Plasma Science & Technology, Vol.7, No.2, Apr. 2005

# Analysis on Pressure Distribution in HT-7 Neutral Beam Injection System*

Zhu Wu(朱武)[1], Chen Lian(陈联)[1], Hu Chundong(胡纯栋)[2], Hu Liqun(胡立群)[2]

[1] Hefei University of Technology, Hefei 230001, China

[2] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

**Abstract** Neutral Beam Injection (NBI) is an effective way to improve the efficiency of tokamak heating system. This article primarily introduces a work on the pressure distribution inside the tank of NBI heating system, especially inside the neutralizer, which is got by selecting a proper mathematical model and constructing a series of rational calculating formulas on pressure distribution. Furthermore, we simulate the pressure distribution by the Monte Carlo method. Comparing the result of simulation with that of theoretical calculation, we find that both the results are very close each other, showing their mutual validity.

**Keywords:** neutral beam injection, vacuum calculation, Monte Carlo simulation

**PACS:** *52.50.G*

## 1 Introduction

In the field of controlled nuclear fusion, Neutral Beam Injection (NBI) is an effective way to improve the NBI heating efficiency. Since the early 1970's, there have been many successful examples of heating systems for tokamak. In China, research in the field of NBI is rather rare. The Institute of Plasma Physics started the NBI project in the middle 1980's, but the project was stopped for some reasons after several years of study. The NBI project was resumed in the HT-7 tokamak again in September, 2002. Up to now, we have made some progress. In the course of constructing NBI heating system, there are many theoretical and experimental issuses; which must be considered such as pressure distribution inside of the NBI system, ion source, high voltage, magnetic field and high power measurement, etc. This article mainly discusses the axial pressure distribution of NBI heating system, especially the pressure distribution inside the neutralizer gas cell, and calculates exactly the pressure distribution in the tank by selecting a proper mathematical model. When analyzing the pressure distribution, the gas source coming from ion sources, the wall of the tank, re-ionization loss, etc. are taken into account. Finally, we have simulated the pressure distribution inside the neutralizer cell based on a mathematical model by the Monte Carlo method. The result of the simulation that is very close to that of theoretical calculation to a certain extent certifies the correctness of the mathematical model to a certain extent.

## 2 Analysis on gas source of NBI heating system

The NBI heating system is generally shown in Fig. 1[1]. It contains a neutralizer, a tank, an ion-bending magnet, a drift tube, a vacuum pump system, etc. The basic aim of the system is to transform a high-energy ion beam into a high-energy neutral particle beam and then transport the particles to the tokamak. All these components offer a basic condition for NBI system operation. The neutralizer neutralizes the high-energy ion beam. The ion-bending magnet bends the un-neutralized ion beam toward the ion dump. The drift tube transports the neutralized ion beam to the tokamak. The vacuum pump system maintains the necessary pressure for the NBI operation.

Generally speaking, in the vacuum area, there are mostly three kinds of gas sources: the residual gas coming from ion source and neutralizer, the sputtering gas bringing forth a bending magnet effect that bends un-neutralized high-energy ion beam to ion dump, and the deflation of tank wall due to scattering beam. Fig. 1 shows these kinds of gases. All of these gases supply for neutralizing operation. Theoretically, the more gas in the neutralizer, the more easily the high-energy ion beams will be neutralized, when going through the neutralizer. However, too much gases will increase re-ionization loss of the high-energy neutral beam.

**a.** Intake quantity $Q_s$ of ion source and residual gas quantity $Q_r$.

In order to change the amount of current, it is necessary to supply various quantities of gas to the ion source. Generally speaking, the gas utilization factor of the ion source is 50%. For a 60 A, 30 keV high-energy H ion beam, its intake quantity needs to be $Q_s = 1.696\ \mathrm{Pa{\cdot}m^3/s}$, $Q_i = 0.849\ \mathrm{Pa{\cdot}m^3r/s}$ or so. The calculations go as follows:

Let's suppose the beam intensity of the ion beam is $I_0$, and the relative scale of $H_1^+$, $H_2^+$, $H_3^+$ is $\varepsilon_1{:}\varepsilon_2{:}\varepsilon_3$.

