Fusion Engineering and Design 101 (2015) 52–55

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Analysis of ion recombination in ionization chambers for tritium measurements

Zhilin Chen[a,b], Shuming Peng[a,*], Shenghan Cheng[a], Zhaoyi Tan[a], Heyi Wang[a], Matsuyama Masao[b]

[a] Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang, Sichuan 621900, China
[b] University of Toyama, Gofuku 3190, Toyama-city, Toyama 930-8555, Japan

HIGHLIGHTS

- A theoretical method was developed to evaluate ion recombination quantitatively.
- The established theoretical method is suitable for both two and three dimensions.
- Recombination coefficient in dry air was determined to be around 6.9×10^{-6} cm^3/ion s.
- This method is also suitable for other kinds of gas and for chambers of different sizes.

ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form
24 September 2015
Accepted 25 September 2015
Available online 21 October 2015

PACS:
29.40.Cs
28.52.Nh

Keywords:
Tritium measurements
Recombination
Ionization chamber

ABSTRACT

Ion recombination in ionization chambers for tritium measurements has been studied theoretically and experimentally. A two-dimensional model for ionization chamber of cylindrical form was introduced to derive theoretical formulas for evaluating ion recombination loss quantitatively, and it can be extended to three dimensions easily. Experiments were carried out with an gold plated ionization chamber of 1.0 L at tritium concentration 1.10×10^{11} Bq/m^3 and 1.98×10^{10} Bq/m^3. With the established theory, recombination coefficient was determined to be around 6.9×10^{-6} cm^3/ion s in dry air, which agreed with value reported recently in the literature. In addition, ion densities in ionization chamber have been investigated, which shows good accordance with experiments. Furthermore, this proposed method for analyzing recombination coefficient is also suitable for other kinds of working gas besides dry air and for ionization chambers of different sizes.

1. Introduction

Tritium is one of the most important fuels in fusion research, and a large amount of tritium will be used in fuel recycling system for a fusion reactor, such as tritium plant in ITER [1,2]. There are many procedures in tritium processing progress, including tokamak exhaust processing, hydrogen isotope separation, tritium storage and delivery, etc. [3]. During these processes, in-line and real-time measurements of high level tritium are indispensable to control fuel balance and provide data for tritium safety [4]. Small volume ionization chamber is highly attractive as a continuous tritium real-time monitor in the fuel processing system for its fast response, wide range, simple structure and no tritium consuming [5–8]. For an ionization chamber, the formation of its output signal can be generally divided into two steps, energy deposition of beta rays into sensitive region of the chamber and collection of ions produced in the first step, which are mainly determined by energy loss on chamber wall and ion recombination in the chamber, respectively. Till now, many people have observed in experiments that both processes might lead to large decrease of output signal [9–11]. In our previous work [12,13], we have proposed two kinds of methods to evaluate energy deposition in the first step quantitatively, theoretical calculation and monte-carlo simulation, which show good accordance with experimental results. However, there is still no quantitative theory to specify count loss caused by ion recombination in the second step.

In this work, a simplified two-dimensional model was established according to the isotropic character of cylindrical ionization chamber. Based on the analysis of charge conservation, expression for ion recombination was deduced. Besides theoretical

* Corresponding author.
E-mail address: pengshuming@caep.cn (Z. Chen).

http://dx.doi.org/10.1016/j.fusengdes.2015.09.014
0920-3796/

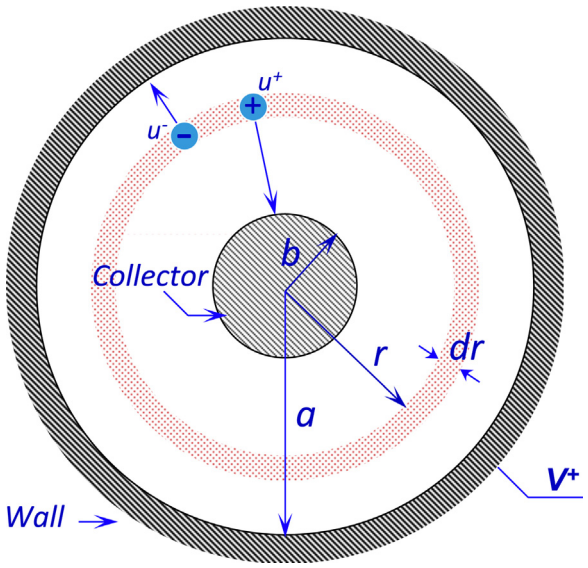

Fig. 1. Cross-section view of the two-dimensional model for an ionization chamber of cylindrical form.

calculations, experiments were carried out to investigate the recombination of ions, in which energy loss on chamber wall could be ignored and ion recombination should dominate the count loss progress. Recombination coefficient was obtained by fitting experiments with established formula. In addition, distribution of ions in ionization chambers is also presented in this paper.

