© Trade Science Inc 2016

Print-ISSN: 2320-6756
Online-ISSN: 2320-6764

Journal of
Physics &
Astronomy

WWW.TSIJOURNALS.COM

Full Paper

A.Khalili[1]*, S.M.Sadat Kiai[2], H.Mahdian[1]

[1] Department of Physics and Institute for Plasma Research, Kharazmi University, Tehran, (IRAN)
[2] Plasma and Nuclear Fusion Research School, Nuclear Science and Technology Research Institute (NSTRI), A.E.O.I, Tehran, (IRAN)
E-mail: amirekhalili@gmail.com

PACS: 52.25.Gj; 52.35.Ra; 05.10.Cc; 05.30.Pr

*Corresponding author's
Name & Address

A.Khalili
Department of Physics and Institute for Plasma Research, Kharazmi University, Tehran, (IRAN)
E-mail: amirekhalili@gmail.com

# Collisional cooling in an inductively coupled plasma torch

## Abstract

The paper presents a simulated model of inductively coupled plasma torches using a numerical code developed in FlexPDE environment. The EM fields, temperature and fluid flow are calculated numerically in a two-dimensional geometry for typical ICP torch. The model is within the assumptions of laminar flow, optically thin plasma and local thermodynamic equilibrium (LTE), negligible viscous dissipation and 2D axisymmetric geometry. This yields a mathematical and virtual tool for predicting the torch performance before running. The main factor in plasma behavior, working gas, is studied in this paper. Various amounts of Helium, Krypton and Xenon are included in the primary Argon gas. The obtained results show a cooling effect in plasma, as a result of collisions, via buffer gas effectively by Krypton and Xenon compared to the Argon case which is taken to be reference case here. There were no signs of heating inside the plasma. Axial velocity of particles is increased by Helium with amounts of more than %0.02 and generally is decreased by Krypton and Xenon different values. The most striking effect observed in this study was elimination of circulating flows (negative axial velocity) inside the torch which would be energy dissipating. The results for gas additive in pure Argon are reported firstly. The importance of the present work would be enabling us to tune and adjust the plasma instability for operation improvements.

## Key Words

Collisions in plasma; Plasma simulation; Plasma torches; Cooling of ions; RF discharges.

## INTRODUCTION

Inductively coupled plasma torches are relatively new tool for producing thermal plasmas, firstly described by Reed in 1962[1]. Introducing ICPTs was then lead to atmospheric-pressure plasmas development. Unlike low-pressure plasma or high-pressure plasma, in atmospheric-pressure plasma, no chamber is required to maintain a certain pressure level. Therefore, no costly chamber for producing a partial vacuum is needed. This simplicity in structure and performance made ICPTs more and more effective in many technological and industrial applications. These torches are extensively employed in a wide range of applications such as plasma spraying, nanoparticles synthesis, waste treatment, and elemental analysis[2]. Optimized utilization of ICPTs depends on better understanding of its characteristics and performance, so several diagnostics are needed. However, reaching the internal zones of the device for diagnosis is difficult. Therefore, mathematical modeling would be a powerful tool to predict and study many parameters and aspects of plasma in different conditions such as plasma flow and temperature[3]. Various 2D and 3D models have been proposed and studied recently for detailed description and simulation of the physical behavior of this device[4–6].

One of the most significant achievements in modeling the ICP torch is to investigate the effective parameters

