity; T — temperature; R_i — gas constant; v_p — plasma's speed; A_p — spout's area; and T_p — temperature of plasma;

2.2 Mathematical model of free jet zone of a compact jet

The plasma interacts with the flake in a form of an impact jet. Its basic structure is shown in **figure 2**. The compact jet can be divided into a free stage, a transition stage and an attachment stage [3].

Some hypotheses and simplification were made: It is stable; The sediment platform can't influence free zone and it is same as a free jet; First speed and temperature distribute equally on the section; The plasma is optically thin; Pressure is about 10 Pa; Only radial change of speed and temperature are considered. Speed at spout is not great; Pressure term and viscosity dissipation term are ignored; The plasma is look as neutral matter in calculation because of no high temperature.

According to the N-S formula, the succession differential formula, the energy differential formula [4], a formula of gas status [5], and functional relationship of specific heat and temperature of plasma [6], a mathematical model is obtained by which distribution of the speed and temperature can be gotten:

$$\begin{cases} \rho v_z \dfrac{dv_z}{dz} = \dfrac{d}{dz}\left(\dfrac{4}{3} \mu \dfrac{dv_z}{dz} \right) + \rho g \\ \dfrac{d}{dz}(\rho v_z) = 0 \\ \rho v_z \dfrac{dh_z}{dz} = \dfrac{d}{dz}\left(\dfrac{K}{c_p} \dfrac{dh_z}{dz} \right) - U \\ h_z = f(T_p) \quad \text{or} \quad T_p = f^{-1}(h_p) \\ \rho_p = \dfrac{p_p}{RT_p} \end{cases} \tag{2}$$

where ρ — density, v_z — axial speed, μ — adherence coefficient, g — constant of gravity, h_z — axial enthalpy, K — conduction coefficient, c_p — specific heat capacity.

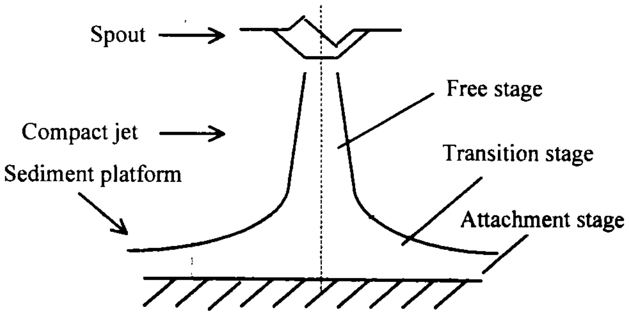

Figure 2 Structure of the compact jet.

2.3 Mathematical model of energy conservation of the flake

There are various means of transferring heat in cavities. The compact jet gives energy to the flake by means of radiation and convection. The flake transfers heat to the sediment platform by conduction too. There is heat transfer by radiation between flake and wall, or plasma and wall, or wall and sediment platform. According to these physical relationships, a mathematical model based on energy conservation of the flake is constructed.

Before analyzing heat transfer by radiation, some appointments are made. "0" refers the free jet zone, "1" the stationary jet zone, "2" the top surface of the flake, "3" the low surface of the flake, "4" the flank surface of the sediment platform, "5" the top surface of the sediment platform, and "6" the surface of the walls.

(1) Heat transfer by convection between the compact jet and the flake.

The energy that is transferred to the flake from the compact jet by convection can be known through solving the experimental formulae [7]

$$\frac{\overline{Nu}}{Pr^{0.42}} = G\left(\frac{r}{D}, \frac{H}{D} \right) \cdot F(Re) \tag{3}$$

where

$$G\left(\frac{r}{D}, \frac{H}{D} \right) = \frac{D}{r} \frac{1 - 1.1(D/r)}{1 + 0.1[(H/D) - 6](D/r)},$$

$$F(Re) = 2\left[Re\left(1 + \frac{Re}{200} \right)^{0.55} \right]^{\frac{1}{2}},$$

r — radius, D — diameter, H — distance from spout to platform, Re — Reynolds number, Nu — Nusselt number; Pr — Prandtl number.

