Achievement of High Energy Density for Plasma Beams†

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Abstract

The basic thermal properties that govern the generation of "high energy density plasma beams" are investigated. The arc state, which is important in the utilization of plasma beams as a high energy density heat source, is studied by separately considering the two regions of the arc: the arc column and an electrode (anode or cathode) region. The mechanism of the "thermal pinch" phenomenon is clarified in the arc column and the role of various parameters which enhance the functioning of the "thermal pinch" phenomenon is examined; including the effect of the column configuration and the roles played by both thermal conductivity and the temperature gradient. The conditions necessary to obtain a plasma column with a high temperature and high energy density are described and actual examples are given. It is also shown that a "point arc" of high energy density can be generated in the region near the electrodes by the supply of a special vortex gas flow. The "arc ball" that appears in the anode region of the "point arc" is found to have an energy density as high as 10^6 W/cm^2, and can be stably sustained in a fixed position.

KEY WORDS: (Plasma Beam) (High Energy Density) (Arc) (Thermal Conductivity) (Electrode)

1. Energy Density of a Thermal Plasma

It is usually more difficult to generate a high energy density in a plasma beam than in laser beams or electrically charged particle beams such as electron and ion beams. Laser beams can be focused up to the diameter of the wavelength by means of an optimally designed lens system. A high energy density can be achieved relatively easily in charged particle beams by such technical means as accelerating individual particles and strongly focusing the beams.

Plasma beams, however, can be neither focused like laser beams nor accelerated like charged particle beams. For the energy per specific volume of a plasma at pressure p, temperature T and number density n, the following equation holds, known as the equation of state,

$$p = nkT\ (= \rho R_0 T), \qquad (1)$$

where k is the Boltzmann's constant, R_0 is the gas constant and ρ is the mass density ($\rho = mn$ and m is the mass of a particle). When the pressure is constant

$$nT = p/k = constant. \qquad (2)$$

For example, in a high power hydrogen plasma jet to obtain the highest possible temperature at atmospheric pressure, we can derive the following values from Eq.(2).

$$T = 3 \times 10^4\ (\mathrm{K}) \cong 2.6\ (\mathrm{eV}), \qquad (3a)$$

$$n = 2.4 \times 10^{17}\ (\mathrm{cm}^{-3}). \qquad (3b)$$

In case of a nuclear fusion plasma, as yet unachieved, we calculated at a pressure of a few atmospheres

$$T = 10^8\ (\mathrm{K}) \cong 10^4\ (\mathrm{eV}), \qquad (4a)$$

$$n = 2.4 \times 10^{14}\ (\mathrm{cm}^{-3}). \qquad (4b)$$

In the former case the energy of a plasma particle acting on a test piece surface at atmospheric pressure is less than a few electron volts and the particle density is only about 1×10^{23}/cm^2 per second. The energy density obtained by this heat flux is 6×10^4 W/cm^2, smaller than that of either a laser or a charged particle beam. In order to obtain an energy density of more than 1×10^6 W/cm^2 which is the same level as the laser or charged particle beam heat sources, we must resort to the high temperature plasmas created by nuclear fusion at one hundred million degrees Kelvin.

Thus, it is very difficult to obtain the same high energy density as laser and charged particle beams in a plasma beam which is governed by Eq.(1). There is a method of utilizing plasma beams as a high energy density heat source by making it at an arc state, whose characteristics

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differ from those of other heat sources in the fact that it behaves in the same way as a gas fluid. For instance, 1) it is easy to obtain dynamic pressures, 2) shock waves are generated at the speed of sound. They can be either an advantage or a disadvantage when used as a heat source.

As described above one of the simple methods of obtaining high energy density plasma beams is to create an "arc state" of the plasma i.e., to generate joule heat by the flow of electrical current through the plasma. When it is used as a heat source, however, we must consider the following problems;

(A) the achievement of a high energy density in the region where joule heat is generated,
(B) the achievement of a high energy density in the region near the electrode.