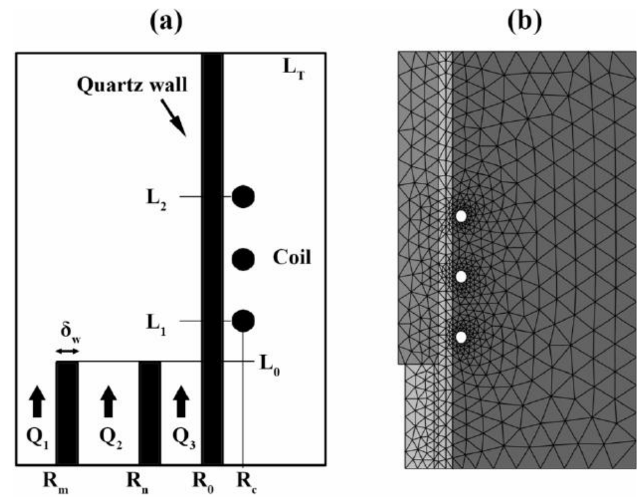


**Figure 1 : (a) Schematic geometry of ICP torch. (b) Grid model for ICP torch**

**TABLE 1 : Plasma torch characteristics and dimensions (slpm: Standard Liter per Minute)**

| | | |
|---|---|---|
| $Q_1 = 1.0$ slpm* | $R_m = 3.7$ mm | $L_0 = 50$ mm |
| $Q_2 = 0.05$ slpm | $R_n = 18.8$ mm | $L_1 = 63$ mm |
| $Q_3 = 1.7$ slpm | $R_0 = 25$ mm | $L_2 = 121$ mm |
| $I_{coil} = 200$ A | $R_c = 33$ mm | $L_T = 200$ mm |
| $R_a = 3$ mm | $R_T = 100$ mm | $\delta_w = 3.5$ mm |

on its performance virtually. These parameters would be the gas flow rate, gas type, current frequency and *etc*. In this paper, some modeling results for an RF-ICP torch will be presented which are affected by the gas admixtures. A typical structure for ICP torch is considered for simulation as shown in Figure 1. The torch consists of three concentric quartz tubes of 3.5 mm thickness. The outer tube length is 200 mm and the others are 50 mm. A 3-turn copper coil carrying RF current (6 mm thickness) is wrapped around the outer quartz tube. The central tube is embedded for central gas injection (normally sample aerosol for analysis applications) with the flow rate of $Q_1 = 1.0\ slpm$ . The intermediate inlet is devised for working gas injection with the flow rate of $Q_2 = 3.0\ slpm$ and finally, the outer inlet is for sheath gas by $Q_3 = 33.0\ slpm$ in order to preserve the quartz wall from destruction. Around the outer tube is a spiral hollow copper coil, cooled by water and confines the plasma inside the inner tube. Charge carriers accelerated in the electric field (produced by RF current) couple their energy into the plasma via collisions with other particles. This collision induced ionization of the gas continues in a chain reaction, breaking down the gas into gas atoms, ions, and electrons', forming what is known as an ICP discharge. In this work, Argon is considered for all inlets as the main gas and some impurities (small percentages of Helium, Krypton and Xenon) are added as a buffer gas and the effects are investigated. Ions can be cooled by collisions with charged or neutral particles which have lower temperatures. The collisions may lead to loss of the ions through charge-exchange or other reactions, or they may cause perturbations of the energy levels. This is called collisional cooling. Cooling of ions is also useful in studies of plasmas and ordered structures. With sufficient cooling so that the Coulomb potential energy between nearest neighbors is much greater than their average kinetic energy, the ions can form ordered structures[7]. In some cases the benefits of the cooling outweigh the latter disadvantages; these cases could be controlling plasma flow velocity and temperature, controlling plasma instability and etc. The calculations are done by modeling the ICP torch via MHD equations and solving them using commercial version of FlexPDE5.

## MATHEMATICAL METHOD

A Radio Frequency (RF) power supply is coupling the energy to the plasma by means of helical coil of n-turns surrounding the plasma tube and a means of initiating the discharge. The operating frequency supplied by RF generator is normally at $\sim 10-40\ MHz$ range or even more. So, at such frequency the wavelength is about $\lambda \sim 30\ m$ which is much larger than dimensions of the torch (few to tens of centimeters). In a sense, this means that the fields inside the ICP torch can be considered as static. When a time-varying electric current is passed through the coil, it creates a time-varying magnetic field around it, which in turn induces azimuthally electric currents in the gas, leading to the formation of plasma. Plasma temperature inside the inner tube can reach $\sim 10000\ K$ . The ICP discharges are of relatively high electron density, on the order of $\sim 10^{15}$ $cm^{-3}$. As a result, ICP discharges have wide applications where high-density plasma is needed[8].

The physical behavior of the plasma torch is modeled via magnetohydrodynamic equations, which is implemented in the FlexPDE environment. Some assumptions are employed during this modeling. Steady and laminar flow, optically thin plasma and local thermodynamic equilibrium (LTE), negligible viscous dissipation and 2D axisymmetric geometry are the assumptions. The following equations are briefly describing the physical behavior of this torch and will be employed for the modeling works:

$$\nabla^2 A = i\mu_0\omega\sigma A \quad (1)$$

$$\rho\frac{\partial v_r}{\partial t} + \rho v.\nabla v_r - \rho\frac{v_\varphi^2}{r} = -\frac{\partial P}{\partial r} + F_r + \nabla.(\mu\nabla v_r) + \nabla.\left(\mu\frac{\partial v}{\partial r}\right) - \frac{\mu v_r}{r^2} \quad (2)$$

