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Prediction of extinguish boundary of radio frequency thermal plasma torch within carrier gas injector

Mingqing Nie[1], Xiangyang Liu[1], Long Miao[1], Ruoyu Han[2], Xiaoyu Wang[1], ZhengXi Zhu[1], Yuri Mihailovich Grishin[3], and Ningfei Wang[1]*

[1]*School of Aerospace Engineering, Beijing Institute of Technology, Beijing, China*
[2]*School of physics, Beijing Institute of Technology, Beijing, China*
[3]*Department of Thermophysics, Moscow State Technical University N E Bauman, Moscow, Russia*
[*]*miaolong@bit.edu.cn*

Abstract. In present paper, a two-dimensional transient laminar model has been developed to predict the extinguishing boundary of radio frequency thermal plasma torch. The influence of the discharge frequency, gas flow rates of central, intermediate and sheath gases (Q_1, Q_2, Q_3) on the extinguishing boundary has been determined. It is found that the value of the minimum sustaining power of rf thermal plasma monotonically rises up with increasing the flow rates of carrier Q_1 and intermediate Q_2 gases. And when the flow rate of sheath gas Q_3 and the discharge frequency f increase, the value of the minimum sustaining power monotonically decreases. The results in present work could provide useful information for organizing the working gas supply system to obtain a stable discharge in induction thermal plasma torches.

Keywords: radio thermal plasma torch; extinguishing boundary; minimum sustaining power; gas flow rates; discharge frequency.

1. Introduction

At present the induction coupled thermal plasma has been widely used for nanoparticle synthesis, particle spherization, spectrum analysis [1]. The precursors are usually injected into the RF thermal plasma torch through the injection probe tip, due to the relatively high specific enthalpy, long resident time and high atmospheric purity of induction thermal plasma, a high processing efficiency of precursors and high purity materials could be obtained. While the stable rf thermal plasma could be observed only when the coupled power in plasma is above the minimum sustaining power. When the coupled power is below the minimum sustaining power, the local energy dissipation through ohmic heating could compensate the energy losses from the discharge through radiative energy transfer, conduction and convection to the surrounding of the discharge rf inductively coupled plasmas and maintain the discharge at the lower limit of its electrical conductivity.

In the past few decades, a series of analytical and numerical models have been developed to predict the extinguishing boundary of ICP torch based on the energy or momentum balances, Klubnikin [2] study the gas dynamic field in rf thermal plasma torch under low and high gas flow rates of working gas. It is found that the increase of gas flow rates blows the high-temperature region downstream, which could finally extinguish the rf discharge under a further increase of its flow rate. Based on a simplified mathematical model, Thorpe [3] clearly indicate that, for a given plasma gas at a given pressure, the minimum power required to sustain a stable discharge, drops exponentially with the increase of the discharge frequency. However, the above studies only qualitatively demonstrate the effect of the working gas flow rate and discharge frequency on the extinguish boundary. Until now the study about the prediction of extinguishing boundary for ICP torch with three gas supply channels under different gas flow rates for carrier, intermediate and sheath gases is still few. The influence of gas dynamic fields (organization of oncoming working gases Q_1, Q_2, Q_3) on the stable discharge characteristics of RF thermal plasma is still now unclear.

In present paper, a two-dimensional transient laminar model has been developed to predict the extinguishing boundary of radio frequency thermal plasma torch. The minimum coupled power to sustain the stable ICP discharge had been determined. Special attention has been paid to investigate the influence of coupled power in plasma on the evolution of gas dynamic fields and discharge characteristics of argon induction thermal plasma torch. The dependence of the minimum sustaining power on the flow rates (carrier gas, intermediate gas, sheath gas) has been determined under different discharge frequencies. The results in present work could provide useful information for organizing the working gas supply system to obtain a stable discharge in induction thermal plasma torches.

2. Physical and mathematical model

Fig.1 shows a sketch of a typical PL-50 torch subjected to radio frequency coil current profile with axial gases supplies and three turns' coils.