* The project supported by the Canada Research Chair Program and Natural Sciences and Engineering Research Council of Canada

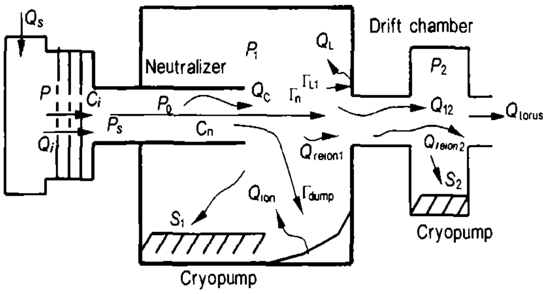


**Fig.1** Structural diagram of NBI system

And generally when taking 1 Pa·m$^3$ $\sim 2.6\times10^{20}$ molecules [2], then the corresponding Pa·m$^3$ quantity of $H_1^+$, $H_2^+$, $H_3^+$ is $\Gamma_1 = 1.188\times10^{-2} I_0\cdot\varepsilon_1$, $\Gamma_2 = 2.375\times10^{-2} I_0\cdot\varepsilon_2$, $\Gamma_3 = 3.563\times10^{-2} I_0\cdot\varepsilon_3$ respectively. So the equivalent gas quantity carrying away by the high-energy ion beams is $\Gamma_{\rm ion} = \Gamma_1+\Gamma_2+\Gamma_3$. The intake quantity of the ion source $Q_{\rm s}$ is $Q_{\rm s} = \dfrac{\Gamma_{\rm ion}}{\eta}$, where $\eta$ is the gas utilization factor of the ion source. In a steady-state condition, the residual quantity of the ion source is $Q_{\rm r} = Q_{\rm s}-\Gamma_{\rm ion}$. When $I_0 = 60$ A, $\eta = 50\%$, then $Q_{\rm s} = 1.696$ Pa·m$^3$/s, $Q_{\rm i} = 0.849$ Pa·m$^3$/s.

**b.** Quantity of operating gas $Q_{\rm n}$ in the neutralizer

The quantity of operating gas in the neutralizer mainly comes from the ion source and the intake gas system. The gas quantity of neutralizer coming from the ion source is $Q_{\rm i} = C_{\rm s}\cdot(P_{\rm i}-P_{\rm s})$, where $C_{\rm s}$ is the tube conductance of the ion source. The intake gas quantity is expressed as $Q_{\rm p}$. High-energy ion beams can be interacted with operating gas going through the neutralizer. So we define the gas in the neutralizer as the gas target. For different high-energy beamlines, different thicknesses of gas-target being often a function of the ion-beam energy are needed. There is an optimal gas target thickness for every kind of ion beam, which will be discussed in detail as follows.

According to some references [3], we obtain:

$$F_0(\Pi) = F_0^\infty\{1-\exp[-\Pi(\sigma_{01}+\sigma_{10})]\} \qquad (1)$$

where: $F_0(\Pi)$ is the ratio of the neutralized high-energy ion beam to the un-neutralized one after going through the neutralizer; $F_0^\infty$ is the quilibrium ratio $F_0^\infty = \lim_{\Pi\to\infty} F_0(\Pi)$; $\Pi$ is the gas target thickness $\Pi = \displaystyle\int_0^L n_{\rm g}(x){\rm d}x$; $\sigma_{01}$, $\sigma_{10}$ are the collision cross sections of high-energy ions.

