The rediscovery of an *old* plasma torch

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Introduction A plasma torch, made half a century ago and then abandoned, is reexamined, despite having been rediscovered ten years after its construction.

Induction Plasma Design for High Power Levels

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Babat[1] investigated the induction heating of stationary air plasmas to produce high-power-density thermal plasmas. Induction coupled plasmas torches with flowing gas at atmospheric pressure were first introduced by Reed.[2,3] Induction heated thermal plasmas have found a wide variety of scientific and technological applications because of the high equilibrium temperatures that can be produced in a variety of gases without contamination from electrodes.

Unfortunately high-power-density plasmas require high voltages between adjacent turns of the induction coil, and in attempting to go to high power levels this high field can cause a breakdown between coils. High power levels also cause more heat transfer to the containing walls, usually made from quartz, and can cause melting of the walls and breakdown. Thus the upper power limit is set by the coil insulation and the nozzle cooling.

A new torch design is described here which gives improved insulation between the coils and at the same time cools the nozzle so that it is possible to go to higher power levels than can be achieved in conventional torches. This is constructed from a helical quartz tube held at the bottom of a coaxial tube either by an external support or by soldering, as shown in Figs. 1 and 2. A flexible conductor is threaded into the quartz helical tube so that water can flow around and along the conductor itself which is heated both by rf losses and by plasma radiation.

The flexible conductor can be a braided shielding of tinned copper wires. The conductor is inserted into the quartz coil by a nylon wire previously inserted with the help of a jet of compressed air.

The quartz coil is easily soldered to the vertical gas carryng tubes that are of quartz too. The soldering is at the bottom of the coaxial tubes but no seal is necessary because the argon streaming is expanding in the free air and the plasma flame may contact the quartz coil.

The torch shown in Fig. 2 has been operated at a calculated power level of 8.1 kW for 3 h without damage. A larger torch was operated at a plasma power level of 37 kW and used to spheroidize uranium dioxide in oxygen. The size of this torch is 20 cm in height and 6 cm in diameter.

The author would like to thank Mr. Arbore for construction of the quartz torches, Mr. Cassina for the use of laboratory facilities of the Soc. Aetron, and the Soc. ARS for financial support.

1 G. I. Babat, J. Inst. Elec. Engrs. (London) **94**, 27 (1947).
2 T. B. Reed, J. Appl. Phys. **32**, 821 (1961).
3 T. B. Reed, J. Appl. Phys. **32**, 2534 (1961).

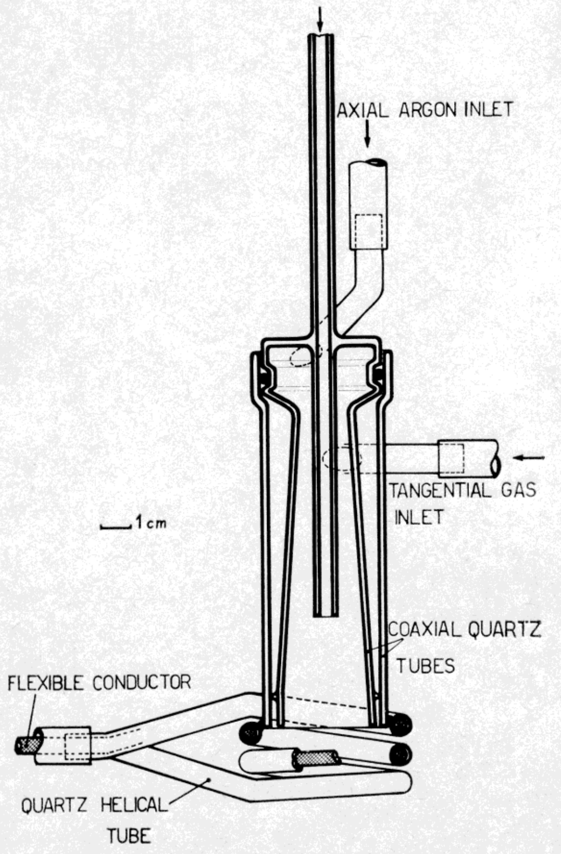


Fig. 1. Schematic view of the first successful plasma torch of new design.

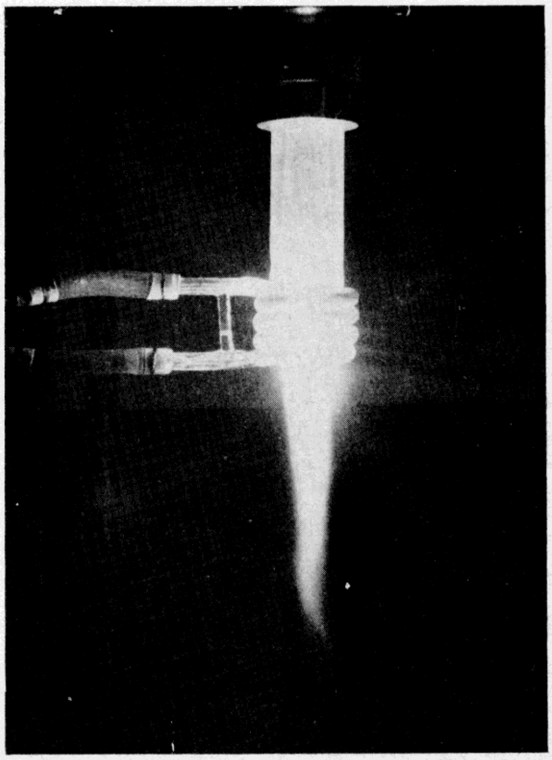


Fig. 2. A typical plasma flame (argon) obtained from the plasma torch of new design.

Fig. 1 Reproduction of the paper (1) published in "***Journal of Applied Physics***, Vol. **41**, No. 7, 3194, (1970)".

Perhaps the first plasma torch, powered by an induced radiofrequency current, was that of Reed (2). As is known, it consisted of a simple quartz tube around which some coils of a thin copper tube were wound. A radiofrequency current (a few MHz) passed through the copper tube, with an intensity of up to some tens of Ampere. The spiral is the primary of a "transformer" whose secondary is made up of the plasma that forms inside the quartz cylinder. Cooling water flows through the spiral. The plasma torch we are talking about (which we will call **torch1** - Fig. 1) was made as part of a program for the preparation of fissile material for a fluidized bed nuclear reactor in which uranium oxide in the form of particles would be used spherical. Sphericity is essential to allow a smooth flow of refrigerant gas. (gas cooled fluidized bed nuclear reactor - High Temperature Gas Cooled Reactor (HTGR)).
The article (1): "Induction Plasma Design for High Power Levels" was taken up by the research group of Yoshida et al. (3) of Tokyo University. Eleven years later they published the study of a similar plasma torch. In the article by Yoshida's group the version of the torch (indicated as TORCH A) was modified with an important innovation. In the aforementioned work by Yoshida et al. (3) the TORCH A, is identical to the torch1 of (1). The dust, or gas to be treated, was entrained by a flow of carrier gas, injected directly into the plasma "flame", with two small tubes passing between the last two turns of the radio frequency coil (see Fig. 2a).

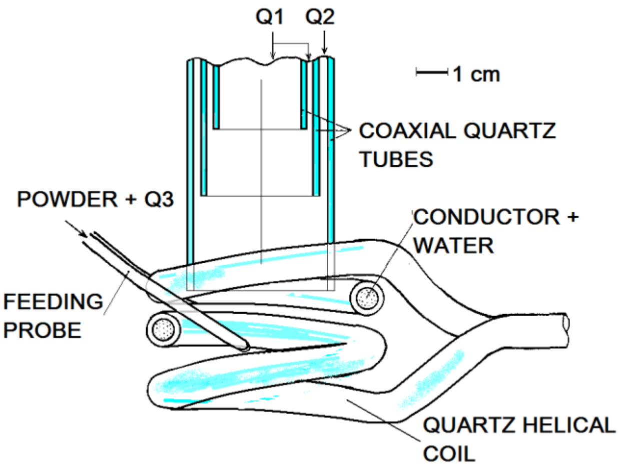
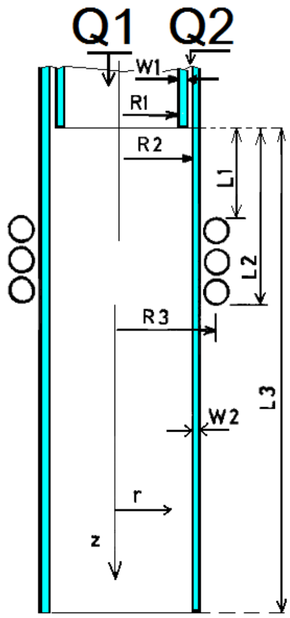


Fig. 10. Schematic view of newly designed rf plasma torch.