The energy which flake get from the plasma jet by convection Q_{d12} is

$$Q_{d12} = F_2 \alpha_{12} (T_1 - T_2) \tag{4}$$

where T_1 — natural temperature of the plasma jet, T_2 — the flake's temperature, α_{12} — coefficient of heat exchange by convection, and A_2 — flake's area.

(2) Heat transfer by radiation in the sediment cavity.

The plasma can be considered as a heat source that give out energy but don't absorb energy according to some hypotheses, shown in **figure 3**. Therefore, it doesn't affect heat transfer by radiation between flake and wall, or wall and platform. Hypothesizing the heat transferred by radiation from plasma to wall is Q_{06}, and the heat to the flake is Q_{02}, a radiation net chart can be drawn and a formula gotten as

$$\begin{cases} Q_{06}+\dfrac{J_4-J_6}{\dfrac{1}{F_4\phi_{4,6}}}+\dfrac{J_2-J_6}{\dfrac{1}{F_2\phi_{2,6}}}+\dfrac{E_6-J_6}{\dfrac{1-\varepsilon_6}{F_4\varepsilon_6}}=0 \\ Q_{02}+\dfrac{J_6-J_2}{\dfrac{1}{F_6\phi_{6,2}}}+\dfrac{E_2-J_2}{\dfrac{1-\varepsilon_2}{F_2\varepsilon_2}}=0 \\ \dfrac{J_6-J_4}{\dfrac{1}{F_6\phi_{6,4}}}+\dfrac{E_4-J_4}{\dfrac{1-\varepsilon_4}{F_4\varepsilon_4}}=0 \end{cases} \tag{5}$$

where $j=2, 4, 6$ representing flake, sediment platform and walls respectively; J_j — efficient strength of radiation; E_j — radiation power of solid surface; F_j — area; $\phi_{j,k}$ — angle coefficient of radiation; and ε_j — darkness.

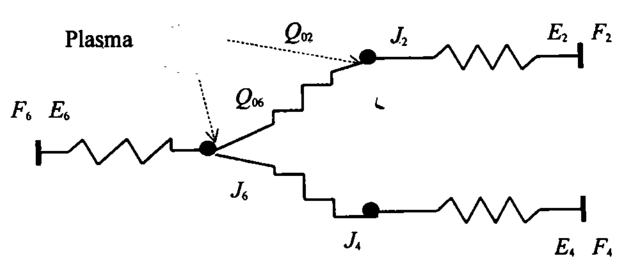

Figure 3 A radiation net.

(3) Calculation of heat transfer by radiation from plasma to flake and to walls.

Investigations show that energy transferring from the transition zone to the flake by radiation can't be ignored when to ascertain the flake's temperature correctly, so the calculation of heat transfer by the plasma's radiation became more intricate. Some parameters are shown **in figure 4**. On the one hand, the free jet zone can be looked as a column, whose diameter of section is D and height is h'. On the other hand, the stationary zone can be looked as a circular platform, whose top diameter is D and bottom diameter is D'. The distance from spout to flake is h'. During the calculation, it is hypothesized that the diagnostic temperature of terminal of the free jet zone and the temperature of the flake are T_0 and T_2 respectively. Furthermore, a diagnostic temperature of the stationary zone can be gotten by the formula $T_1=(T_0+T_2)/2$. Let $H'=k'H$, where k' is a coefficient. The two formulae about Q_{02} and Q_{06} (heat transfer by radiation from the free zone to the flake and to the walls respectively), Q_{12} and Q_{16} (energies from stationary zone to the flake and to the walls respectively) are

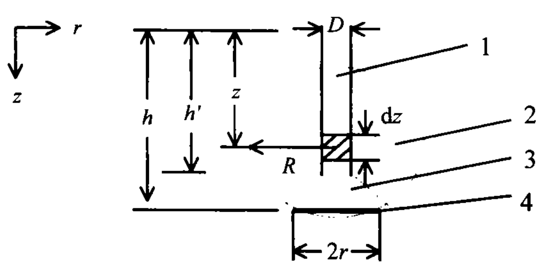

Figure 4 Parameters of structure for calculation. 1 — free jet zone, 2 — a tiny cell of calculation, 3 — a stationary stage, and 4 — a flake and sediment platform.