2 Achievement of a High Energy Density in the Region Where Joule Heat is Generated

The region is generally called an "arc column". In order to maintain a temperature T in this arc column, a certain amount of energy (the input energy W_a) per second and per unit length of the arc column must be input. At the same time, there is an energy output (energy loss W_L), resulting in the following energy balance.

$$W_a = W_L \quad (5a)$$

$$= W_{LT} + W_{LR} + W_{LO}\,, \quad (5b)$$

where W_{LT} is the energy loss related to the increase in temperature and is the most important factor in the generation of a high energy density. W_{LR} is the radiant energy, and W_{LO} is all energy loss other than W_{LT} and W_{LR}, as described below.

The energy loss W_{LT} is carried out through the surface of the arc column. This loss is thus proportional to the surface area S_L, to the temperature gradient from the center to the surface, and to the thermal conductivity κ.

When the plasma column has a temperature gradient in the radial direction and heat is generated only by the flow of electrons, the thermal flux density, $i_T = \kappa E_T = -\kappa$ grad T, has the same form as in a simple Ohm's law, $i = \sigma E = -\sigma \operatorname{grad} V$. Therefore, the energy W_{LT} that is transferred outside the arc column through the surface area S_L is

$$W_{LT} = S_L\, i_T\, (\equiv I_T), \quad (6)$$

where,

$$i_T = -\kappa \text{ grad } T \quad (7a)$$

$$= \kappa E_T, \quad (7b)$$

$$E_T = -\text{grad } T. \quad (8)$$

Thermal conductivity κ is primarily dependent on temperature T, as shown in the following equations. For a fully ionized hydrogen plasma,[1)]

$$\kappa = 4.67 \times 10^{-10}\, T^{5/2}\, (C^* \ln \Lambda)\ \text{(cal/deg-m-sec)} \quad (9a)$$

$$\cong 2 \times 10^{-11}\, T^{5/2}\ \text{(cal/deg-m-sec)} \quad (9b)$$
(in hydrogen plasma)

where $C^* \equiv \kappa^*_L/Z$, Z is the charge number and κ^*_L is the correction term of collision, such as ion recoil due to collisions of electrons or ions. C^* is 0.225 for a high power hydrogen plasma jet with $Z = 1$, and the plasma parameter in $\ln \Lambda$ is 5-6 (this is 15-20 in nuclear fusion plasma), thereby resulting in Eq.(9b).

S_L and i_T have a very close relationship which forms the basis for the generation of a high energy density in an arc column. If S_L is constant, i_T is a function of the temperature only and becomes heat loss due solely to electrons. Therefore the energy loss W_{LT} or total heat flux I_T increases dramatically as the temperature increases. In other words, the greater the increase in I_T, the higher the temperature of the arc column and the higher the energy density that can be obtained. This is the important point of the so-called "thermal pinch" phenomenon[2)], and studies have been made on how to cool the arc column from the "Gerdien arc"[3)] up to the present day plasma jet. This problem must be studied on in more detail by examining various factors to increase i_T.

2.1 Effect of S_L

S_L is an important parameter which plays a fundamental role in increasing i_T, dominating the functioning of the "thermal pinch" phenomenon. There are two ways of reinforcing the function of this phenomenon by increasing i_T.

2.1.1 *Increase in i_T due to a reduction in S_L*

When the cross-section of an arc column is circular and the plasma behaves in a self-sustaining manner according to the "minimum energy principle", reduction in S_L will result in an increase in i_T. Conventional arc columns which are governed by the thermal pinch effect belong to this category. Their examples are a plasma jet and "Gerdien arc", where S_L is written by

$$S_L = 2\,\pi \mathrm{r} \quad (10)$$

per unit length of the column and r is the column radius. The gas tunnel type plasma beam,[4)] or plasma jet,[5)] developed by the authors, also belongs to this category. It is important to obtain practical methods to decrease S_L as low as possible or to make it at a constant value even at an increase in the arc current.

2.1.2 *Increase in i_T due to an increase in S_L*

As described already, an arc column autonomously forms a profile which minimizes energy loss. Since the development of arc by Davy in 1801 and the application of the carbon arc heat source to welding by Benardos and Olszewski in 1885, it has been considered that the energy density of the arc column is very difficult to control. Only the plasma jet, which follows a Gerdien arc or a wall stabilized arc, etc., were examples overcoming this difficulty, although they still follows the autonomous variations of the arc column.