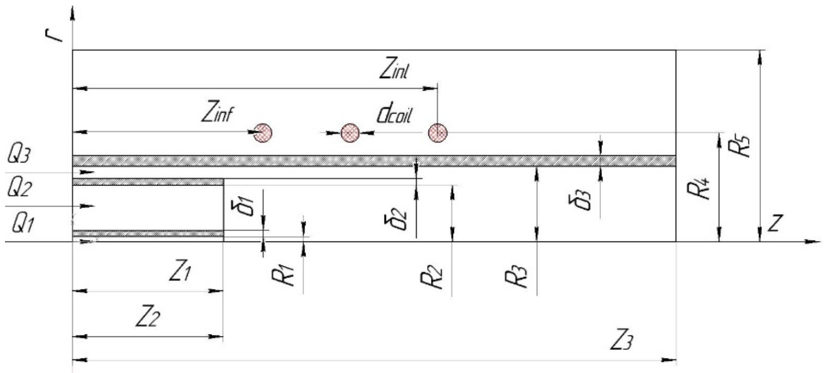

Fig.1. Schematic of the ICP torch.

The ICP torch dimensions and operating parameters are as follows: three copper coils with the same coil diameter d_{coil} = 6 mm and loop radius R_4 = 33 mm is evenly distributed. The first coil is located at Z_{inf} = 63 mm. The distance between the first and last coils is $l_{\text{ind}} = Z_{\text{inl}} - Z_{\text{inf}}$ = 60 mm. The amplitude of discharge current I_{coil} varied in the range of 50–180 A, the discharge frequency f of coil current varied in the range of 3–13.56 MHz, respectively.

The injection probe tip is fixed at Z_1 = 50 mm, the wall thickness of injector probe is δ_1 = 2 mm, while its internal radius R_1 = 1.7 mm. The flow rate of central gas changes in the rangeQ_1 = 1–8 slpm, the intermediate gas Q_2 = 3–12 slpm and the sheath gas Q_3 = 30–70 slpm. The length of plasma confinement tube is Z_3 = 200 mm with an internal radius R_3 = 25 mm and wall thickness δ_3 = 3.5 mm. The peripheral slit channel is also located at Z_2 = 50 mm with an internal radius R_2 = 18.8 mm. The width of coaxial cylinder δ_2 = 2.2 mm. The outer vanishing boundary for the electromagnetic field (where the magnetic potential is equal to zero) is R_5 = 125 mm.

In present work, the plasma is pure argon at atmospheric pressure and in Local Thermodynamic Equilibrium (LTE); the plasma is optically thin body without self-absorption of radiation; the stream flows of central, plasma and sheath gases at the entrances are azimuthally symmetric and stationary; the plasma flow is subsonic and laminar. The spiral inductor is assumed as three axisymmetric parallel coils. Under the fulfillments of these assumptions, the electromagnetic and gas dynamic equations could be written under a two-dimensional model in the (r, z) cylindrical coordinates.

MHD equations are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla P + \nabla \cdot (\mu \nabla \mathbf{U}) + \frac{1}{2}\mathrm{Re}\{\mathbf{J} \times \mathbf{B}^{*}\} \tag{2}$$

$$\frac{\partial(\rho h)}{\partial t}+\nabla\cdot(\rho h\mathbf{U})=\nabla\cdot\left(\frac{\lambda}{C_P}\cdot\nabla h\right)+\frac{1}{2}\mathrm{Re}\{\mathbf{J}\cdot\mathbf{E}^*\}-q_{\mathrm{rad}} \tag{3}$$

$$\nabla^2\mathbf{A}-\mathrm{i}\omega\mu_0\sigma\mathbf{A}+\mu_0\mathbf{J}_{\mathrm{coil}}=0 \tag{4}$$

$$\mathbf{E}=-\mathrm{i}\omega\mathbf{A},\mathbf{B}=\nabla\times\mathbf{A} \tag{5}$$

where ρ is the plasma density, U is the velocity, P is the pressure, μ is the dynamic viscosity, h is the total enthalpy, λ is the effective thermal conductivity; C_p is the specific heat capacity of the plasma gas , q_{rad} is the volumetric radiative loss; μ_0 is the magnetic permeability of the free space, σ is the plasma electrical conductivity and $\omega = 2\pi f$, f is the discharge frequency.