$$\begin{cases} Q_{02}=2\pi^2\sigma\left(\dfrac{D}{2}\right)^2+\displaystyle\int_0^h \varepsilon T(z)^2\left(1-\dfrac{H-z}{\sqrt{(H-z)^2+r^2}}\right)\mathrm{d}z \\ Q_{06}=2\pi^2\sigma\left(\dfrac{D}{2}\right)^2+\displaystyle\int_0^h \varepsilon T(z)^2\left(1+\dfrac{H-z}{\sqrt{(H-z)^2+r^2}}\right)\mathrm{d}z \end{cases} \tag{6}$$

$$\begin{cases} Q_{12}=\dfrac{1}{3}\pi^2\varepsilon'\sigma\left(r^2+\dfrac{D^2}{4}+\dfrac{Dr}{2}\right)H(1-k')\times \\ \qquad\left(1-\dfrac{H(1-k')}{\sqrt{[H(1-k')]^2+4r^2}}\right)T_1^4 \\ Q_{16}=\dfrac{1}{3}\pi^2\varepsilon'\sigma\left(r^2+\dfrac{D^2}{4}+\dfrac{Dr}{2}\right)H(1-k')\times \\ \qquad\left(1+\dfrac{H(1-k')}{\sqrt{[H(1-k')]^2+4r^2}}\right)T_1^4 \end{cases} \tag{7}$$

where ε, ε' — darkness and σ — radiation constant.

(4) Conduction between the flake and the platform.

Because the surface of the flake and the copper platform isn't absolute smooth, the place where they contact with each other is rough. There is a gap whose thickness is δ_g. The area of the contact-segment include two parts. One part is solid contraction region whose area is A_c and the other is gaseous contraction region whose area is A_g. If the heat running out from the edge of the gap ignored, the following formula about conduction through the gap would be developed using some theories of conduction and vacuum [8].

$$\begin{cases} Q_{23}=Q'+Q'' \\ Q'=\dfrac{2A_c}{\delta_g}\dfrac{\lambda_1\lambda_2}{\lambda_1+\lambda_2} \\ Q''=\displaystyle\int p\sum_{i=1}^{2} f_i'y_i\dfrac{\mu_i+1}{\mu_i-1}\sqrt{\dfrac{R_i}{2\pi m_i}}\,\mathrm{d}A_g \end{cases} \tag{8}$$

where Q_{23} — heat transfer through the gap between the flake and platform; Q' — energy transfer through solid contraction area; Q'' — energy transfer through the gas contraction area; p — pressure; λ_1, λ_2 — conduction coefficient of flake and platform; μ_i — insulation index of gas; m_i — molecular fraction of gas; y_i — volume fraction of gas; and f_i' — adaptation module of gas.

(5) Conservation of energy of the flake.

In the stable position, the following formula, by which its temperature can be calculated, is gained based on conservation of energy of the flake:

$$Q_{12}+Q_{02}+J_6F_6\phi_{6,2}+Q_{d12}=J_2F_2\phi_{2,6}+\int(\mathrm{d}Q'+\mathrm{d}Q'')+\varepsilon_2\sigma(T_1^4-T_2^4)\pi r^2 \qquad (9)$$

3 Theoretical Results

Figure 5 shows that power of the plasma jet has the greatest influence on the flake's temperature when other conditions are fixed. When the power rises, the flake's temperature will go up. This graph is similar with a quadratic graph. As the power is bigger than 10kW, the rate of rise increase obviously. It is said that tiny change of the power can cause bigger increase of the flake's temperature.

Figure 6 shows that pressure of cavities has more great influence on the flake's temperature. When other conditions is fixed, the flake's temperature rises with the vacuum strength ascending. This theoretical graph of change is also similar with a quadratic graph. When the vacuum strength becomes more than 80 kPa, the rate of increase also becomes bigger.