The authors have tried to overcome the autonomous characteristic of the arc column and examined to increase S_L. As shown in **Fig. 1**, we thought of flattening the circular cross-section of the arc column,[6] and succeeded in obtaining such a configuration by applying the cusp magnetic field shown in **Fig. 2.**[7] The i_T increased dramatically and W_{LT}, or I_T were enlarged thus creating a high energy density. This has been named a "magnetized sheet arc" by the author. **Figure 3** shows a comparison of the current density of this arc and a conventional arc.

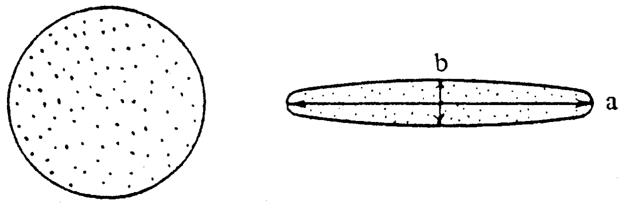

Fig. 1 Column cross-sections of open arc and magnetized sheet arc.

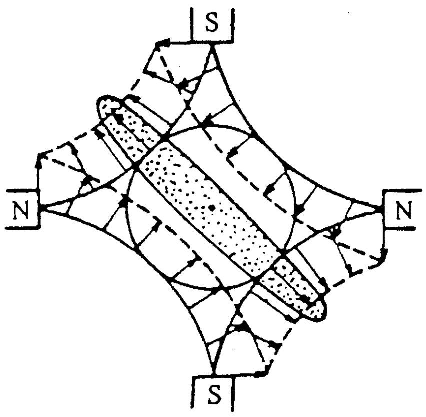

Fig. 2 Block diagram of cusp field.

2.2 Roles of thermal conductivity and temperature gradient

The thermal flux density i_T is determined by both κ and $-$grad T ($\equiv E_T$) as given in Eq.(7). It has been interpreted that the "thermal pinch" phenomenon strengthens whenever there is a large energy loss by cooling of the arc column. The reason why this happens is more clearly understood if we briefly look at the role of the parameters which determine energy loss and dominate the generation of a high energy density. For example, in the following equation.

$$i_T = \kappa_T E_T \tag{11}$$

an increase in E_T and not in κ_T will generate a high

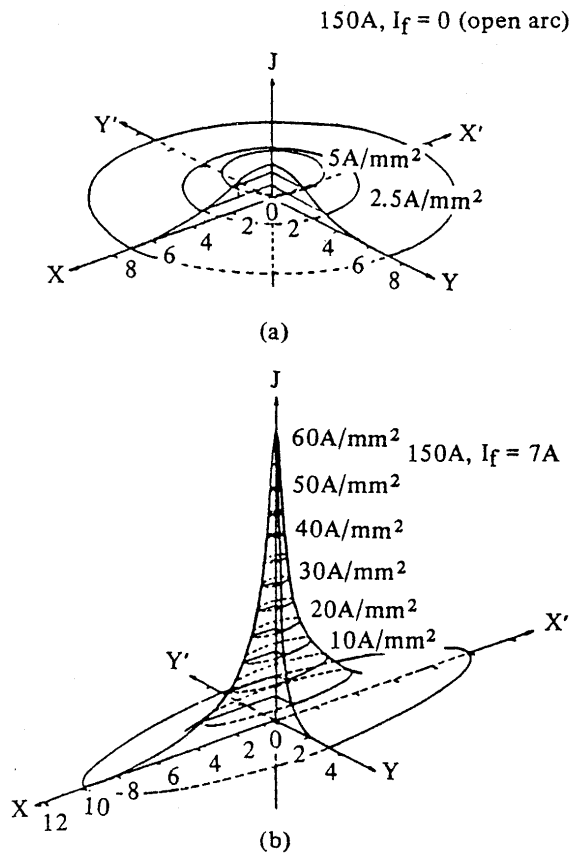

Fig. 3 Current density distributions of open arc and arc in cusp field.

energy density by the increase in i_T. When $\kappa_T = \kappa$, as shown in Eq.(9), κ_T can be determined only by the temperature T. While in case of $\kappa_T = \kappa_{eff}$ as descided later, the situation becomes more complex and generally κ_{eff} is larger than κ and sometimes $\kappa_{eff} \gg \kappa$.