$$\rho\frac{\partial v_\varphi}{\partial t} + \rho v.\nabla v_\varphi + \rho\frac{v_r v_\varphi}{r} = F_\varphi + \nabla.(\mu\nabla v_\varphi) - \frac{\mu v_r}{r^2} - \frac{v_\varphi}{r}\frac{\partial \mu}{\partial r} \quad (3)$$

$$\rho\frac{\partial v_z}{\partial t} + \rho v.\nabla v_z = -\frac{\partial P}{\partial z} + F_z + \nabla.(\mu\nabla v_z) + \nabla.\left(\mu\frac{\partial v}{\partial z}\right) \quad (4)$$

$$\rho c_p\frac{\partial T}{\partial t} + \rho c_p v.\nabla T = \nabla.(k\nabla T) + P_r - Q_r \quad (5)$$

where $= \frac{\partial}{\partial r}r + \frac{\partial}{\partial z}z$ , $\varphi$ -dependency is ignored in 2D due to axi-symmetry. In the foregoing equations, $\vec{A}$ is vector potential, $v_r$, $v_\varphi$ and $v_z$ are the gas velocity components in the radial, azimuthal and axial directions. $P$ , $T$ , $P_r$ , $F_i$ and $E_i$ are the gas pressure, temperature, dissipated power, Lorentz force component and electric field component, respectively. Values of density $\rho$ , viscosity $\mu$ , specific heat $c_p$ , thermal conductivity $k$ , electric conductivity $\sigma$ and volumetric radiation loss $Q_r$ for pure Argon gas are taken from[9–11] and for admixtures are taken from[12,13]. All characteristics and dimensions applied in this work are listed in TABLE 1.

The boundary conditions implemented in this work are $A = 0$ at $r = 0$ (torch axis) and along the torch wall $\partial A/\partial z = 0$ and on the current coil $n.\nabla A = \mu_0 K$ . On the outer wall of the tube, a fixed temperature value of $300\,K$ is imposed and on the walls $\partial T/\partial r = \left(k_w/k_{Ar}\right)\left(\Delta T/\delta w\right)$

Eq. (1) corresponds to the vector potential equation deduced from Maxwell's equations, Eq. (2)-(4) are three components of momentum (Navier-Stokes) and Eq. (5) is energy equation. Foregoing equations are solved numerically with proper boundary conditions for the geometry shown in Figure 1-b which is generated automatically by FlexPDE5 and consists of 2482 nodes and 1192 cells. The obtained results from calculations will be shown and discussed in the following.

## RESULTS AND DISCUSSION

The governing Equations with the prescribed boundary conditions are solved numerically by applying Finite Element Method (FEM) with Partial Differential Equation solver (FlexPDE5) using parameters listed in TABLE 1. The calculations were performed for about 2482 nodes and 1192 cells in non-uniform grid system. For the present plasma torch, the computed results for temperature and axial velocity, when the working gas is pure Argon, are shown respectively in Figure 2-a and Figure 3-a. Total temperature distribution inside the torch is shown in Figure 2-a and the axial profile of temperature along the central axis is depicted in Figure 2-b. Coil region is highlighted in the axial profile.