(a

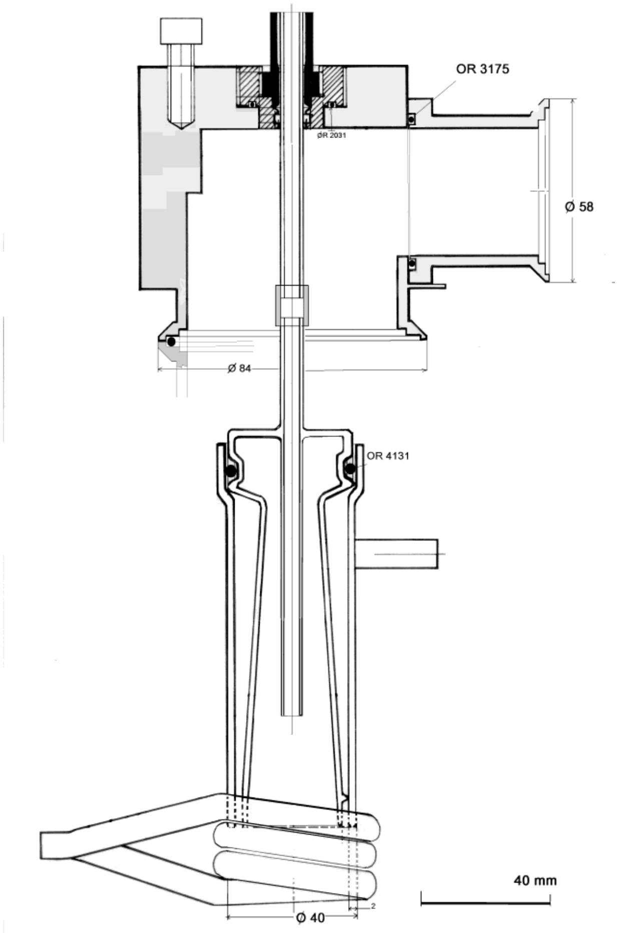


(b

Fig.2a (from Fig 10 in ref. (3)) view of the torch with the inlets of the material to be treated.
Fig.2b shows the model in which all the gas inlets are shown (TORCH B). This scheme is the basis for the calculation of the temperature and plasma velocity in torch-like **torches1** carried out by Yoshida et al. Ref. (3)

From (3) "*In the new rf plasma torch …….., the reagent is radially injected into the hottest part of the plasma through quartz capillary tubes set symmetrically between an inductor coil.*"
The Yoshida paper (3) shows a research that can be considered a continuation and a completion of my work (1) published in 1970. The research of the Japanese was aimed at realizing a plasma torch suitable for many uses. The concern was to make a torch with stable operation, without the risk to extinguish. I quote from (3) "… *there are only a few successful processes. Especially in cases in which endothermic reactions or evaporation of solid particles are used in the plasma pro-*

cess, the efficiency has been much less than what would be expected from thermodynamic considerations. The major reason is that the injection of reagents into the plasma resulted in turbulence and rapid cooling when the amount of the reagents exceeded a certain relatively small quantity. Accordingly, the key to success for the operation of rf plasmas in various applications depends to a large extent upon the ability to sustain a stable plasma, in particular, when reagents are being injected.…Though a large number of theoretical and experimental investigations of rf plasmas have been reported, …. surprisingly little attention has been given to the plasma extinction phenomena. Even the stability problem of an rf plasma has been explained only qualitatively"



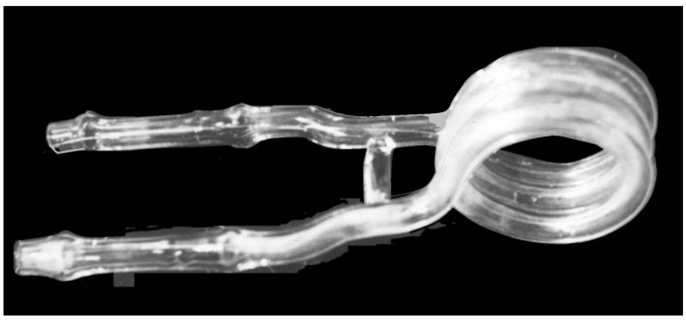


Fig. 3 The torch1 was mounted on the top of powder cooling column. On the right is represented the quartz spiral in which the conductor for the rf current is inserted.

By adopting **torch1** as TORCHA the result was a very stable plasma. From (3): "*The flow and temperature fields in the torch of two different types (i.e., general configuration and new-design one) were calculated. The method employed here is based on the model developed by Boulos, (4) that is, the continuity, momentum, and energy equations were solved simultaneously with the electric and magnetic field equations making use of the numerical procedure developed by Gosman et al. (5) The equations were essentially the same as those used in Boulos' model except that the magnetic and electric field equations were integrated as a two-point boundary-value problem rather than the initial-value problem. … the axial profile of the magnetic field intensity along the symmetry axis differs from the results of Boulos. Therefore, we shall now present here only the electromagnetic field equations and the auxiliary equations … The relevant Maxwell equations, neglecting the displacement currents, are:*

$$\text{rot } \mathbf{E} = -\xi \frac{\partial \mathbf{H}}{\partial t} \quad (1)$$

$$\text{rot } \mathbf{H} = \sigma \mathbf{E} \quad (2)$$

*where **E**, **H**, ξ, and σ are the electric field, the magnetic field, the magnetic permeability, and the electrical conductivity, respectively. If the magnetic field produced by the inductor coil is essentially in the axial direction, we have **H** = H_z (of course, H_z is a phasor quantity). Consequently, an equation containing only H_z is obtained by substituting Eq. (2) in Eq. (1). ….. Computation was made for an argon plasma under atmospheric pressure with an oscillator frequency of **4 MHz** and an rf coil current of **110 A** in order to compare it with our experimental conditions. The parameters used for the computation are the plasma gas flow rate **Q1**, the sheath gas flow rate **Q2**, the carrier gas flow rate **Q3**, and the average swirl velocity at the sheath gas inlet V_θ (the swirl was restricted to the sheath gas). The operating conditions are shown in Table I…..*

*2.3.2. Temperature and Flow Fields **- T**he energy equation used in this model was written in terms of the enthalpy. … Note that the temperature for the central part at the three levels is practically the same in spite of notable differences of the input power profiles. ,... Figure **4a** shows the stream-line patterns (left) and temperature distributions (right) for plasma No. 1* (see Table 1).*It can be seen that a large recirculation eddy exists in the upper part of the plasma. This eddy produces a back flow of the order of 10 m/sec and extends the high-temperature region above the inductor coil. Therefore, if one wants to introduce reagents into the plasma perfectly, the injection velocity of the carrier gas must be high enough to overcome the back-flow velocity. As a rule, 2-3 liters/min carrier gas with a linear velocity of more than 5-6 m/sec at the outlet of a feeding probe located at an appropriate position is needed to do so. However, this carrier gas injection forms a low-temperature channel along the centerline, resulting in a hollow plasma, which means that the convection heating of the central part is negligible with the exception of the region of the recirculation eddy, as is clearly shown in the figure. … if higher feeding rates are adopted, some percentage of the reagent will deviate from the channel and diffuse into the recirculation eddy. percentage of the reagent will deviate from the channel and diffuse into the recirculation eddy. Consequently, this may bring about a substantial change in the temperature and flow fields in the recirculation eddy, resulting in an instability of the plasma impedance leading to extinction of the plasma.*

*Note that the recirculation eddy exists above the second turn of the coil. Therefore, the disturbance of the recirculation eddy will be minimized if the carrier gas is radially injected into the hottest part of the plasma from the level between the second and third turn of the coil. Figures **2a**, **2b** show this case (plasma No. 4 – Table 1). The assumed carrier gas flow rate is 9.5 liters/min, which corresponds to a linear velocity of 1.0 m/sec at the exit. As mentioned in Section 2.2, a ring slit had to be assumed in this calculation, which resulted in this low linear velocity. The plasma gas and sheath gas flow rates are the same as those of plasma No. 1 (TORCH A). The presence of such a radial flow seems to have relatively little effect on the temperature contours, except that the radial flow pushes the contours slightly inward. …. the radial injection only results in a 2-mm shrinkage of the plasma radius, and that the carrier gas can be heated up effectively by the input power. The stream-line patterns, even when a high carrier gas flow rate was used, exhibit little change in the recirculation eddy, as expected. The carrier gas with a linear velocity of the order of 1 m/sec cannot penetrate the plasma, as shown in the figure. However, if the ring slit were replaced with capillary tubes, the carrier gas could have higher linear velocities even when a low carrier gas flow rate of the order of 1-2 liters/min were adopted. In this case, penetration and more effective heating might be achieved. These results provide evidence that the new injection method* *is superior to conventional injection because of its ability to sustain the plasma when reagents are injected…"*

In those years it was impossible to simulate the boundary conditions due to the quartz spiral. In the simplified model adopted by Yoshida (Fig. 2b, 3a) the spiral with the rf current was placed outside a simple cylindrical tube. Figure 3 shows the model adopted by Yoshida (3) for the simulation. The result is in Figure 4a (the coloring to highlight the distribution of temperatures has been added). In Fig. 4b the temperature distribution as it results from Voronov's calculations (6,7)