On the other hand, if we suppose the existence of an arc column which has the property of $\kappa_T \approx 0$ and which is thermally insulated from the outside, we can imagine that the i_T loss is remarkably small and E_T is very large. It is considered that this thermally-insulated state is very useful in generating both a high temperature and a high energy density. In other words, E_T is the most important parameter affecting whether or not a high energy density is generated. Thus increasing i_T by increasing E_T is a very effective way to enhance the functioning of the "thermal pinch".

Moreover, if a special phenomenon of $\kappa_T \approx 0$ as described above occurs, for example if κ approaches zero on the surface of the arc column, the energy loss become extremely small and a state of thermal insulation will occur. Even though there is a cold wall outside the arc column, due to the state of thermal insulation, both a high temperature and a high energy density can be generated inside the column. If such an arc column can be created, it will have great advantages over a conventional plasma in a high-vacuum and will be a preferable method of producing high temperature plasma for bringing about nuclear fusion. The author is very interested in what level the "magnetized arc column" can approach to this special condition. The problem is how to reduce the magnetized thermal conductivity, κ_{mag} compared to κ.

As an example of making κ_T be very small with a large E_T in case without external magnetic field, there is so-called "Kapitza plasma"[8]. It was reported that a high temperature hydrogen plasma of 10^6K was obtained steadily in an atmospheric pressure by using a high power microwave energy. The author was so much interested in this result and made a study of confirmation. But we obtained a plasma beam with a temperature of only about 1×10^4K.[9] Therefore, we tried to use a pulse discharge to heat this plasma beam adiabatically. We super-imposed a pulsed high current of a few kA on this plasma beam, resulting in obtaining a fully ionized plasma beam with a temperature of 5×10^4K at atmospheric pressure during a few microseconds.[10]

This experiment was carried out without an external magnetic field. If a strong external magnetic field is applied upon this plasma beam with the supply of a rapidly rising pulsed high current to obtain an effective self magnetic pinch, a stable heating would be carried out more effectively, inducing the production of ultra-high temperature plasma. It will eliminate the "wall-problem" in a high-vacuum type nuclear fusion plasma and are sure that it will lead to studies into new types of plasma production for nuclear fusion.

2.3 Forced cooling of the arc column

The arc column can be cooled by an electrically insulating fluid (gas or liquid). If cooled by a liquid, the energy loss from the arc is mainly the energy of vaporization, and in case of a gas cooling the loss appears in the form of dissociation and/or ionization energy. This energy is equal to W_{LO} in Eq.(5b). It is the energy loss not directly related to the temperature rise.

2.3.1 *Forced cooling by a laminar vortex flow*

Forced cooling of the arc column by a laminar vortex flow maintains an outside temperature to a fixed valve and does not make it increase. Therefore, an increase in the joule heating of the arc column will correspondingly raise the arc temperature. In this case, the heat flux within the arc column i_T follows the Eqs.(6) – (9).

One of the most effective example of this is the "gas tunnel"[11] type plasma beam developed by the authours. **Figure 4** compares the pressure distribution in the special vortex flow of a gas tunnel type plasma beam and that in the conventional type of vortex flow used for typical plasma jets. In the former a vacuum of only a few Torr can be maintained under appropriate conditions along the central axis against a gas pressure of 1 atmosphere at the circumference. When an arc column is generated in this

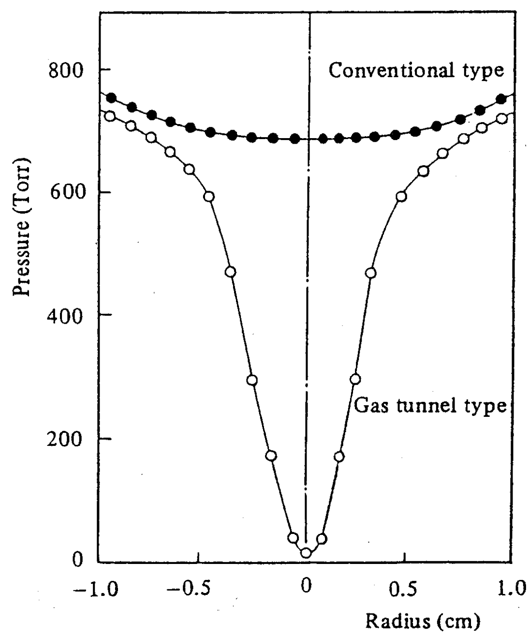

Fig. 4 Pressure distribution in a vortex chamber.