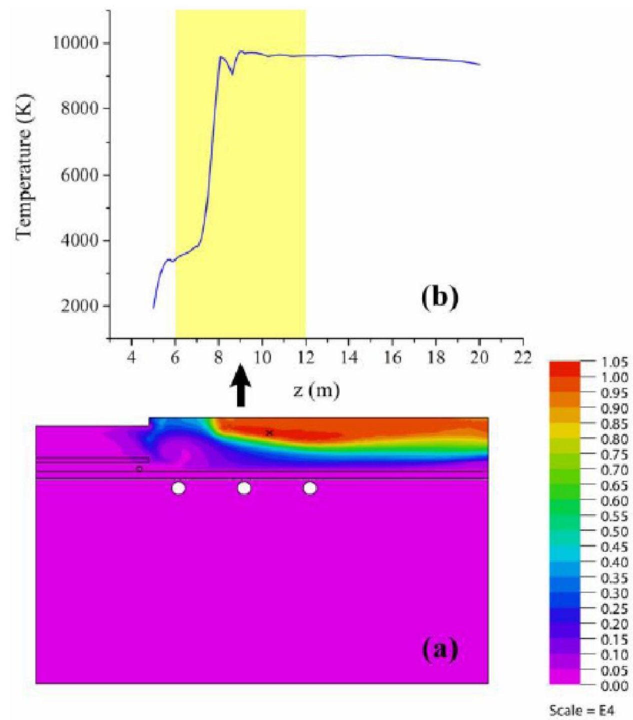


**Figure 2 : (a) Temperature distribution (K) for the case of pure Argon. (b) Temperature profile along the torch axis**

Clearly, calculations show that plasma is heated up right after the first loop of the coil; temperature gradually increases and immediately saturates. Figure 3-a also shows the total axial velocity distribution over the torch and besides, Figure 3-b presents the profile of axial velocity along the torch axis. According to this profile, particle velocity inside the coil region is not considerable, however, velocity increases towards the torch exit and saturates. Circulating flow inside the torch, regarding

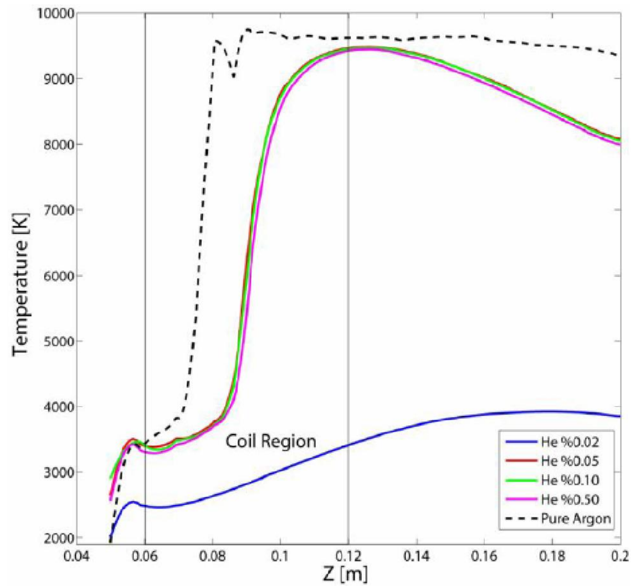


**Figure 4 : Temperature profile along the centerline for the case of Helium admixtures by various amounts compared with the pure Argon**

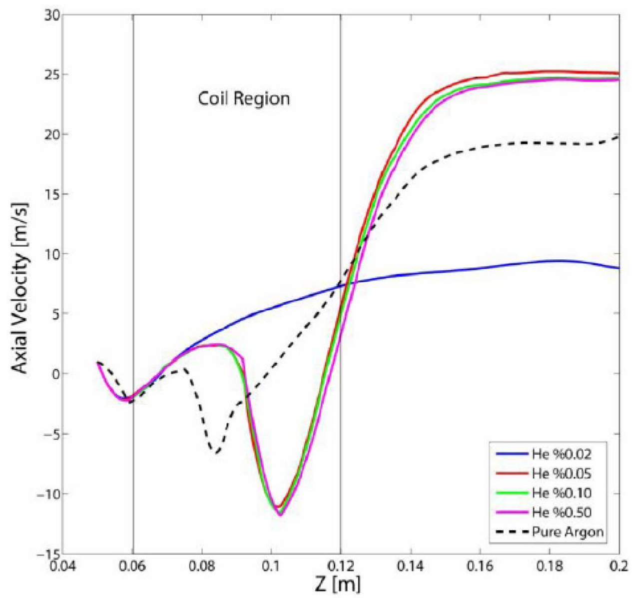


**Figure 5 : Axial velocity profile along the centerline for the case of Helium admixtures by various amounts compared with the pure Argon**

the negative values of axial velocity, is remarkable in the case for pure Argon as shown in Figure 3-b which could be energy dissipating. Controlling the torch parameters, including the geometrical and operational parameters, would be the best and effective approach to boost up the performance of the torch. Obviously the plasma gas is the most important item in this field which is chosen to be studied in the present work. Argon gas is chosen to be the primary gas and alongside, minor percentages of Helium, Krypton and Xenon are added as the buffer gas, impressing the temperature and velocity (See Figures 4-9).