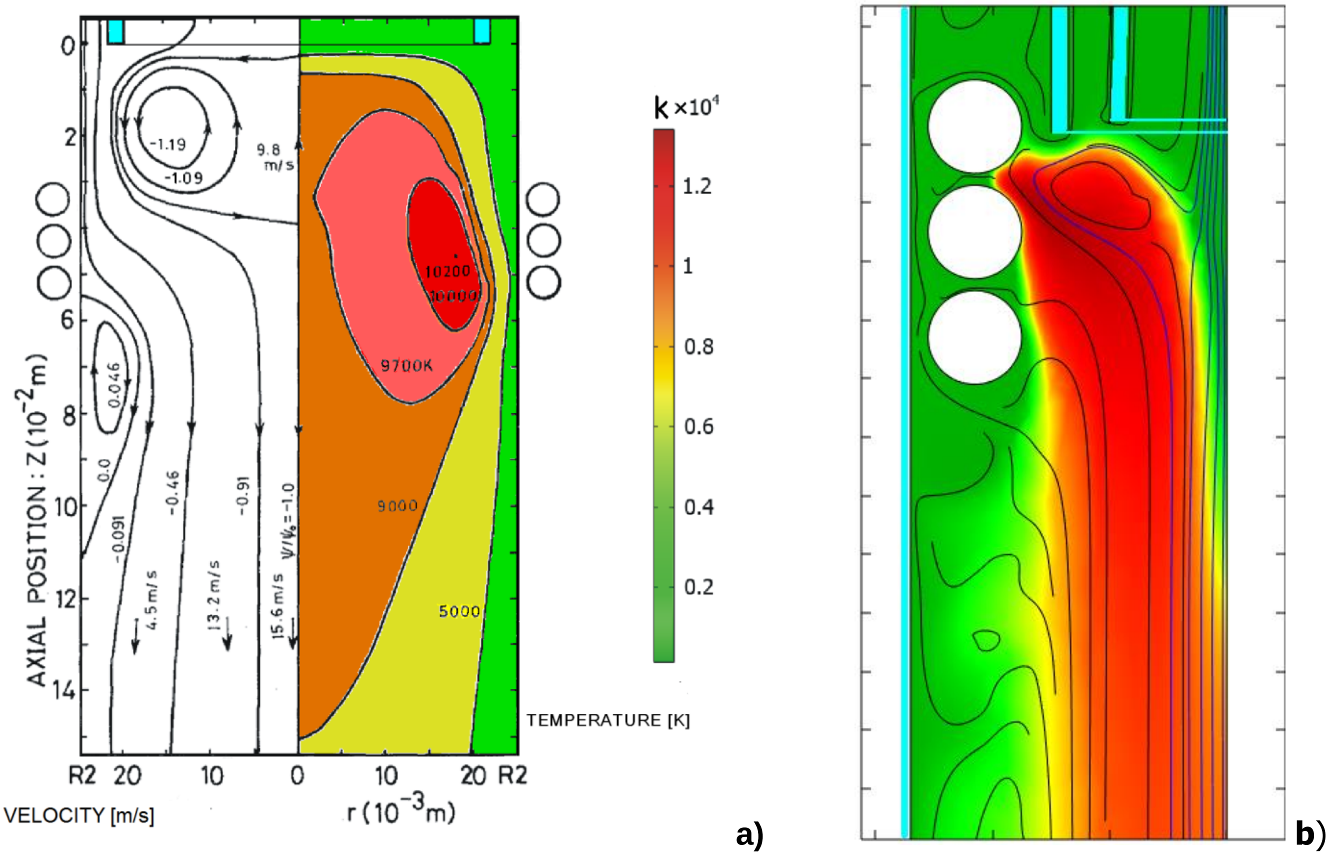


Fig. **4a (From ref. (3): Fig.7 - Stream-line (left) for plasma No.1 (TORCH A)**

Fig. 4b Temperature and flow lines for TORCHA, equal to **torch1** calculated by Voronov (5,6). Comparison between the result of Voronov's calculation on the torch of Fig.1, 5 and the calculation for torch A in the work of Yoshjda *et al.* (3). The difference is radical.

From (3): "*2.3.3. Overall Energy Balance. - The overall energy balance for the four types of plasmas calculated in this study is shown in Table I. For all cases, the coil current and the frequency were* ***110 A*** *and* ***4 MHz****, respectively. The values of the plasma power, … would therefore reveal the power coupling efficiency to the plasma (i.e., the ratio of plasma power to coil power). However, heat conduction losses to the torch wall and radiation losses are of no use for the actual application of rf plasmas. Therefore, the actual power coupling efficiency to the plasma is considered to be expressed by the value of the exit gas enthalpy. It is noticed that the difference between plasma No. 1 and plasma No. 3 (Table 1) is negligible, which means that the presence of the sheath gas swirl velocity of the order of 10 m/sec has little effect on the temperature profile, though the velocity of the back flow in the recirculation eddy was decreased from 9.8 to 7.5 m/see. Notice that similar results were obtained by Boulos et al. (4) The effect of the sheath gas flow rate is found by comparing plasmas Nos. 1 and 2. The high flow rate of the sheath gas decreases the total power* *input but increases the exit gas enthalpy. This is because heat conduction is decreased drastically by the high sheath gas flow rate. Plasma No. 4 has the highest exit gas enthalpy and the highest actual power coupling efficiency. It should be pointed out that the effects of the carrier gas flow were not considered, with the exception of plasma No. 4. If the carrier gas is fed axially into each plasma, not only the plasma power, but also the exit gas enthalpy, will be decreased, as shown in Section 2.3.2. The same is frequently experienced in experimental investigations. In conclusion, these theoretical investigations show that the radial injection method offers higher efficiencies for practical processing than conventional injection.* "

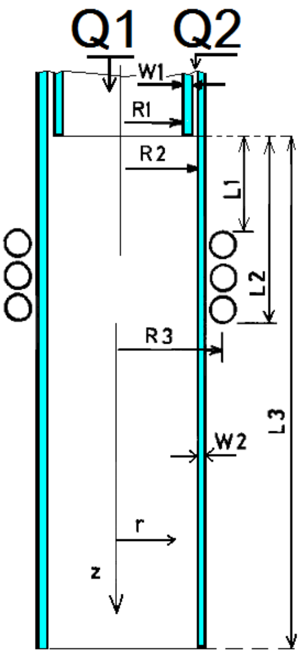


Fig.3 TORCH A (Fig. 1 in Yoshida *et al*. (3)) The different geometries as modeled symbol are as follows: R1, R2, R3 =20, 25, 30rmm, L1, L2, L3, L4 = 30, 60, 160, 48 mm and W1, W2, H = 2, 2, 1 mm, respectively

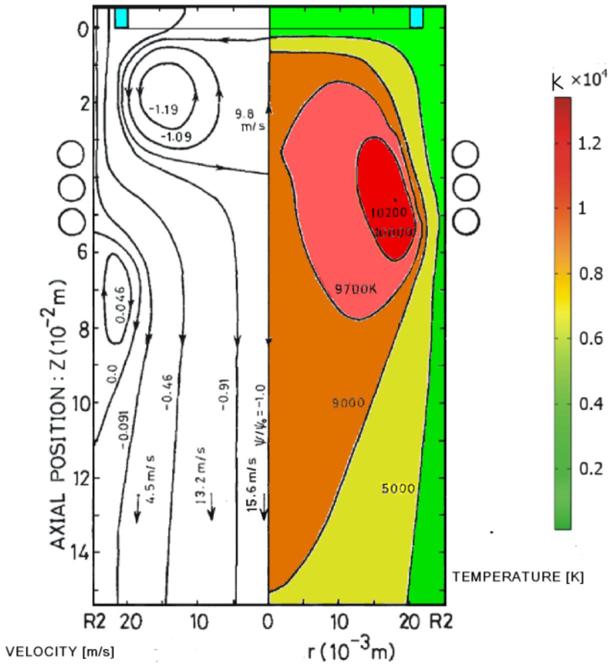


Fig. 4 (From ref. (3) :Fig. 7 - Stream-line patterns (left) and temperature distributions (right) for plasma No. 1 (Table 1).

The parameters used for the Yoshida computation are the plasma gas flow rate **Q1**, the sheath gas flow rate **Q2**, the carrier gas flow rate **Q3**, and the average swirl velocity at the sheath gas inlet Vo (the swirl was restricted to the sheath gas). The operating conditions are shown in Table I.