Figure 7 shows that the sediment platform's temperature has some influence on the flake's temperature. When other condition is fixed, the flake's temperature rise with the platform's temperature, and the trend of change is linear. The rate of rise is about 1.00.

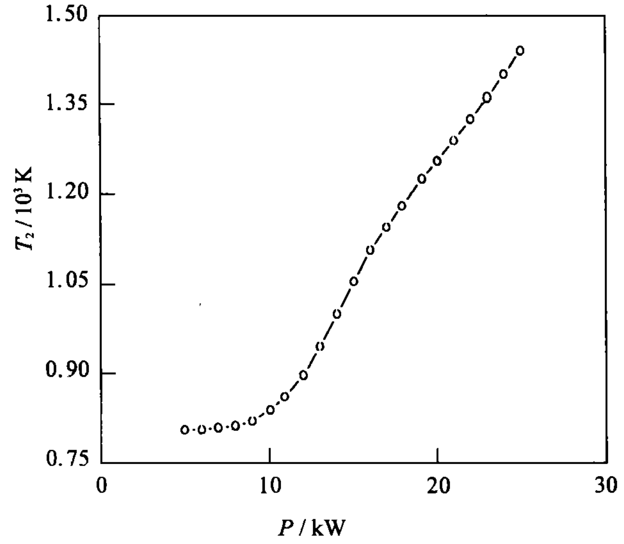

Figure 5 Relationship between the flake's temperature and the power of the plasma jet. $p=20$ **kPa,** $H=0.2$ **m,** $T_4=700$ **K,** $T_6=700$ **K.**

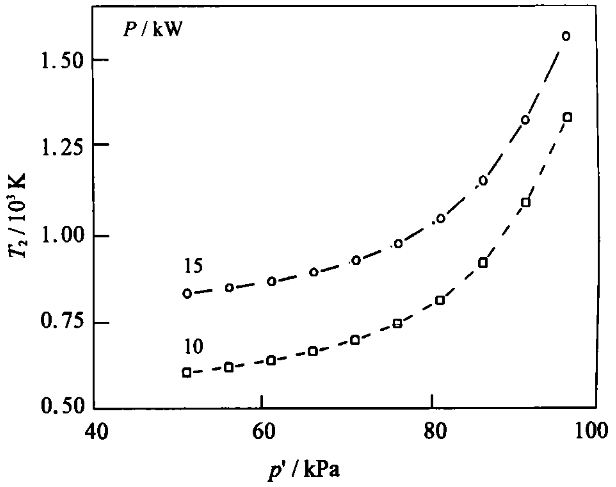

Figure 6 Relationship between the flake's temperature and the vacuum strength. $H=0.2$ **m,** $T_4=700$ **K,** $T_6=700$ **K.**

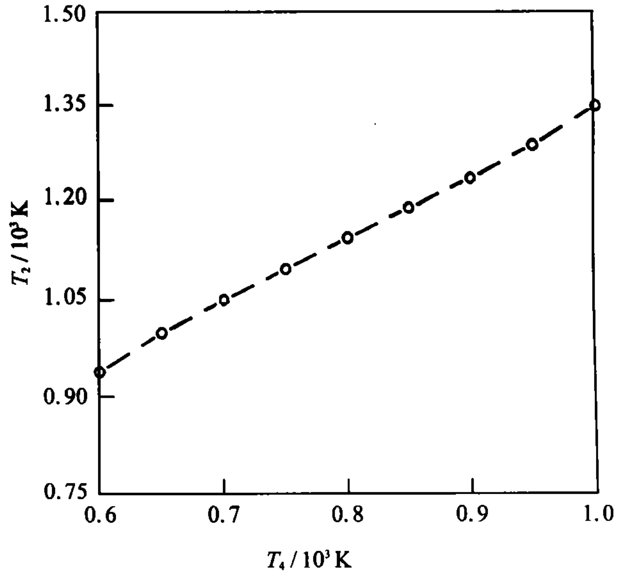

Figure 7 Relationship between the flake's and the sediment platform's temperature. $P=15$ **kW,** $H=0.2$ **m,** $T_6=700$ **K,** $p=20$ **kPa.**