The boundary conditions are given as follows: the gases velocities at the walls are zero. The temperature on the external surface of plasma confinement tube ($r = R_3 + \delta_3$) is equal to 300 K. At the inlets ($z = 0$ mm) the temperature $T = 300$ K. All of the working gases are injected by axis into ICP torch. The injection probe is water-cooled and the temperature is $T = 300$ K. At the outlet ($Z_4 = 200$ mm) the pressure of ICP torch is constant and set at 1atm. The boundary conditions for the vector potential formulation are given as in accordance with [4].

The thermophysical properties and electrical conductivity of argon plasma gas are obtained in the approximation of local thermodynamic equilibrium (LTE) from calculated data [5, 6], a discussion of the use of LTE conditions were made in [7–10]. Under atmospheric conditions, the plasma as a whole could be considered in LTE except at the moment of working modes changing.

3. Results and discussions

3.1 Minimum sustaining power at basic condition

In order to demonstrate the distinguish process under basic condition (Q_1 = 1 slpm, Q_2 = 3 slpm, Q_3 = 31 slpm, f = 3MHz), the amplitude of initial coil current is set at 180A (corresponding $P \approx 8$ kW) to ignite and stabilize the ICP discharge (Fig.2a). When the ICP torch reaches a stable discharge regime, the coil current starts to reduce to a certain constant value. As can be seen that when the amplitude of the coil current reduces to 130A (corresponding coupled power in plasma P = 2.5 kW), the ICP discharge zone still could be sustained (Fig.2b). Even though in this case the dimensions of the skin zone and high temperature zone significantly reduce, the value of maximum gas temperature T_{max} in the ICP torch a little reduce from 9800 to 9500K under stable discharge regimes. The transition time τ for establishing the low coil current regime (I_{coil} = 130 A) from high coil current regime (I_{coil} = 180 A) is found around 320 ms after the pulse front, when the relative changes of the maximum Joule heating and gas temperature are below 5%. A further decrease of the coil current from 130 to 120A could not sustain the stable ICP discharge, the ICP discharge would extinguish after t = 1250 ms (when the maximum gas temperature T_{max} < 7 kK) (Fig.2c). A further detailed study has proved that the minimum coil current (or coupled power in plasma) to sustain the stable ICP discharge is around $I_{coil,min}$ = 121 A (corresponding $P_{min} \approx 1.85$ kW).

3.2. The influence of discharge frequency and flow rates of carrier, intermediate and sheath gases on the minimum sustaining power

In this section, we investigate the minimum sustaining power at different frequencies and different flow rates of carrier Q_1, intermediate Q_2 and sheath Q_3 gases. The typical coupling frequencies f = 3, 8 and 13.56 MHz are chosen. The flow rates of carrier, intermediate and sheath gases vary in the range Q_1 = 2–8 slpm, Q_1 = 3–12 slpm, Q_1 = 30–60 slpm, respectively. Similar to section 3.1, we set a large initial coil current to ignite the ICP torch.