Table I. Operating Conditions and Results of Overall Energy Balance

Plasma number	Torch type	Operating conditions: Plasma gas $Q1$ (liters/min)	Sheath gas $Q2$ (liters/min)	Carrier gas $Q3$ (liters/min)	Swirl velocity V_θ (m/sec)
1	A	10	20	0	0
2	A	10	30	0	0
3	A	10	20	0	7.5
4	B	10	20	9.5	0

Experimental Conditions

1. **Gas flow rate**: Plasma gas: **Q1** = 10 liters/min (Ar) - Sheath gas: **Q2** = 30 liters/min (Ar)+ 2 liters/min (H_2) - Carrier gas: **Q3** = 0- 20 liters/min (Ar) - 2. Plate power output = **20 - 30 kW**
3. Coil current = **100 ~ 130 A**

After the research illustrated in (1), my work continued with the construction of a plasma generator in which the **torch1** was incorporated into a large quartz cylinder. represented in Fig. 5. The results achieved with this torch were only mentioned in the paper (1)

Yoshida conclusions (3)

"*A new design of an rf plasma torch was proposed, in which the reagent was radially injected into the hottest part of the plasma through quartz capillary tubes set symmetrically between the inductor coil. The proposed design was examined theoretically and experimentally, and the following conclusions have been reached.*
(1) Theoretical investigations showed that the injected high carrier gas flow could be effectively heated by the rf power in the new torch design, which means that the radial injection method may have a high efficiency for practical processing.
(2) Experimental investigations showed that the rf plasma could be sustained only by the upper part of the plasma, which means that the recirculation eddy might play an important role similar to that of the recirculation flow induced by the flame-stabilizing baffle in an aircraft jet engine.
(3) The new torch was very resistant to disturbance during actual processing and had a superior efficiency compared with our old torch.
(4) The torch used in the experimental investigations is not a perfect torch, but rather a prototype of the proposed design. It needs many improvements; in particular, an integration of the various components of the torch (i.e., outer tube, inductor coil, and feeding probes) will be needed for easier handling".

This is Yoshida's conclusion. Later the Tekna was created by Boulos and Jurewicz, a torch in which the rf spiral is embedded in insulating material that allows close proximity between the contiguous coils. But the coupling with the plasma is less tight than this solution in which the spiral is "drowned" in the plasma.

The plasma parameters (ref.1):

- Atmospheric pressure
- RF frequency 5.0 MHz
- Power consumed by the plasma: **37 kW**
- Amplitude of the electrical current in the load coil: **340 A**

Ar flow	(1)	(2)	(3)
(1) central channel (injector):	**0** *Lpm*	***5 Lpm***	***10***
(2) middle channel:	***5 Lpm***	***10 Lpm***	***20***
(3) outer channel:	***25*** *Lpm*	***9.5 Lpm***	***9.5***
(4) outer cover:	***10*** *Lpm*	***0 Lpm***	**0**

Because of cylindrical symmetry of the model, the middle and the outer gases are introduced into the volume through thin ring-shape slots. The slots are situated approximately where the input channels are, and have similar area of their cross-sections. With this approach the initial gas velocities and the gas flows are similar to the velocities and the gas flows of the experimental setup. Because the model is cylindrically symmetrical, this and the other images illustrate only a half of the cross-section limited by the axis. So, the full 3D result is rotation of the presented cross-sections around the axis.

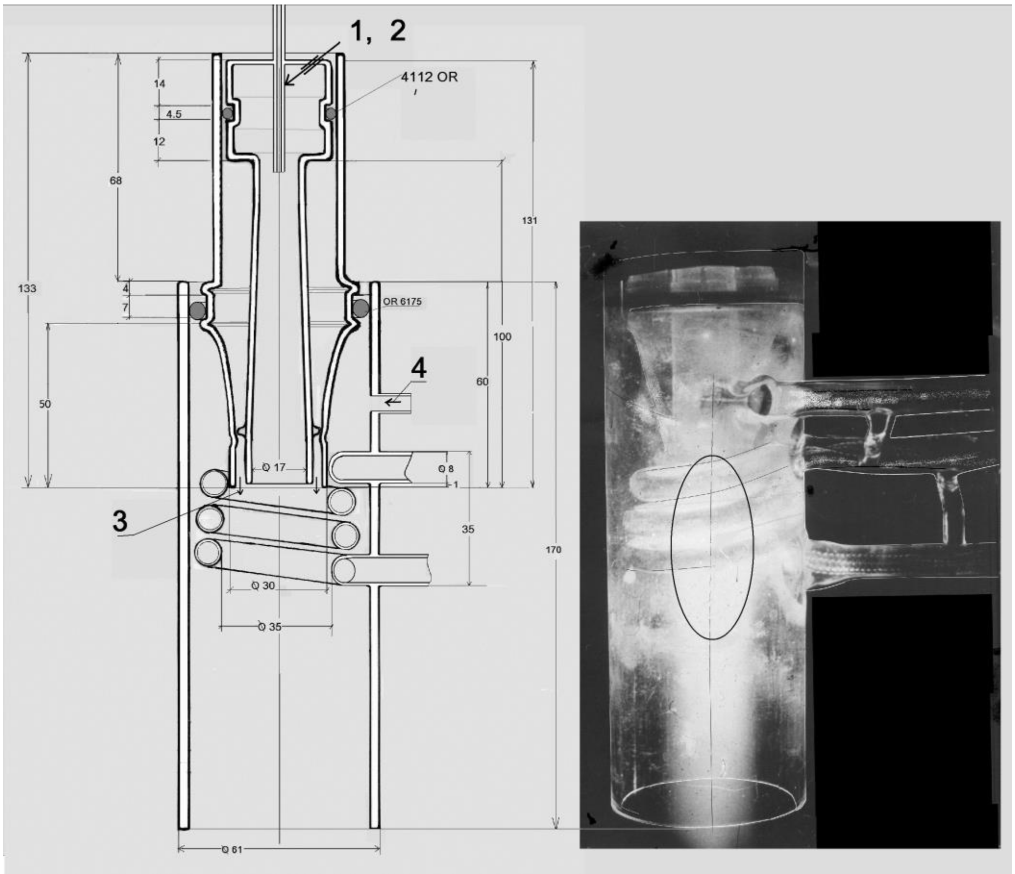


Fig.5. Radio frequency plasma torch with 4 argon inlets. The power transferred into the plasma reached **37 kW** in continuous operation with the frequency of about 5 MHz

In the model for the Voronov calculation it is possible to take into account the real boundary conditions (6,7,8)

The Voronov models are based on a modular structure. The electro-magnetic module (EMM) is used for calculation of electro-magnetic fields, the fluid kinetics module (FKM) is used for simulation of gas dynamics, and the plasma ionization module (PIM) is used to simulate the degree of ionization of the plasma and related electrical properties. The implementation of the PIM module for the LTE and two-temperature models is different because there are different models of ionization in a plasma . The EMM and FKM are similar in both models used below. All the three modules are combined in different ways to implement the algorithms. The EMM and PIM modules are developed in a Pascal-family programming language (Oberon, compiler XDS, Excelsior, Novosibirsk, Russia). **A commercial program “COMSOL Multiphysics” (version 4.3b, COMSOL AB, Burlington, USA) was used to develop the FKM.** The EMM calculates the distribution of electro-magnetic fields using Maxwell equations and uses two input parameters. The first one is the distribution of electrical conductivity of the plasma $\sigma(\vec{r})$ as function of the radius vector $\vec{r}$. The second parameter is either the electrical current in the coil I_{coil} or the power consumed by the plasma W. The output of the EMM are the plasma power W (if I_{coil} is used as an input parameter) or the current in the coil I_{coil} (in the opposite case), the distribution of electro-magnetic fields, the density of power $P(\vec{r})$, which is resistively consumed by charged particles, and the density of Lorentz force $\vec{F}(\vec{r})$, which affects the charged particles.

The FKM solves Navier–Stokes and heat transfer equations to simulate dynamics of the gas. The FKM uses the following input parameters: geometry of the plasma torch, values of the input gas flows applied as boundary conditions; atmospheric pressure at 1013 hPa. Other input parameters are density of power $P_{FKM}(\vec{r})$ and density of Lorentz forces $\vec{F}_{FKM}(\vec{r})$, which are used as heat and force source applied to the gas, respectively. In both the LTE and the two-temperature models the Lorentz forces resulting from the EMM are directly used as input parameter for the FKM: $\vec{F}_{FKM}(\vec{r}) = \vec{F}(\vec{r})$. However $P_{FKM}(\vec{r})$ is introduced in the FKM in different ways (see description of the models below). The output of FKM are distributions of the temperature $T(\vec{r})$ and gas velocity $\vec{v}_{gas}(\vec{r})$. In contrast to the previous models, temperature inside the torch walls is comprehensively simulated. Therefore, T is either the gas temperature T_{gas} or the wall temperature T_{wall}, depending on $\vec{r}$.

Important parameters of the FKM are the dynamic properties of gas: mean molar mass, thermal conductivity, thermal capacity, and viscosity. It is assumed in the model that 100% Ar is situated inside the torches, and 100% air is outside (see Fig. 1). Therefore, the corresponding properties of air, which are built-in to the COMSOL program, are used in the model outside of the torches.

A more complex description of the gas dynamic properties is necessary for Ar. Because the ICP has a high degree of ionization, these parameters depend strongly on density and temperature of the electrons and on the composition of the gas. These parameters are calculated using a multi-element model proposed by Lindner *et al.*(8), where a gas-kinetic approach is employed for their description. These parameters are incorporated into the COMSOL program as function of T.

Power introduced into the plasma is dissipated to the plasma gas, then removed from the plasma volume by the Ar flow and transferred outside through the torch walls. In addition, the hot plasma loses energy by radiation. In case of the LTE model, the density of radiation loses $R(T)$ is additionally incorporated in the **FKM**. The two-temperature model takes this term into account in PIM rather than in FKM.