We usually take $F_0(\Pi)\geq 0.95F_0^\infty$, then

$$F_0(\Pi) = F_0^\infty\{1-\exp[-\Pi(\sigma_{01}+\sigma_{10})]\}\geq 0.95F_0^\infty, \quad (2)$$

from it, we have

$$\Pi \geq \frac{3}{\sigma_{01}+\sigma_{10}}. \qquad (3)$$

If the optimal gas-target thickness given, the average pressure of the neutralizer $\bar{P}$ will be approximately acquired. And the pressure difference between the two ends of neutralizer is $\Delta P\approx 2\bar{P}$. So the quantity operating gas in the neutralizer $Q_{\rm n}$ is $Q_{\rm n} = \Delta P\cdot C_{\rm n}$. Here $C_{\rm n}$ is the computed conductance of the neutralizer based on a formula [4].

For our NBI heating system, the length of the neutralizer is $L = 1.4$ m, and the diameter is $D = 25$ cm[5]. Furthermore, if the energy of the high-energy ion beam is 30 keV, then the quantity of operating gas in the neutralizer is $Q_{\rm n} = 1.803$ Pa·m$^3$/second.

**c.** Other gas sources of the tank

(1) Equivalent gas source generated by the unneutralized high-energy ion beam $Q_{\rm ion}$.

After the high-energy ion beam passing through the neutralizer, it is partially neutralized. The unneutralized part can be deflected from the axis of the neutral beam by a bending magnet. If the neutralizing efficiently is $\eta_{\rm G}$, then

$$\Gamma_n \cong \eta_G\cdot\Gamma_{\rm ion}, \qquad \Gamma_{\rm dump}\cong(1-\eta_{\rm G})\cdot\Gamma_{\rm ion},$$

$$Q_{\rm ion}\cong\gamma_{\rm ion}\cdot\Gamma_{\rm dump}\cong\gamma_{\rm ion}\cdot(1-\eta_{\rm G})\cdot\Gamma_{\rm ion}, \qquad (4)$$

where $\gamma_{\rm ion}$ is the high-energy ion absorption efficiency of ion dumps, usually $\gamma_{\rm ion} = 1$. Supposing $\eta_{\rm G} = 0.703$, then we can get $Q_{\rm ion}\cong 0.252$ Pa·m$^3$/s.

(2) Equivalent quantity of gas source generated by the ionized neutral-beam transmission $Q_{\rm reion1}$.

The reionization of high-energy neutral beams during their transmission in the tank is undesirable, so we need to decrease the re-ionization loss of the neutral beam. Supposing the ratio of re-ionization loss is $\eta_1$, usually $\eta_1 < 5\%$. Here, assuming $\eta_1 = 5\%$, then we obtain $Q_{\rm reion1}\approx\eta_1\cdot\Gamma_n = 0.032$ Pa·m$^3$/s.

(3) Equivalent quantity of gas source generated by beam-defining plates $Q_{\rm L}$.

The beam-defining plates are used to control the shape of the neutral beam and the filter-fringe neutral beam where the density is less than that of center neutral beam [7]. Under the action of beam-defining plates, the circular neutral beamline becomes rectangular. If $p_{12}$ is the ratio of beam -defining plates intercepting $\Gamma_{\rm n}$, then we can make use of the following equation to compute the equivalent gas quantity $Q_{\rm L}$:

$$Q_{\rm L}\approx\gamma_{\rm L}\cdot p_{12}\cdot(1-\eta_1)\Gamma_{\rm n}, \qquad (5)$$

where $\gamma_{\rm L}$ is the sputtering coefficient, usually $\gamma_{\rm L} = 1$, $p_{12}$ is variable and it can be adjusted during the experiment. It $p_{12} = 0.1$, then $Q_{\rm L} = 0.057$ Pa·m$^3$/s.