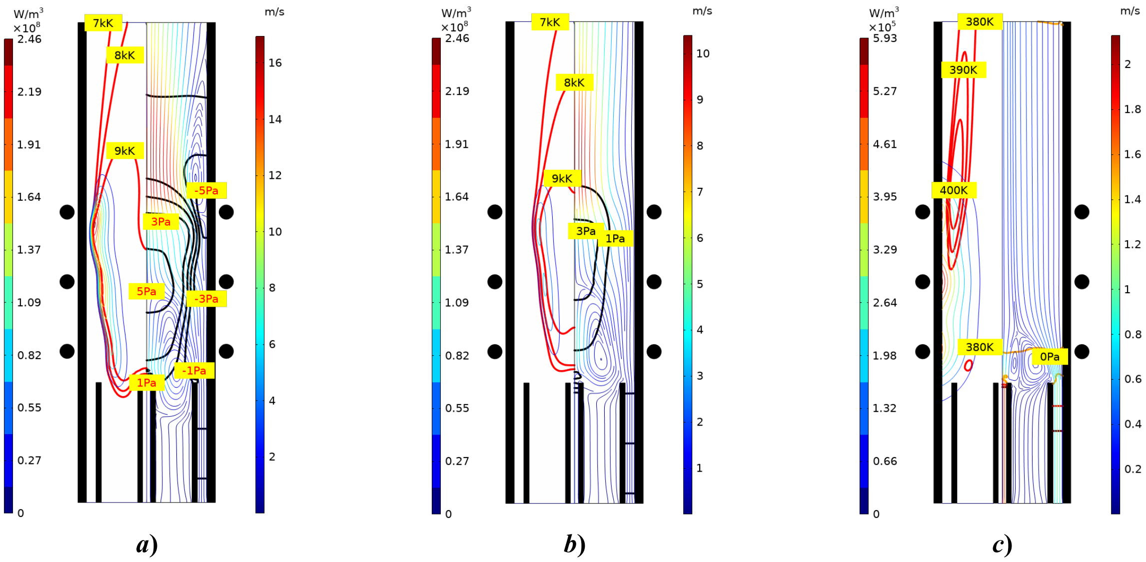

Fig.2. Contours of Joule heating, gas temperature, static pressure and vortex streamlines: (a) I_{coil} = 180 A; (b) I_{coil} = 130A, Δt = 320 ms; (c) I_{coil} = 120 A, Δt=1250 ms.