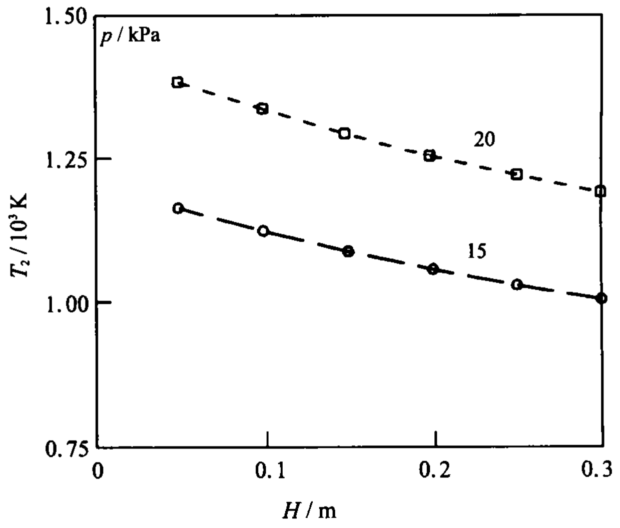

Figure 8 Relationship of the flake's temperature and the distance between the spout and the flake. $p=20$ **kPa,** $T_4=700$ **K,** $T_6=700$ **K.**

Figure 8 shows that the distance from spout to sediment platform can change the flake's temperature. The flake's temperature decreases following its going down with fixed conditions. The trend of change is linear and the rate of descend is about 6 K/mm.

Figure 9 shows that the walls' temperature has a little influence on the flake's temperature. When other condition is fixed, the change trend of the flake temperature with the walls' temperature is linear. T_2 will go up with increase of T_6, but the rate of rise is very small. Because the change is very tiny, its effect in practical process can be ignored.

Figure 10 shows that the contact status between the flake and the platform give important influence on the flake's temperature. With fixed conditions, the flake's temperature declines quickly with the solid contact area's rising. In general, while the rate is between 10^{-5} and 0.2, the speed of falling is small and the flake's temperature will approach to the platform's temperature increasingly. While it is smaller than 10^{-5}, the platform's temperature have less influence on the flake's temperature. So improving the contact status of flake and platform is advantage to control flake's temperature. However, to create a good contact status is very difficult using present technologies, and taking the measure to control flake's temperature isn't practical.

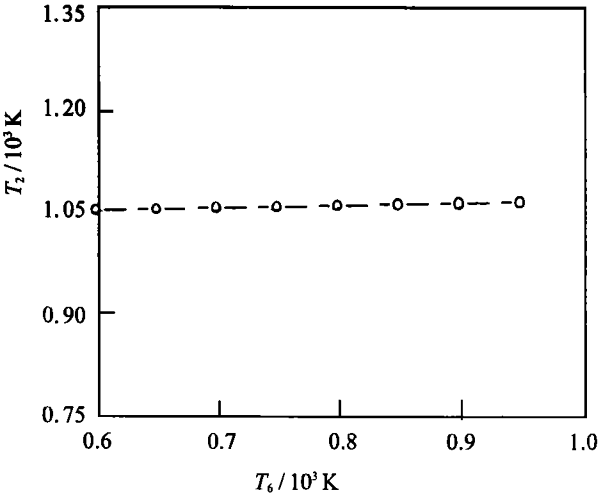

Figure 9 Relationship between the flake's and the wall's temperature. P=15 kW, H=0.2 m, T_4=700 K, p=20 kPa.

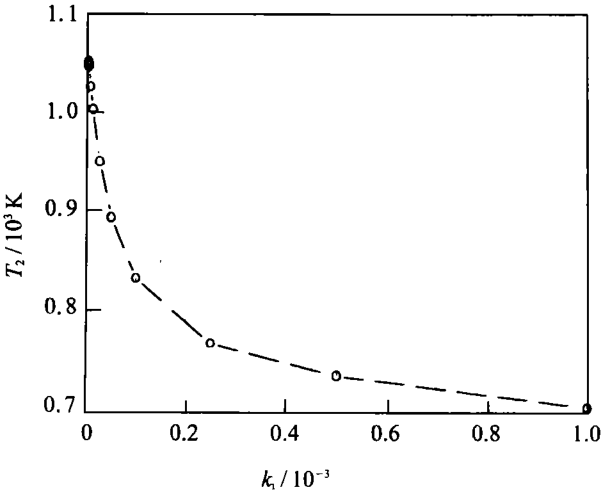

Figure 10 Relationship between the flake's temperature and the rate of solid contraction. P=15 kW, H=0.2 m, T_2=700 K, T_4=700 K.