**d.** Analysis on the gas source in the drift chamber.

A calorimeter and a cryopump are placed in the drift chamber. The pump speed of cryopump is determined, depending on the vacuum kept enough in the drift chamber without deteriorating the vacuum of HT-7 tokamak system. The main gas source in the drift chamber system comes from the re-ionization loss generated by the high-energy neutral beam in the course of the transmission and diffusion gases coming from the tank. Both quantities of the gases are about $10^{-3}$ Pa·m$^3$/s order of magnitude, which were not given

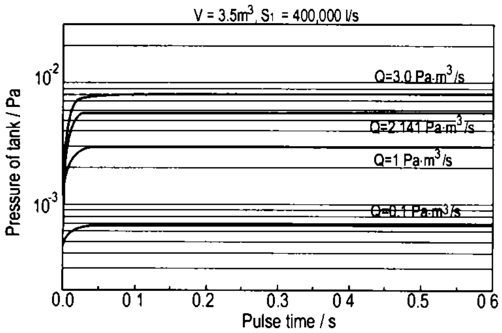


**Fig.2** Various curves of the vacuum pressure in the tank

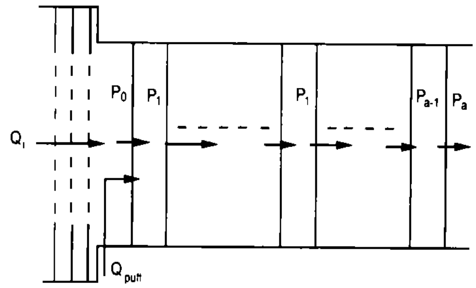


**Fig.3** Computation model of neutralizer cell pressure

here separately one by one.

## 3 Theoretical calculation of vacuum pressure distribution

**a.** Calculation of pressure distribution in the tank chamber.

From the above analysis, the pressure in the tank chamber $P_1(t)$ can be derived from[7].

$$V\frac{dP_1(t)}{dt} = Q_c+Q_{ion}+Q_{reion1}+Q_L-Q_{12}-S_1\cdot P_1(t), (6)$$

where $V$ is the volume of the tank, $V=3.5\ m^3$, $S_1$ is the pump speed, and the initial condition $P_0$ of $P_1(t)$ is the background pressure of the tank, If $P_1(0) = P_0 = 4\times10^{-4}$ Pa, then

$$P_1(t) = \frac{Q}{S_1}(1-e^{-\frac{s_1}{V}}) + P_0, \qquad (7)$$

where $Q = Q_c+Q_{ion}+Q_{reion1}+Q_L-Q_{12}$, and it varies with the energy of the injection beam. Based on the supposed energy, we can obtain $Q = 2.141\ Pa{\cdot}m^3/s$. Fig. 2 shows the pressure $P_1(t)$ varying with $Q$ when $V$ is 3.5 $m^3$ and $S_1$ is $4\times10^5$ l/s.

**b.** Calculation of pressure distribution in the neutralizer cell.

Pressure distribution in the neutralizer cell is more complicated than any of the others. A model in the following figure is used to compute it.

Fig. 3 shows that the neutralizer is divided into $n$ segments which have the same volume $V$ and the same conductance $C$. Furthermore, the center pressure of each segment is regarded as one of the corresponding segments $P_i$. When the gas flows from the last segment into the tank chamber, its displacement is only one half of that of other segments and the conductance is expressed as $C_1$. Then we obtain the following series of differential equations:

$$\nu\frac{dP_0}{dt} = C_i\cdot(P_s-P_0)+Q_{puff}-C(P_0-P_1),$$

$$\nu\frac{dP_1}{dt} = C\cdot(P_0-P_1)-C\cdot(P_1-P_2),$$

$$\cdots$$

$$\nu\frac{dP_i}{dt} = C\cdot(P_{i-1}-P_i)-C\cdot(P_i-P_{i+1}),$$

$$\cdots$$

$$\nu\frac{dP_{n-1}}{dt} = C\cdot(P_{n-2}-P_{n-1})-C\cdot(P_{n-1}-P_n),$$

$$\nu\frac{dP_n}{dt} = C\cdot(P_{n-1}-P_n)-C_1\cdot(P_n-P_1). \qquad (8)$$

But $P_1$ is determined by equation (5), and after considering the effect of $C_1$, we can rewrite it as the following:

$$\nu\frac{dP_1}{dt} = C_1\cdot(P_n-P_1)+\acute{Q}-S_1\cdot P_1.$$

Clearing up these equations, we obtain:

$$\frac{dP_0}{dt} = -\frac{C+C_i}{\nu}P_0+\frac{C}{\nu}P_1+\frac{C_i}{\nu}P_s+\frac{Q_{puff}}{\nu}, \quad (9)$$

$$\frac{dP_i}{dt} = \frac{C}{\nu}P_{i-1}-2\frac{C}{\nu}P_i+\frac{C}{\nu}P_{i+1}, \quad i=1,2,\cdots,n-1, (10)$$

$$\frac{dP_n}{dt} = \frac{C}{\nu}P_{n-1}-\frac{C+C_1}{\nu}P_n+\frac{C_1}{\nu}P_1, \qquad (11)$$

$$\frac{dP_1}{dt} = \frac{C_1}{V}P_n-\frac{C_1+S_1}{V}P_1+\frac{\acute{Q}}{V}, \qquad (12)$$

where $P_i$ ($i$ = 0, 2, $\cdots$, n) is the pressure of each segment field, $v$ is their volume and $C$, $C_1$ are their conductances, $P_1, V, S_1$ is the pressure of the tank, the tank volume, and the pumping speed of the cryopump respectively, $\acute{Q}$ is the total amount of gas deflation, air leakage and other gas flows. It determines the background pressure of the system, and theoretically its value is much less than that of $C_1\cdot(P_n-P_1)$.

The Runge-Kutta method is used to solve these equations, and its solution can be demonstrated by using equation (10). Here supposing $a = 2\frac{C}{\nu}$, $b=c=\frac{C}{\nu}$, then $\frac{dP_i}{dt} = -aP_i+bP_{i-1}+cP_{i+1}$. Using the Runge-Kutta method to analyze the equation [8], we have

$$P_{i,j+1} = P_{ij}+\frac{\Delta t}{6}(K_{1ij}+2K_{2ij}+2K_{3ij}+K_{4ij}),$$

$$K_{1ij} = -a\cdot P_{ij}+b\cdot P_{i-1,j+1}+c\cdot P_{i+1,j},$$

$$K_{2ij} = -a\cdot(P_{ij}+\frac{\Delta t}{2}K_{1ij})+b\cdot P_{i-1,j+1}+c\cdot P_{i+1,j},$$

$$i=1,2,3\cdots,n-1, \quad j=1,2,\cdots,m,$$

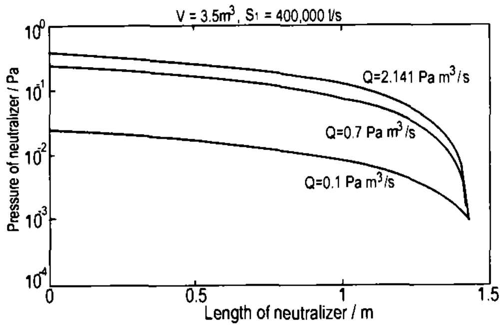


**Fig.4** Various curves of vacuum pressure distribution in the neutralizer

$$K_{3ij}=-a\cdot(P_{ij}+\frac{\Delta t}{2}K_{2ij})+b\cdot P_{i-1,j+1}+c\cdot P_{i+1,j},$$

$$K_{4ij}=-a\cdot(P_{ij}+\Delta t\ K_{3ij})+b\cdot P_{i-1,j+1}+c\cdot P_{i+1,j},\quad(13)$$

where $P_{ij}$ and $P_{ij+1}$ are the iterative values of $P_i$ for No $j$. and No $j+1$ respectively and are the iterative values of $P_{i+1},j$ for No $j$, $K_{1ij}$, $K_{2ij}$, $K_{3ij}$, $K_{4ij}$ are the iterative values of $K_1, K_2, K_3, K_4$ of $P_i$ for No.$j$, respectively. For other differential equations, similar conclusions can be made by solving them in the same way. By using these iterative formulas, the pressure distribution in the neutralizer cell can be calculated. And the results of these calculations are shown in Fig. 4.