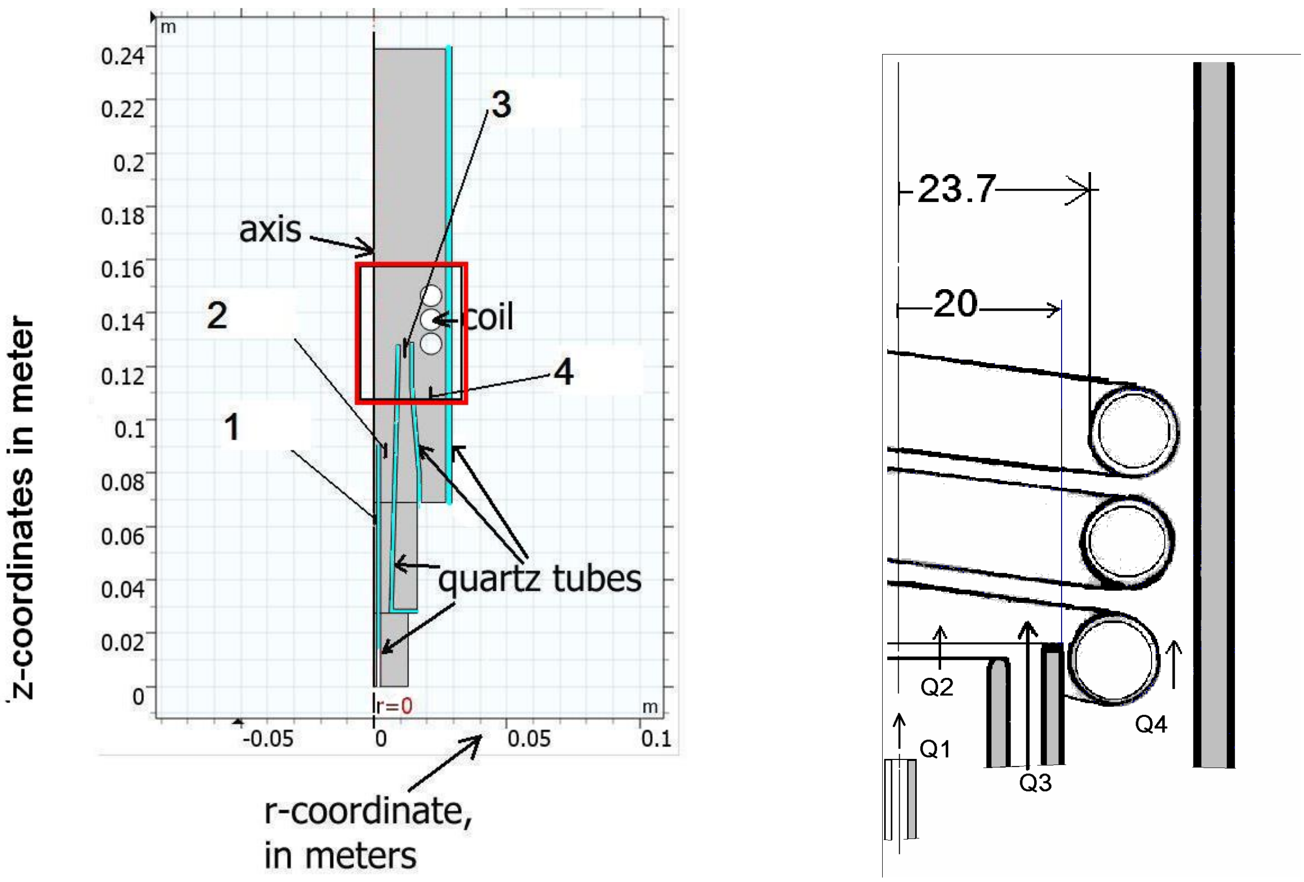
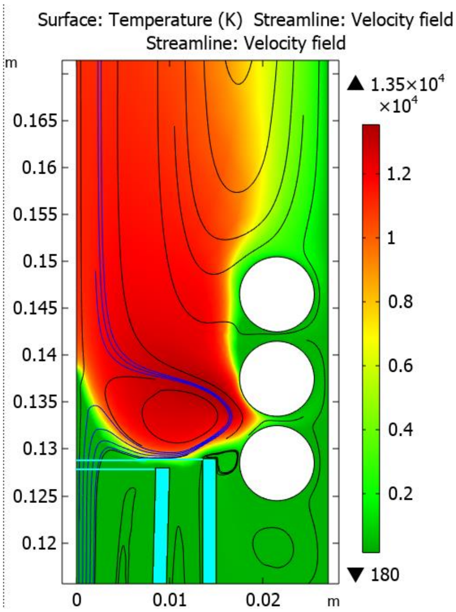
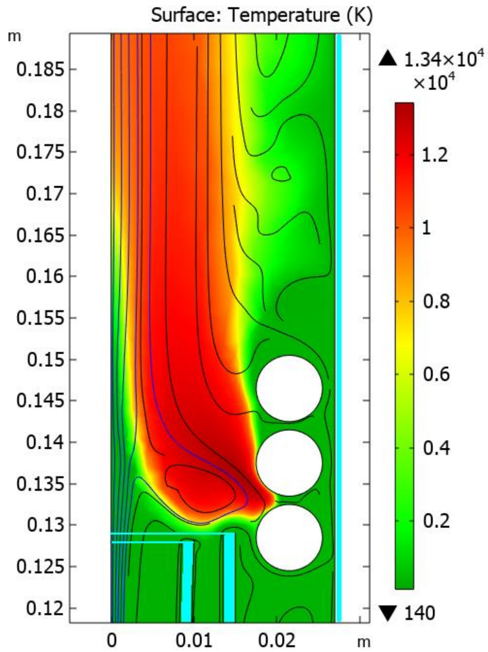


Fig. 6 Geometry of Voronov calculus for ha plasma torch of Fig 5. The numbering of the gas inlets (see Fig.5) is that adopted in Voronov's calculations(6,7). The rectangle encloses the area of the magnified results