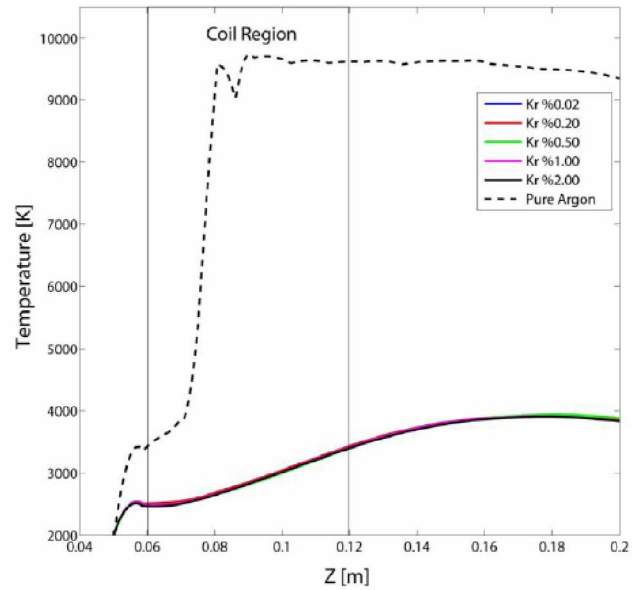


**Figure 6 : Temperature profile along the centerline for the case of Krypton admixtures by various amounts compared with the pure Argon**

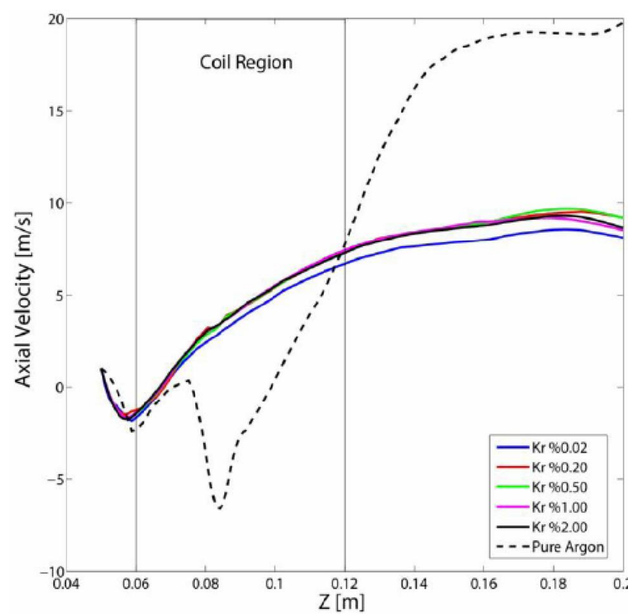


**Figure 7 : Axial velocity profile along the centerline for the case of Krypton admixtures by various amounts compared with the pure Argon**

As Figure 4 shows, adding %0.02 He to Argon cools the plasma down to 4000 K at the head, lowers the output velocity down to about 9 m/s and also causes the circulating flows to eliminate. This reduction in temperature and velocity is considerable for %0.02 He; beyond this value; temperature decreases so smoothly in comparison with pure Argon case but the velocity increases up to 25 m/s (even more than pure Argon case). This phenomena is related to the low atomic mass of Helium than Argon. Krypton and Xenon are heavy atoms rather than Argon, so every tiny percentage of

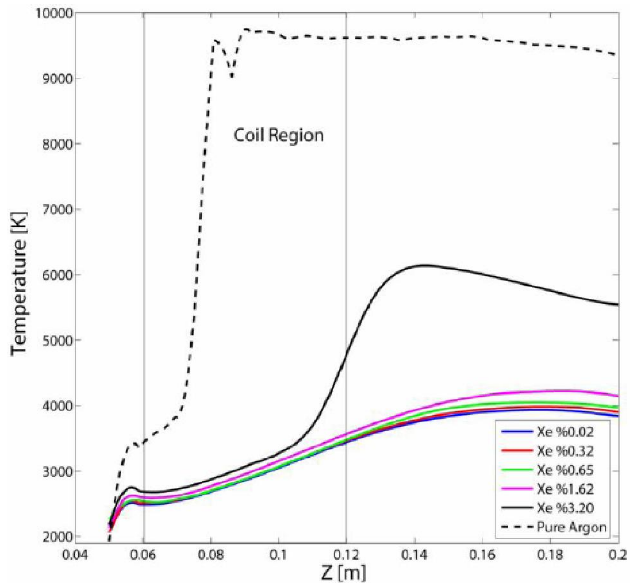


**Figure 8 : Temperature profile along the centerline for the case of Xenon admixtures by various amounts compared with the pure Argon**