Furthermore, in order to avoid confusion of the iterative value, we must choose an appropriate iteration step length $\Delta t$. The following Table 1 shows the relation of the iteration step length and the maximum number of segments.

**Table 1.** The relation of the iteration step length and the maximum number of segments

| Step $\Delta t$ | Segments $n$ |
|---|---|
| $\leq 10^{-3}$, $> 10^{-4}$ | 3 |
| $\leq 10^{-4}$, $> 10^{-5}$ | 7 |
| $\leq 10^{-5}$, $> 10^{-6}$ | 23 |
| $\leq 10^{-6}$, $> 10^{-7}$ | 70 |
| $\leq 10^{-7}$ | 210 |

## 4 Result of pressure distribution by Monte Carlo simulation

Theoretically, we have discussed the pressure distribution of the NBI system. But its correctness is unknown, to this end, here we decided to verify it by Mont Carlo simulation. The axial pressure distribution in the neutralizer and tank, along with pressure change in the neutralizer during the process of operation is simulated. In the following, we discuss briefly the axial pressure distribution in the neutralizer as an example of simulation.

The principle of Monte Carlo simulation is to divide the neutralizer into n segments (generally $n > 50$). All of the gas molecules entering the neutralizer and their propagation paths are tracked and recorded. When one gas molecule passes through one segment, we make $n_i = n_i + 1$ (where $n_i$ is the number of molecules passing this segment). After tracking a good many of molecules, we can use the equation $P = nkT$ to calculate the relative gas density over each segment. Then, we can convert the relative gas density into actual pressure of the neutralizer. The following figure shows the pressure distribution of the neutralizer when number of simulated gas molecules is $10^5$.

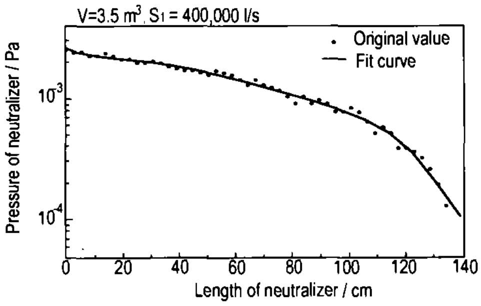


**Fig.5** Various curves of vacuum pressure in the neutralizer by Mote Carlo simulation

From the Fig. 5, we can find that the result of the Monte Carlo simulation is consistent with that of the theoretical calculation, showing that both of them are valid.

## Acknowledgement

The author is indebted to his colleagues in the Neutral Beam Injection group at ASIPP for their support and suggestions.

## References

1 Claesen R, Mondino P L. Neutral Beam injection and radio frequency power supplies, Fusion Technology, 1987: 141 ~ 162

2 Uhlemann R. Variation of injected neutral beam power at constant particle energy by changing the beam target aperture of the TEXTOR neutral beam injections, Fusion Techology, 1999, 35: 45 ~ 50

3 Zhang Huashun. Ion Source and High-power Neutral Beam Source, Beijing: Atomic Energy publishing Company. 1987, 461 ~ 462

4 Da Daoan. Handbook of Vacuum Design. Beijing: The Defence Industry Publishing Company. 1991, 111 ~ 113 (in Chinese)

5 Seeber B. Handbook of applied superconductivity. Bristol: Institute of Physics Publishing. 1988, 1028 ~ 1045

6 Bessette D, Zapretilina E, Shatil N. Nuclear heat, disruption loads and other AC losses and their impact on the ITER Toroidal field coils conductor design. IEEE transaction on Applied Super conductivity, 2000, 10(1): 1074 ~ 1077

7 Guo Hongzheng. The Design and Calculation of Vacuum System. Beijing: The Metallurgical Industry Publishing Company. 1986, 63 (in Chinese)

8 Li Youfa. The Numerical Calculation Ways. Beijing: the Higher Education Publishing Company. 1996, 129 (in Chinese)

(Manuscript received 13 October 2003)

E-mail address of Zhu Wu: zhuwu8443@sina.com