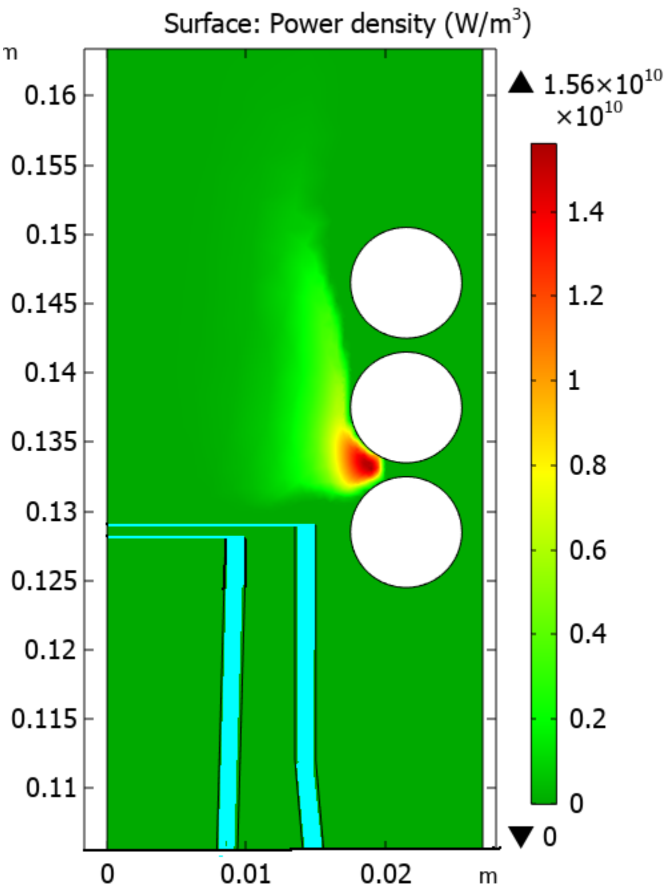
1



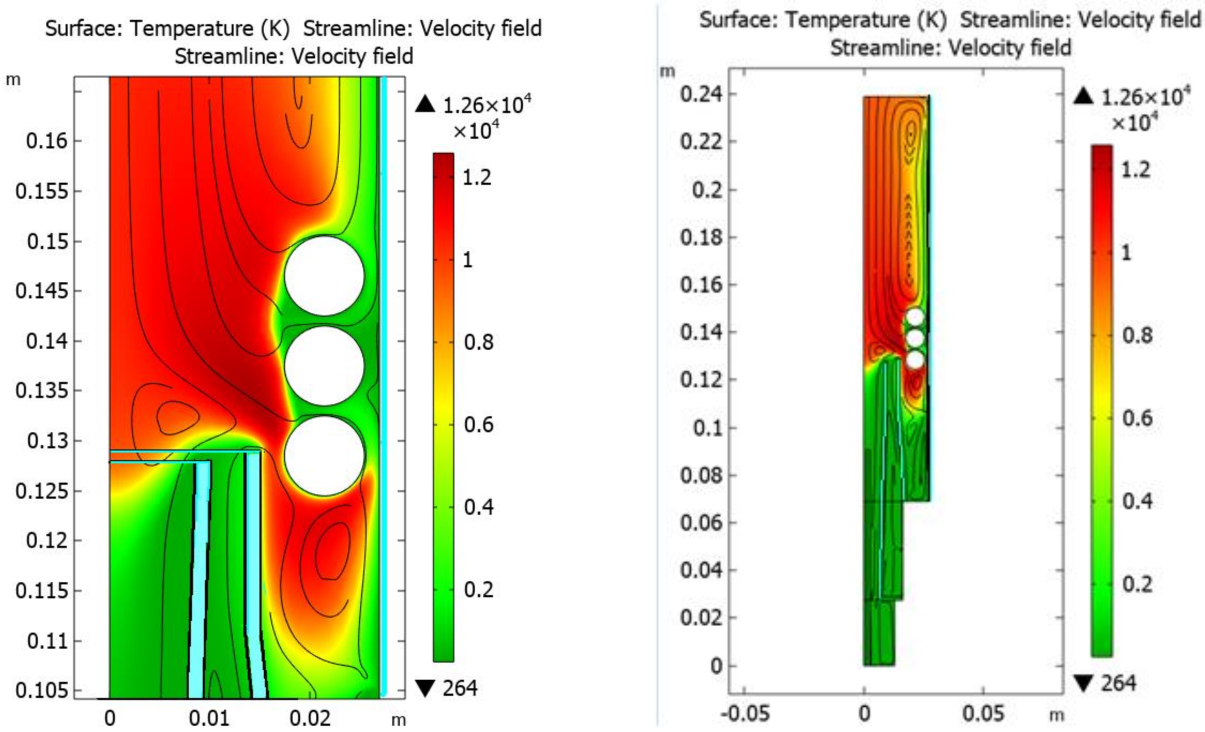
2

1. - Q1 = 0 Lpm - Q2 = 5 Lpm - Q3 = 25 Lpm - Q4 = 10 Lpm
2. - Q1 = 5 Lpm - Q2 = 10 Lpm - Q3 = 9.5 Lpm - Q4 = 0 Lpm

This is intermediate parameters between the 1 and what I've sent you before.