2. Theory

Theoretically, all the ions created in the sensitive region of an ionization chamber should be collected by anode/cathode and results in saturation output signal. However, some ions will recombine before they can arrive at collector, which will decrease the collection efficiency, η. Assume that beta particles lose all their energy into the sensitive region of a chamber, then collection efficiency can be expressed as follows,

$$\eta = 1 - \frac{R}{N} \tag{1}$$

where R is the number of ions lost by recombination, which is mainly determined by two factors, concentration of ions and composition of working gas. N is the total number of ions produced by beta rays in the chamber.

For an ionization chamber of cylindrical form and with uniform tritium distribution in it, the ion densities, both positive (n^+) and negative (n^-), should be isotropic at the same cross section and remain constant along its axis direction. Therefore, calculations with a two-dimensional model are expected to be suitable for such problems. Cross section view of the two-dimensional model for an ionization chamber of cylindrical form is shown in Fig. 1. As shown in Fig. 1, ions will move to anode/cathode driven by electric force. To simplify calculations, two assumptions are employed. Firstly, the movement of ions is totally determined by electric field produced by voltage (V^+) biased to the chamber, while the effects of both space charge and diffusion caused by variation of tritium density are negligible. Secondly, ions move directly to anode or cathode, and their velocities are u^+ and u^-, respectively. For positive ions, the number of ions go through the section of radius r per unit time should be equal to the amount of ions generated in the region outside r within the same time, and then, we can obtain,

$$2\pi r u^+ n^+(r) = n_0 \pi (a^2 - r^2) \tag{2}$$

where u^+ is the drift velocity of positive ions, $u^+ = \mu^+ E(r)$, and μ^+ is the mobility of positive ions, $cm^2/s\,V$. $n^+(r)$ is the density of positive ion at radius r, ions/cm^2. n_0 is the initial ions created by beta rays per unit area and per unit time, ions/cm^2 s, $n_0 = C\bar{E_\beta}/\bar{W}$. C is the tritium density in the chamber, Bq/cm^2. $\bar{E_\beta}$ is the average energy of beta rays emitted by tritium, 5.7 keV. $\bar{W}$ is the average energy to produce an ion pair by beta rays in air, 33.6 eV. a is the inner radius and b is the radius of the collector, cm.

Similarly, for negative ions, the relationship can be expressed as,

$$2\pi r u^- n^-(r) = n_0 \pi (r^2 - b^2) \tag{3}$$

where $u^- = \mu^- E(r)$, and μ^- is the mobility of negative ions, $cm^2/s\,V$.

In an ionization chamber of cylindrical form, electric field is,

$$E = \frac{V}{r \ln a/b} \tag{4}$$

In Fig. 1, the total number of ion loss by recombination can be denoted as,

$$R = \int_b^a \alpha n^+(r) n^-(r) 2\pi r dr \tag{5}$$

where α is the recombination coefficient of ions. In this two-dimensional model, α is in unit of cm^2/ion s.

In the same region, the total number of ions created by beta rays is,

$$N = \pi (a^2 - b^2) n_0 \tag{6}$$

Combining Eqs. (1)–(6), finally collection efficiency can be expressed as,

$$\eta = 1 - \frac{\alpha}{6\mu^+\mu^-}(a^2 - b^2)^2 \left[\frac{\ln(a/b)}{2}\right]^2 \times \left[\frac{\bar{E_\beta} C}{\bar{W}}\right] \frac{1}{V^2} \tag{7}$$

In order to compare results between theoretical calculations and experiments, we need to extend Eq. (7) to three-dimensional ionization chamber of cylindrical form. In Eq. (7), C is the tritium density in the chamber, in unit of Bq/cm^2, while α is in unit of cm^2/ion s. Besides these two parameters, the others are independent of dimensions of the model. Therefore, we can easily obtain the expression of collection efficiency (η) for three-dimensional chamber by substituting C and α in Eq. (7) with tritium concentration (C', Bq/cm^3) and volume recombination coefficient (α', cm^3/ion s). In the following part, η in the three-dimensional form (η') is used in calculations.

3. Experiments

In calculations above, there is an assumption that beta rays will deposit all their energy into the sensitive region of the chamber. In fact, beta rays might lose their energy by colliding with atoms on the surface of chamber wall. As depicted in Fig. 2(a), beta rays emitted by tritium in red region might deposit part of their energy into chamber wall. λ is the range of beta rays. In the red region, energy deposition rate decreases as the position of tritium atom approaches chamber wall, as shown in Fig. 2(b). Therefore, to specify the effects of recombination, experiments should be designed to minimize energy loss on chamber wall. However, it is very difficult to calculate energy deposition in the red region due to the complicated interaction process between beta particles and atoms of both carrier gas and chamber wall. According to theory we have already established before [12,13], energy deposition rate greatly depends on wall materials, gas pressure, composition of carrier gas, etc. For an ionization chamber of 1.0 L volume and with gold plated wall, energy deposition rate in its sensitive region is higher than 98% at 1 atm. As a result, an ionization chamber with such parameters is