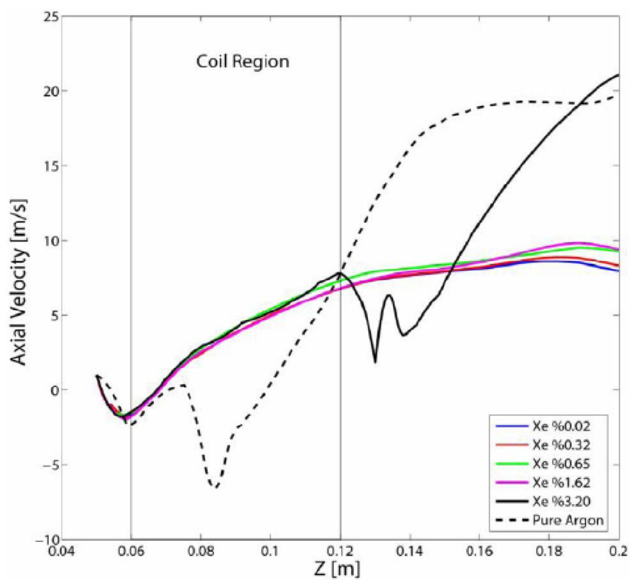


**Figure 9 : Axial velocity profile along the centerline for the case of Xenon admixtures by various amounts compared with the pure Argon**

them cool down the plasma nearly to 4000 K due to ion collisions. Cooling rate is same in all cases except for %3.20 Xenon. Output velocity is decreased for both Krypton and Xenon at the head compared to the pure Argon. By adding %3.20 Xenon to Argon, velocity has a bit different behavior, increasing within the coil region, a rapid fluctuation beyond the coil region and rise up to nearly 21 m/s.

## CONCLUSION

A two-dimensional magneto-hydrodynamic code has been developed to acquire a description of physical behavior of the ICP torches. The outcome is tool for virtually running the device and investigating the performance under various operational conditions. One of the most impressing factors, the working gas, is investigated through admixtures of tiny impurities. Generally, admixtures of Helium, Krypton and Xenon with Argon cool down the plasma within the centerline of the torch. This is called plasma cooling via buffer gas. In the present study, plasma temperature lowered from 9000 K to 4000 K at the torch head in the case of Krypton and Xenon. Axial velocity at the torch head is also decreased in mentioned cases and increased for Helium additive. Decrease in velocity and temperature is inferred as collisional cooling through the plasma. The prominent and striking effect of buffer gases observed in the plasma behavior is the circulating flows elimination which is energy consuming and causes the torch to be low-efficient. The significance of the presented model is that it enables us to adjust the plasma temperature and output velocity in virtual lab and tune the stability of the plasma inside the torch. If the additives change to other gases with different values, it might have some different influences in the temperature and velocity fields.

## ACKNOWLEDGMENT

The authors would like to gratefully and sincerely thank *Dr. Murphy* from *CSIRO Materials Science and Engineering* for his cooperation and providing the data needed for calculations.

## REFERENCES

**[1]** T.B.Reed; Int.Sci.Tech., **6**, 42–48 **(1962)**.

**[2]** D.Bernardi, V.Colombo, E.Ghedini, A.Mentrelli; Pure Appl. Chem., **77**, 359–372 **(2005)**.

**[3]** X.Chen, M.Sugasawa, N.Kikukawa; J.Phys.D.Appl.Phys., **31**, 1187–1196 **(1999)**.

**[4]** J.Mostaghimi, M.I.Boulos; Plasma Chem.Plasma Proc., **9**, 25–44 **(1989)**.

**[5]** S.Xue, P.Proulx, M.I.Boulos; J.Phys.D.Appl.Phys., **34**, 1897–1906 **(2011)**.

**[6]** D.Bernardi, V.Colombo, E.Ghedini, A.Mentrelli; Eur.Phys.J.D., **27**, 55–72 **(2003)**.

**[7]** W.M.Itano, J.C.Bergquist, J.J.Bollinger; D.J.Wineland, Phys.Scr. T, **59**, 106–120 **(1995)**.

**[8]** A.Montaser, D.W.Golightly; Inductively Coupled Plasmas in Analytical Atomic Spectrometry, **(1992)**.

**[9]** R.S.Devoto; Phys.Fluids, **9**, 1230 **(1966)**.
**[10]** D.L.Evans, R.S.Tankin; Phys.Fluids, **10**, 1137–1144 **(1967)**.
**[11]** R.C.Miller, R.J.Ayen; J.Appl.Phys., **40**, 5260–5273 **(1969)**.
**[12]** A.B.Murphy; IEEE Trans.Plasma Sci., **25**, 809–814 **(1997)**.
**[13]** A.B.Murphy, E.Tam; J.Phys.D Appl.Phys., **47**, **(2014)**.