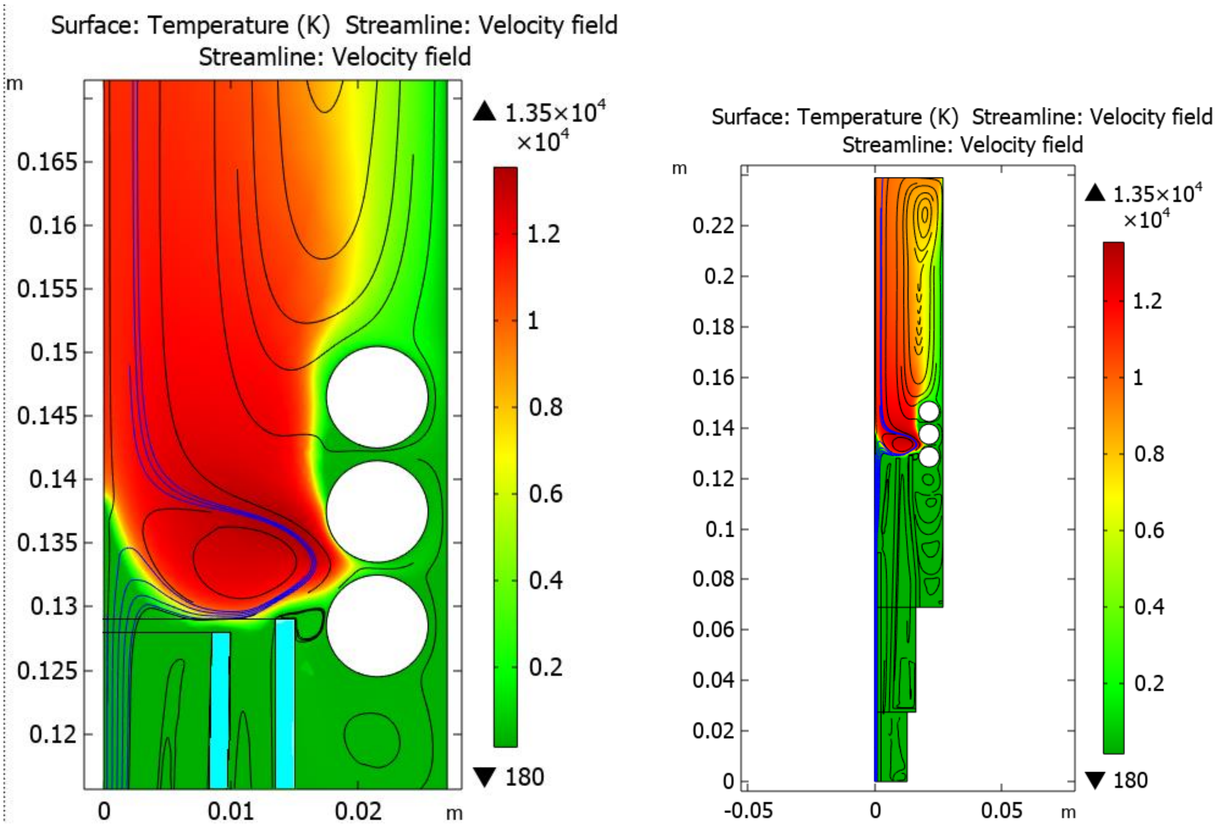


3P



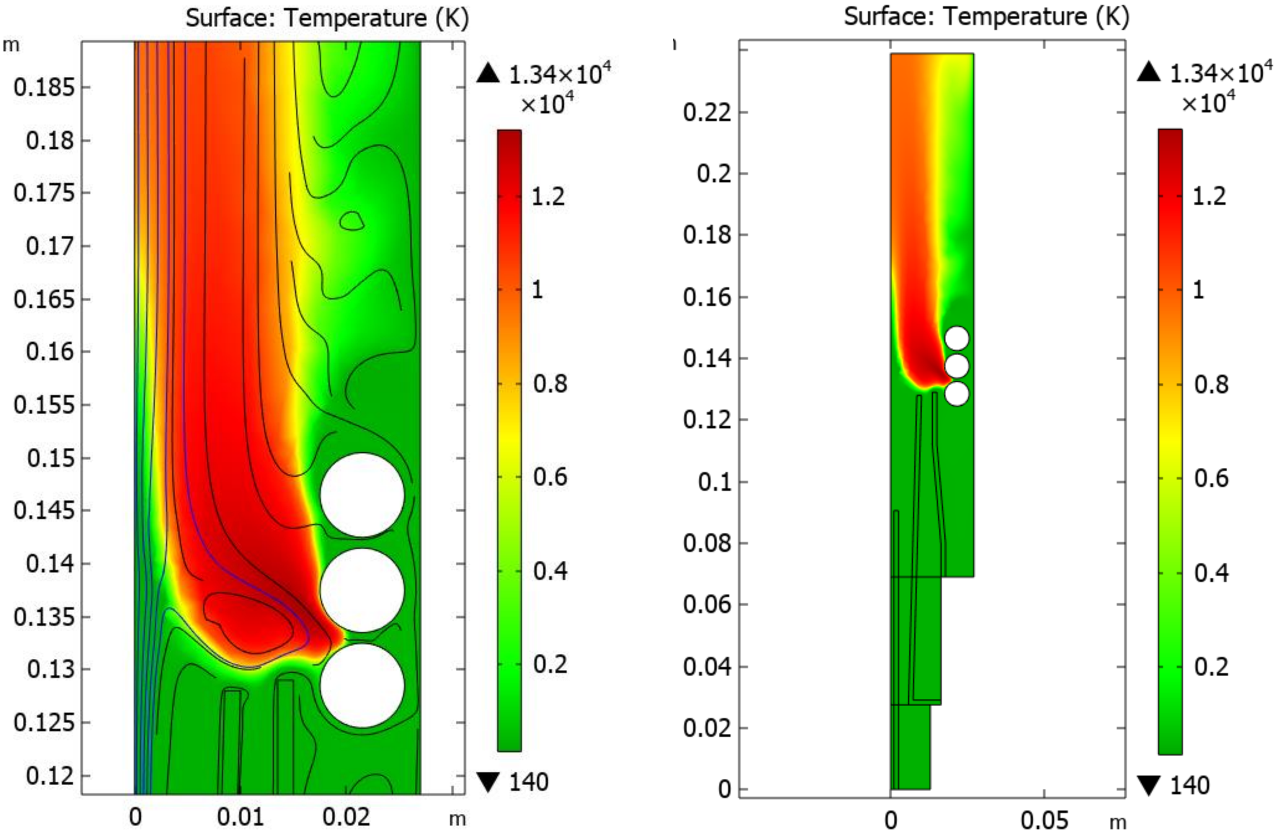
1

- Q1 = 0 Lpm - Q2 = 5 Lpm - Q3 = 25 Lpm - Q4 = 10 Lpm



2

- **Q1 = 5 Lpm - Q2 = 10 Lpm - Q3 = 9.5 Lpm - Q4 = 0 Lpm**

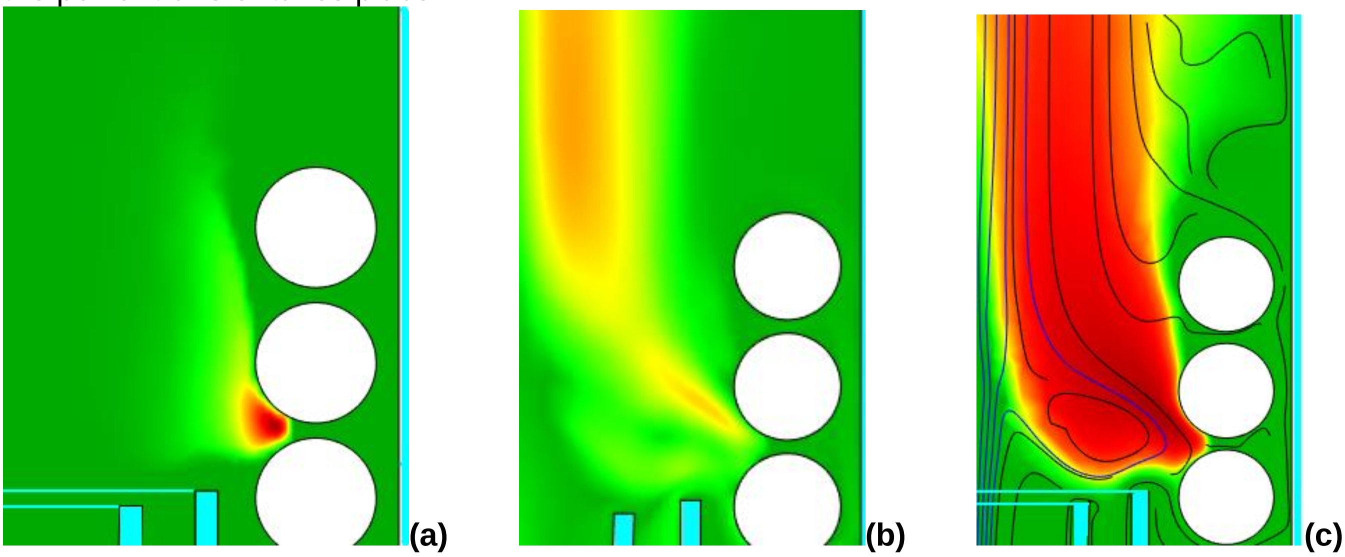


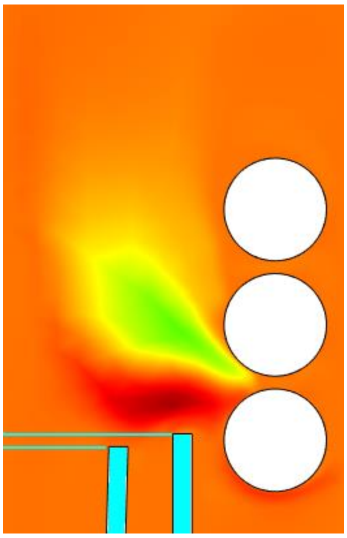
3

Q1 = 10 LPM; - Q2 = 20; - Q3 = 9.5; - Q4 = 0

DISCUSSION

From this simulation it is evident that the plasma creation is concentrated in the space between the first two turns of the quartz spiral, where a very tight coupling is achieved and where most of the power transfer takes place.

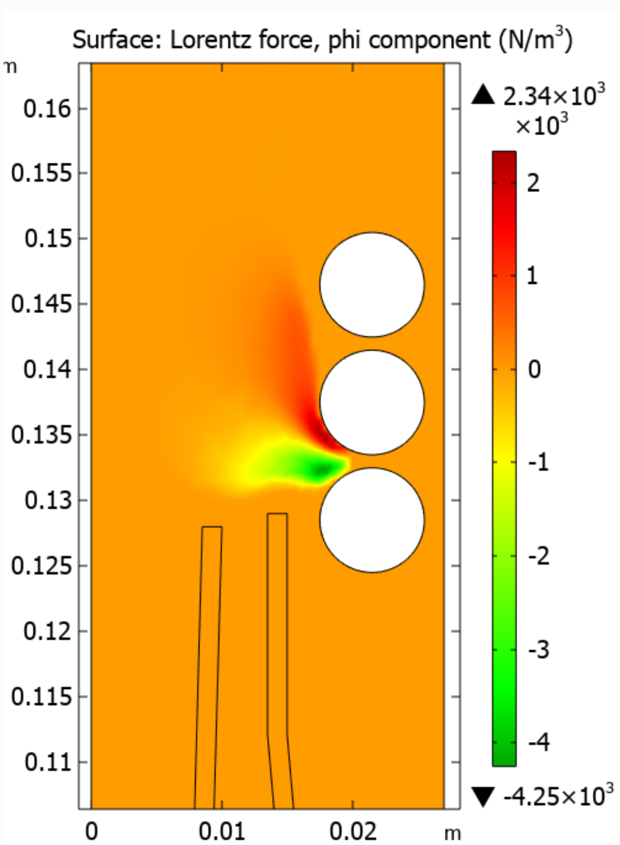


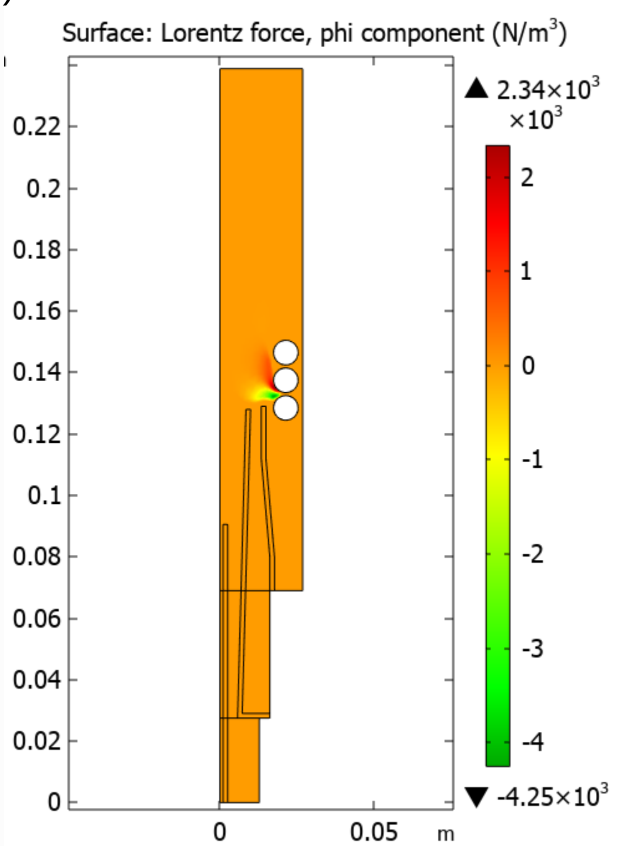
 (d)

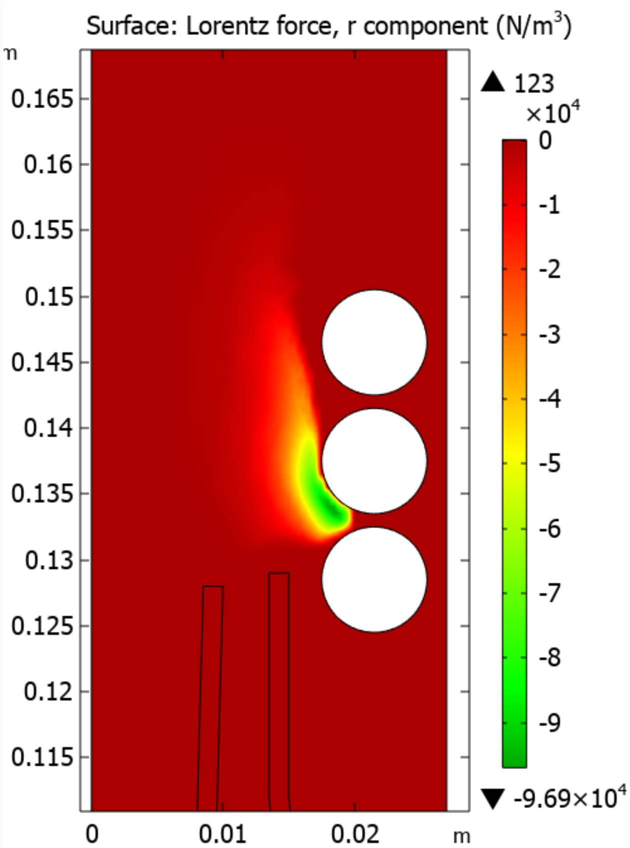
(a) Power absorbed by the induced field - (b) Axial speed ***Vz*** *- (c) Temperature* ***K*** *- max (d) Radial velocity* ***Vr***