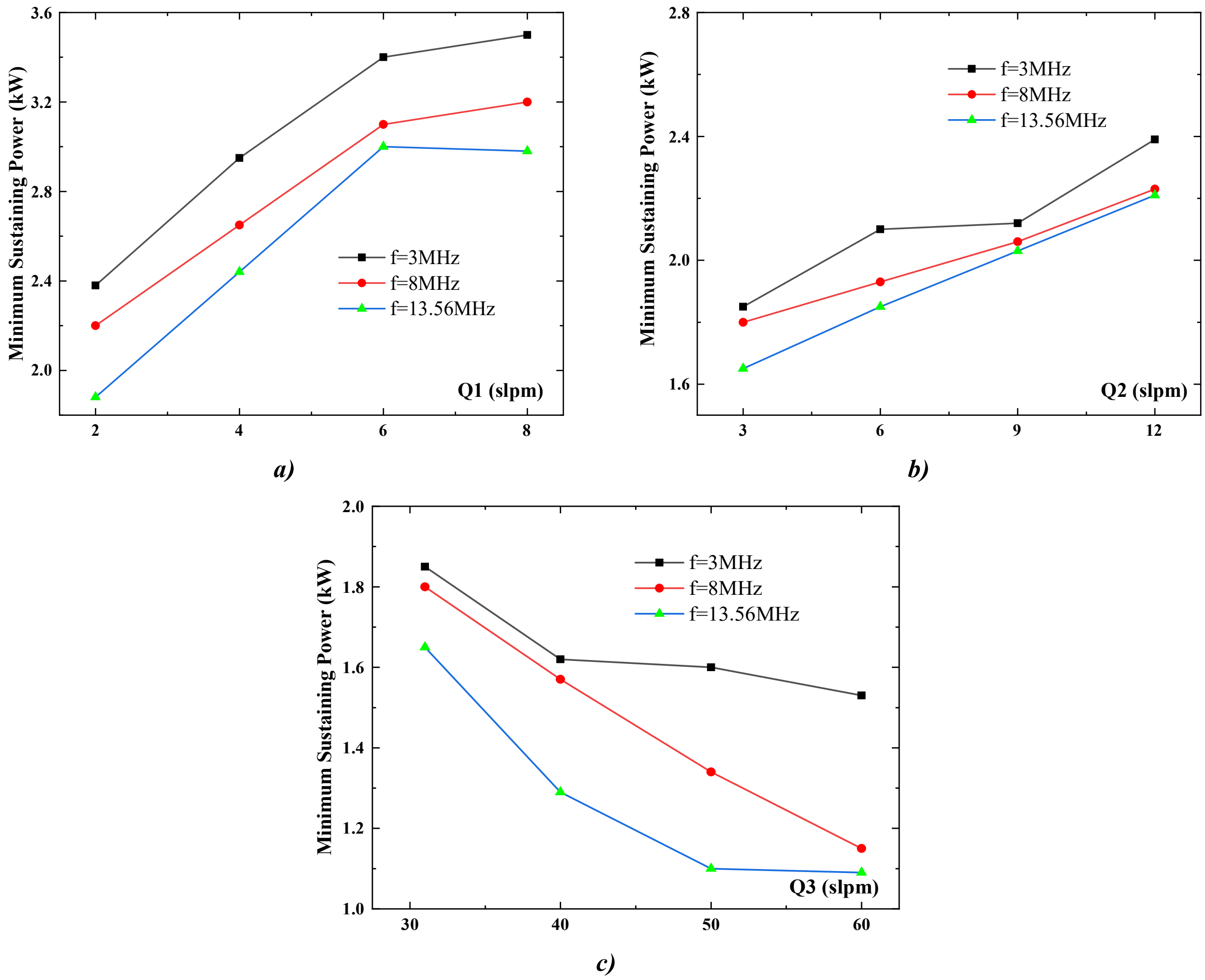

Fig.3. The dependences of minimum sustaining power on the flow rate of carrier gas Q_1 (a), intermediate gas Q_2 (b), and sheath gas Q_3 (c) under different coil current frequencies f = 3, 8, and 13.56 MHz.

Form Fig.3, we can see that as the discharge frequency increases the minimum sustaining power decreases, which fits well with Poole's results [11]. As for the different gas flow rates, when the carrier gas Q_1 and the intermediate gas Q_2 increase, the minimum sustaining power increases monotonically (Fig.3a,b). But the perverse thing is that the minimum sustaining power decreases as the sheath gas Q_3 increases within a specific range (<60 slpm). This can be explained by the fact that a larger Q_3 leads to a reduction in the high temperature zone and a significant reduction in the temperature near the wall, resulting in a reduction in the total heat radiation loss and wall heat loss with little difference in Joule heat power for the same coupling power (see Fig.4 and Table 1.). So, at a same power level, a larger Q_3 allows gas to receive a greater amount of energy, that means the minimum sustaining power will be smaller. However, it is foreseeable that as Q_3 continues to increase, the energy required to sustain plasma generating will be higher, so there must be a limit to the minimum sustaining power, and when this limit is reached, the minimum sustaining power will no longer decrease, but increase.

By the way, the central gas has the most significant influence on minimum sustaining power, followed by the intermediate gas and finally the sheath gas. Taking the case of f = 3MHz as an example, we can find: As Q_1 increases from 2 to 8 slpm, Q_2 increases from 3 to 12 slpm and Q_3 increases from 30 to 60 slpm, this will result in an increase in minimum sustaining power from 2.38 to 3.5 kW, 1.85 to 2.39 kW or a decrease from 1.85 to 1.53 kW, respectively.