Working gas:	air
Gas flow rate:	250 ℓ/min
Velocity at wall:	150 m/s

gas tunnel, V-I characteristic of the discharge is different from that of a conventional plasma jet and typically displays "a positive characteristic"[5]. As a result, it is easy to obtain high temperatures of a few tens of thousands of degrees Kelvin.

2.3.2 *Forced cooling by fluid flowing through the arc column*

A strong cooling effect can generally be achieved by means of turbulence caused by convection between the inside and the outside of the arc column. This cooling phenomenon is easily generated in an actual arc column. The following two methods in particular are used, allowing gas flowing from outside through the arc column to pass along and/or across the column. The former method is used for conventional plasma jets, while the latter is realized in "high-speed linear running arcs" by the magnetic drive, and "rotating arcs," or in a "arc in high-speed fluid". For these methods, it is necessary to consider not only Eqs.(6) – (9), but also the new factors of energy loss. As described above in Eqs.(6) – (9), the current of thermal electrons plays the main role in the heat loss of i_T or I_T, which are necessary for increasing the temperature. This increase in heat loss, however, is extreme in cases where the arc column is cooled by fluid flowing through the column because the fluid carries energy away from it corresponding to the fluid velocity. In other words, the time that a plasma particle in the arc column stays in the column, i.e., the "average lifetime" τ_{ap}, becomes very short, and new cold particles enter into the column. Thus the heat loss from the arc column becomes greater, and the thermal conductivity changes to the so-called "effective thermal conductivity", κ_{eff} which is larger than κ in Eq.(9). κ is affected solely by the electron flow, while κ_{eff} includes the influence of various types of particles – electrons, ions and neutrals. Consequently,

$$i_T = -\kappa_{eff}\,\mathrm{grad}\,T\;(\equiv \kappa_{eff}E_T)\,, \qquad (12a)$$

$$I_T = S_L\, i_T\;(= W_{LT}). \qquad (12b)$$

The energy loss by Eq.(12) is larger than Eq.(6), but it does not always lead to a higher temperatures or a higher energy density, as described in section 2.2. Therefore, it is necessary to decide on an actual case by case basis which way is more advantageous in practical use of this energy loss.

3. High Energy Density at the Point of an Electrode

In many cases, the region in the vicinity of the electrode (around the anode or cathode drop) of the arc column is utilized actually as the practical heat source. Typical examples are arc welding, plasma arc welding, arc spraying, and discharge processing in liquid. Usually the electrode drop of arc heat sources is usually ten volts or less and the current density in about $10^2 - 10^4$ (A/cm^2). The energy density is higher than that of an arc column. But the conventional method used for generating high energy density plasma beams has disregarded to make use the electrode spots.

The energy density of an anode spot is generally smaller than that of a cathode spot. Using the vortex flow of a gas fluid, the authors were able to generate a high energy density at the anode spot[12]. The method and a cross-section of the apparatus used are shown in **Figs. 5** and **6**. A high energy density anode spot was obtained, which the author has named an "arc ball,"[13] as shown in **Fig. 7**. The current density of this arc ball is an extremely high value of 10^5 (A/cm^2) or greater, and the energy density is as high as even over 10^6 (W/cm^2). This state can be constantly and stably maintained at a fixed position. The authors call this arc a "point arc." This arc has a superior character as a heat source for processing. We have obtained using this arc a weld bead cross-section with a similar penetration as the one obtained by non-vacuum EB welding as shown in Fig. 7(C).