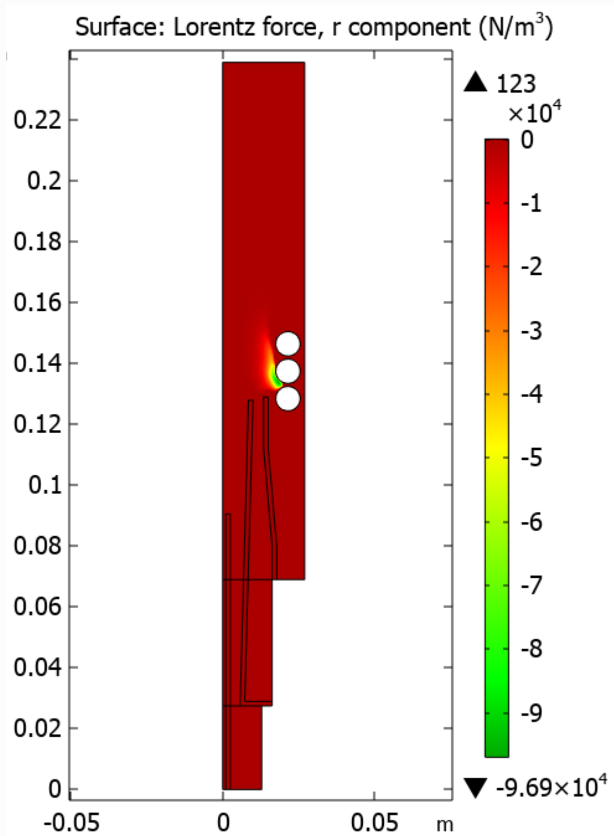
Most interesting is the power transfer into the plasma, which occurs mainly between the first two turns (5, 6). As we can see, the configuration of the "flame" does not change much as the flow rate of the gas feeding the plasma area varies. The flow lines in (3) show mixing

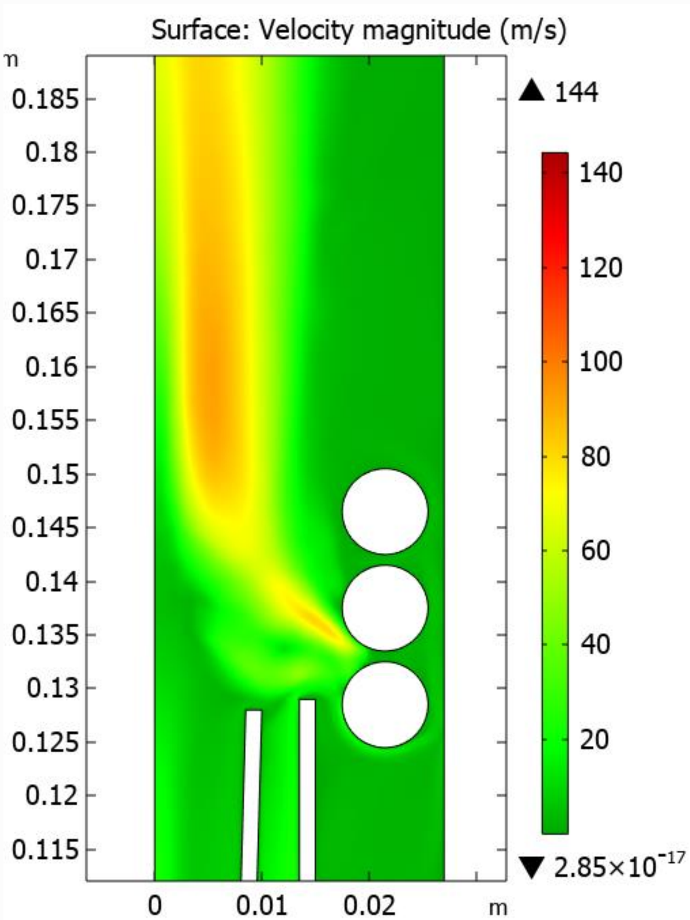
Gallery of results for parameters (3)

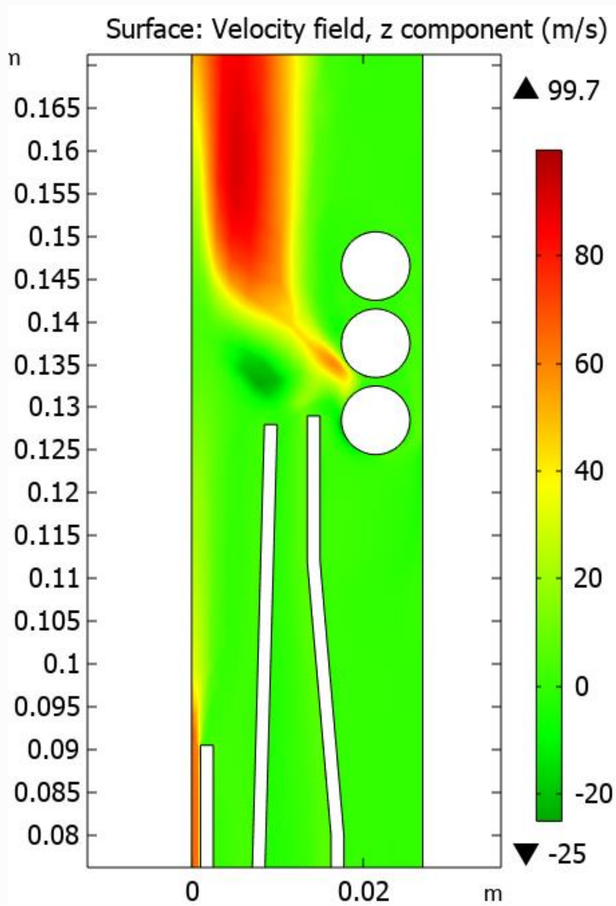





Surface: Lorentz force, r component (N/m3)
▲ 123
×10⁴
▼ -9.69×10⁴
m


Surface: Lorentz force, r component (N/m3)
▲ 123
×10⁴
▼ -9.69×10⁴
m


Surface: Velocity magnitude (m/s)
▲ 144
▼ 2.85×10-17
m


Surface: Velocity field, z component (m/s)
▲ 99.7
▼ -25
m

Acknowledgements

First of all, I want to thank Arbore, the technician who made the quartz torches, which is difficult to work with due to the high temperature required to make it malleable. Arbore used the flame with oxygen and hydrogen, not without dangers. Only now have I appreciated his skill. I must then thank Voronv who carried out the numerical solution of the problem in his spare time. After contacting many authors of publications in which the results of similar calculations were reported, only Voronov finally said he was available. The results are very interesting, as mentioned, for the very close coupling between the plasma and the radiofrequency coil.
Yoshida (3) with an analytical-numerical solution had obtained the temperature distribution in the plasma using a model (far from reality) in which the plasma was confined in a quartz tube with the rf spiral outside. With the mathematical and numerical tools available then it was not possible to impose complex boundary conditions such as those of a spiral. The plasma that is formed in this way is stable but is “closed” to the point that the powders to be treated cross the plasma with difficulty and therefore are not treated because they do not melt on the surface and therefore do not spheroidize. In fact, Yoshida thought of overcoming the obstacle by injecting the powders with the carrier gas transversely into the plasma flame, with two injectors entering between the last two turns.
This torch was made for the nuclear sector of a very important private industry as part of the rivalry between private industry and state industry. The torch was born on Reed's pioneering project (2). It was intended to melt on the surface to spheroidize uranium oxide particles, intended for the construction of a "fluid bed" nuclear reactor. The Torch did not work well for the purpose for which it was intended because the uranium oxide particles did not penetrate the plasma area. In fact, Yoshida (3) in the replica of this torch introduced the powders to be treated directly in the "flame" with two side injectors between the last two coils. The vacuum-tight system was built with the flanges of the engineer Allaria of Turin. Engineer Allaria had found simple and effective solutions for vacuum-tight joints and flanges (see Fig.3).

References

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2) **Reed,Thomas B.**, *"**Induction-Coupled Plasma Torch**". J. Appl. Phys.* ***32*** *(5): 821–824* (1961) *ABSTRACT* A new method of generating a stable plasma at atmospheric pressure using inductive coupling at a frequency of several Mc is described. Methods of starting and operating this plasma in argon, and mixtures of argon with helium, hydrogen, oxygen, and air are discussed. The Fowler and Milne method was used to measure the temperature profile of the plasma under various conditions of gas flow and composition, and at several power levels. Measured peak temperatures ranged from 14 000°K–19.000°K**. T**he power losses from the plasma in the form of convection, radiation, and conduction to the nozzle walls were measured under the same conditions. Total power transferred to the plasma ranged from 1.6–3.1 kw which was approximately 50% of the input power. The extent to which local thermal equilibrium prevails in the plasma is discussed; the available evidence indicates that under the operating conditions described herein, equilibrium is closely approached

3) **Yoshida** et al. "***New design of a radio-frequency plasma torch***", (Departent of Metallurgy, Faculty of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo, 113, Japan) - **Plasma Chemistry and Plasma Processing,** Vol. 1, No. 1, (I980**)**

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