4 Experimental Demonstration

Many experiments show that the theoretical results are accord with the practical. The greatest error is smaller than 10%. It can be show in the **figures 11 and 12**.

Figure 11 shows two curl lines about relationship of flake's temperature and pressure. One is according to experimental data, and the other is according to calculation results. Trends of them are alike. While other conditions are fixed, the flake's temperature will decrease

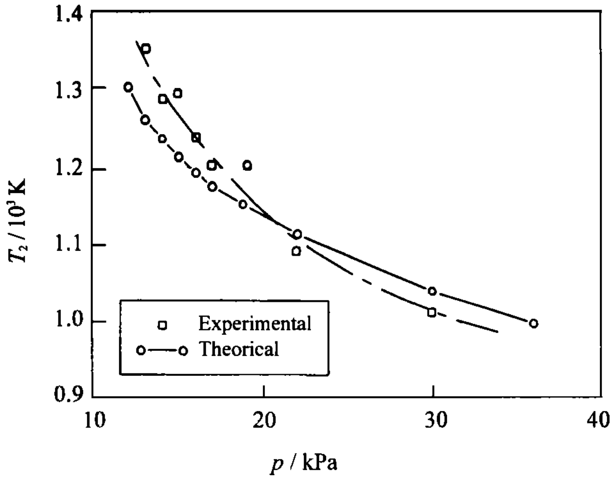

Figure 11 Relationship between the flake's temperature and the presure. P=97 V × 95 A, H=0.1 m, T_4=800 K, T_6=500 K.

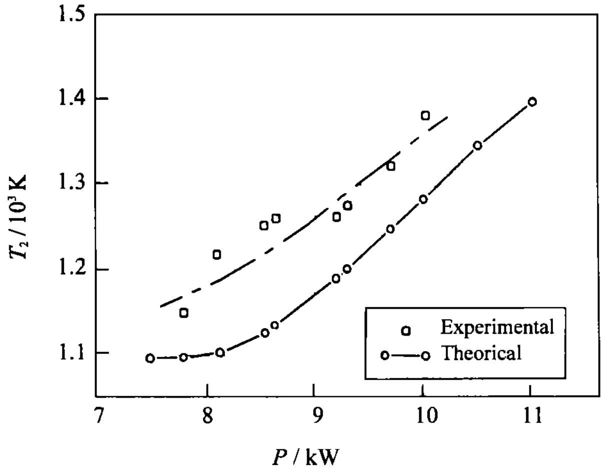

Figure 12 Relationship between the flake's temperature and the power of the plasma jet. p=16 kPa, H=0.1 m, T_4=800 K, T_6=500 K.

with pressure going down.

Figure 12 shows two curl lines about relationship of the flake's temperature and plasma jet power. One is according to experimental data, the other is according to calculation results. Trends of them are also alike. While other conditions are fixed, the flake's temperature will decrease with power going up.

5 Conclusions

(1) Main factors influencing the flake's temperature include power of the plasma jet, vacuum strength, platform's temperature and distance between sediment platform and spout. Power of the plasma jet and vacuum strength all have the greatest influence, but the flake's temperature will go up. The wall's temperature has lest influence on the flake's temperature, and it can be ignored. It is practical to adjust the flake's temperature through changing three parameters: power of plasma jet, and pressure of sediment tube, and distance between spout and platform.

(2) The contact status of flake and platform has important effect. At present, because the rate of solid contact is small, it is limited to reduce the flake's temperature through cooling platform by water, and its effect is not obvious.

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