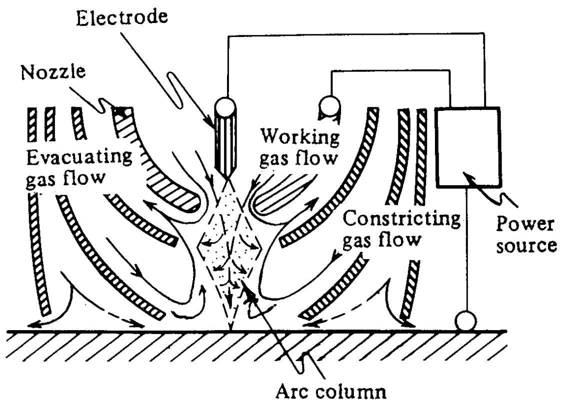

Fig. 5 Principle for generating "point arc".

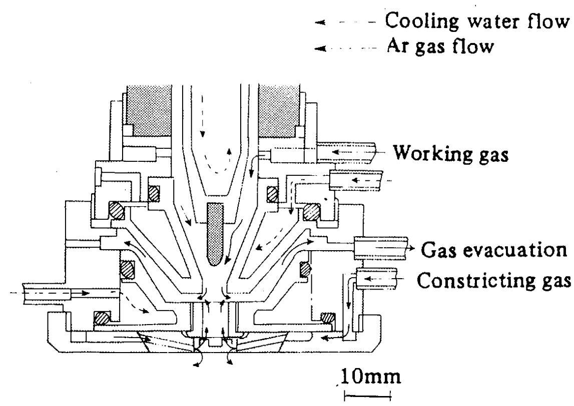

Fig. 6 Cross sectional view of point arc torch.

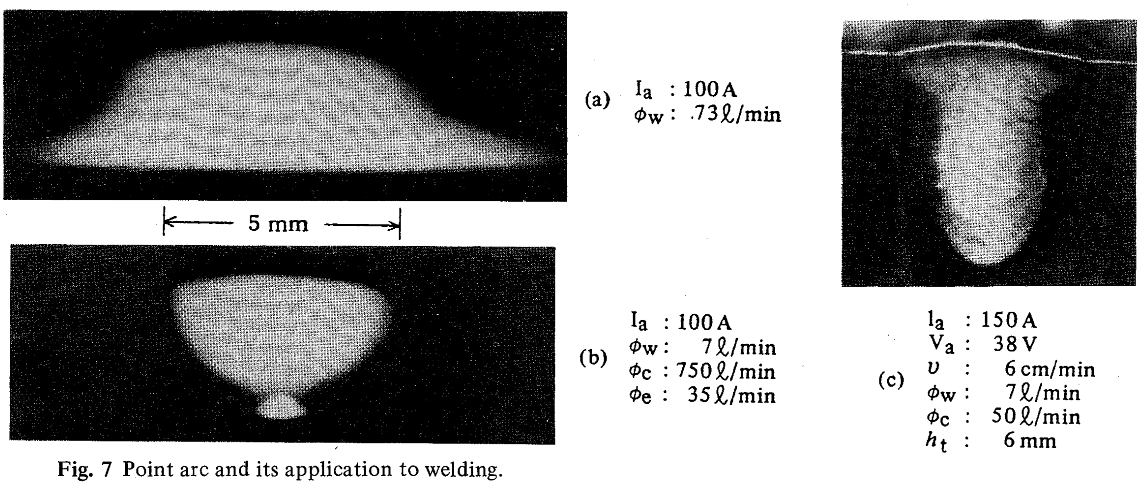

Fig. 7 Point arc and its application to welding.
(a) (b); Various aspects of arc constricted by gas flow.
I_a : Arc current
ϕ_w : Working gas flow rate
ϕ_c : Constricting gas flow rate
ϕ_e : Evacuating gas flow rate
(c); Bead cross section by point arc welding.
V_a : Arc voltage
v : Welding speed
h_t : Thickness of work
Material of work : Stainless steel SUS 304

4. Summary

This paper describes in general the thermal characteristics of a plasma beam as well as some properties, which enable the achievement of a high energy density. The author hopes that the results shown in this work will help to open a new area of study in the field of plasma heat sources.

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