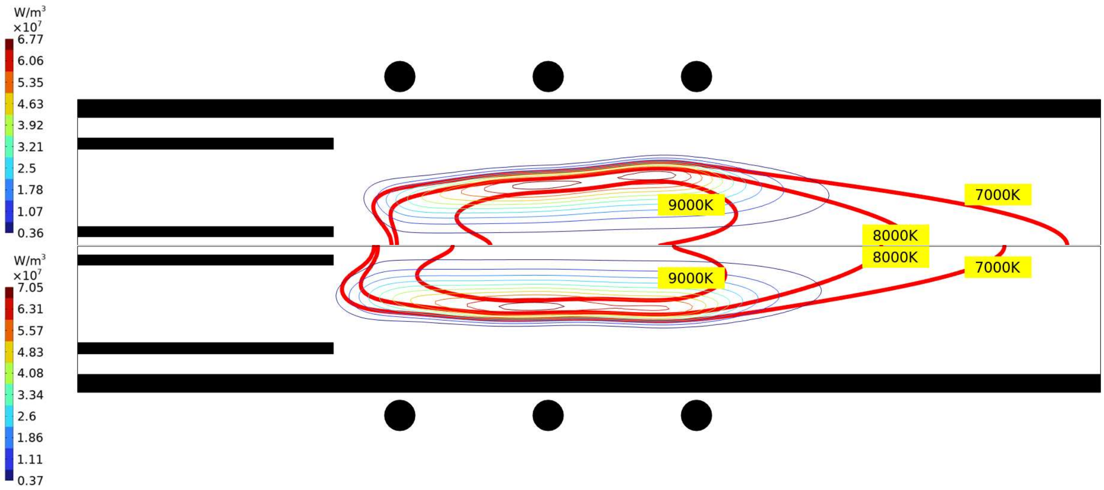

Fig.4. Contours of Joule heating, gas temperature under different sheath gas flow rate: Q_3 = 30 slpm (upside) and Q_3 = 60 slpm (downside) when f = 3 MHz, P = 2 kW.

Table 1. Temperature and energy parameters at different Q_3 when f = 3MHz, P = 2kW

Parameters	Q_3 = 30 slpm	Q_3 = 60 slpm
Average temperature, K	3465.8	3138.9
Joule heating power, W	1973.6	1973.2
Radiation loss, W	446.46	417.33
Wall heat loss (heat transfer + heat convection), W	416.64	143.52

4. Conclusion

In present paper, a two-dimensional transient laminar model has been developed to predict the extinguishing boundary of radio frequency thermal plasma torch. The influence of the discharge frequency, gas flow rates of central, intermediate and sheath gases (Q_1, Q_2, Q_3) on the extinguishing boundary has been determined. It is found that the value of the minimum sustaining power of rf thermal plasma monotonically rises up when the flow rates of carrier gas Q_1 and intermediate Q_2 gases increase, while the minimum sustaining power reduces within increasing the flow rate of sheath gas Q_3. This can be explained by the fact that a larger Q_3 leads to a reduction in the high temperature zone and a significant reduction in the temperature near the wall, resulting in a reduction in the total heat radiation loss and wall heat loss with little difference in Joule heat power for the same coupling power. The results in present work could provide useful information for organizing the working gas supply system to obtain a stable discharge in induction thermal plasma torches.

Acknowledgments

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5. References

[1] Li Y., Tang H., Cai G., Fu C., and Wang W., *Plasma Sources Sci. Technol.*, **31**, 035009, 2022; doi: 10.1088/1361-6595/ac525b

[2] Klubnikin V.S., *High Temp.*, **13**, 439, 1975; http://www.mathnet.ru/links/5be8a49076964d551848bdd18412457c/tvt8907.pdf

[3] Thorpe M.L., Scammon L.W., *Induction plasma heating – High power, low frequency operation and pure hydrogen heating* [online], 1969; url: https://ntrs.nasa.gov/citations/19690014677

[4] Miao L., Grishin Y.M., *Plasma Sources Sci. Technol.*, **27**, 115008, 2018; doi: 10.1088/1361-6595/aae8f2

[5] Cressault Y., Gleizes A., *J. Phys. D: Appl. Phys.*, **46**, 415206, 2013; doi: 10.1088/0022-3727/46/41/415206

[6] Boulos M., *Thermal plasmas: fundamentals and applications*. (New York: Springer Science Business Media, 1994).

[7] Lindner H., Murtazin A., Groh S., Niemax K., and Bogaerts A., *Anal. Chem.*, **83**, 9260, 2011; doi: 10.1021/ac201699q

[8] Aghaei M., Lindner H., and Bogaerts A., *Spectrochim. Acta, Part B*, **76**, 56, 2012; doi: 10.1016/j.sab.2012.06.006

[9] Gravelle D.V., Beaulieu M., Boulos M.I., Gleizes A., *J. Phys. D: Appl. Phys.*, **22**, 1471, 1989; doi: 10.1088/0022-3727/22/10/009

[10] Mostaghimi J., Proulx P., Boulos M. I., *J. Appl. Phys.*, **61**, 1753, 1987; doi: 10.1063/1.338073

[11] Poole J.W., Freeman M.P., Doak K.W. and Thorpe M.L., *Simulator test to study hot-flow problems related to a gas cooled reactor* [online], 1973; url: https://ntrs.nasa.gov/citations/19740002564