Simulation Study of the Relation between MRPC Performances and Working Gas

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Abstract With an excellent time resolution, the Multi-gap Resistive Plate Chamber (MRPC) has been applied as TOF detector in particle physics experiments. We constructed more than 30 MRPC modules that were set up on the tray of RICH-STAR successfully. By the program of Magboltz, the parameters of working gases in MRPC were calculated. Based on the detector physics the relation between MRPC performance and working gas was analyzed, which is helpful to optimize the proportion of gas mixtures for RPC and MRPC.

Key words MRPC, working gas, gas parameters, performance

1 Introduction

Developed in the 1980s[1] and then evolved into MRPC in 1995[2], the Resistive Plate Chamber (RPC) has become an integral part of the present high energy physics experiments. Several groups in the world have made great efforts on studying RPC & MRPC and achieved a lot of progress on the technology for constructing RPC & MRPC and deep understanding of their performances. As one of the co-workers in RHIC-STAR[3], based on the technology of ALICE group (Fig.1 shows the structure of MRPC developed by ALICE group)[4], we developed the procedure for MRPC mass production successfully. Tested by cosmic rays or beams at BNL, the time resolution of our MRPC is less than 70ps which can meet the requirements of RHIC-STAR completely.

As for MRPC, the common working gas is $C_2F_4H_2$ with a bit of i-C_4H_{10} and SF_6. However SF_6 is a kind of heavy green-house effect gas abandoned by RHIC-STAR, so it is urgent to select a proper gas mixture as working gas in MRPC for RHIC-STAR. In order to optimize the gas mixture with appropriate proportion in MRPC, it is necessary to test the performances of MRPC with different gas mixtures. However, before carrying out the test, it is useful and instructive to know the gas parameters and analyze the roles of different gas mixtures on the performances of MRPC. In this paper, by making use of the program: Magboltz[5] and the theory of gas electric conduction, the transport parameters of different gas mixtures are

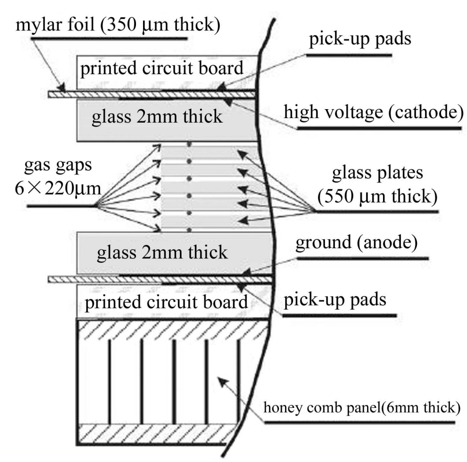

Fig. 1. The cross-section of 6×0.22mm MRPC for TOF.

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calculated, Meanwhile, the function of different gases in MRPC is also analyzed.

The results of gas parameters as Townsend coefficient, electron attachment coefficient and others are presented in Section 2, the relation between working gas and MRPC performances is studied in Section 3, and finally Section 4 is discussion and conclusion.

2 Gas parameters in MRPC

There are several transport parameters of working gas in gas detectors: Townsend coefficient, electron attachment coefficient, drift velocity and diffusion coefficient, which influence the performance of gas detectors strongly. The familiar working gas in MRPC is $C_2F_4H_2$ added with a little of i-C_4H_{10} and SF_6. The following are the computed gas parameters of $C_2F_4H_2$, i-C_4H_{10} and SF_6, and gas mixtures filled in MRPC by some experimental groups. The program for calculating those parameters is Magboltz, and all of them are simulated under the condition of $T=293$K and $P=1$atm.

2.1 Townsend coefficient and attachment coefficient

Fig. 2(a) and 2(b) show the Townsend and electron attachment coefficient for pure $C_2F_4H_2$, i-C_4H_{10}, SF_6 and their gas mixtures with different proportion respectively. Although it drops with electric field increasing, the attachment coefficient of SF_6 is still much higher than that of $C_2F_4H_2$ and i-C_4H_{10} (in Fig. 2(a)); on the other hand, the attachment coefficient of $C_2F_4H_2$ and i-C_4H_{10} is very small and changes little with electric field increasing. Therefore it can be predicted that SF_6 is a kind of strong electronegative gas, and however the electron attachment effect in $C_2F_4H_2$ and i-C_4H_{10} may be ignored in MRPC.

As shown in Fig. 2(a) and Fig. 2(b), the effective Townsend coefficient for the pure gases of $C_2F_4H_2$, SF_6 and i-C_4H_{10} or gas mixtures with different proportion, increases linearly with electric field in strong electric field. For gas mixture without SF_6, the effective Townsend coefficient reduces with proportion of $C_2F_4H_2$ increasing.

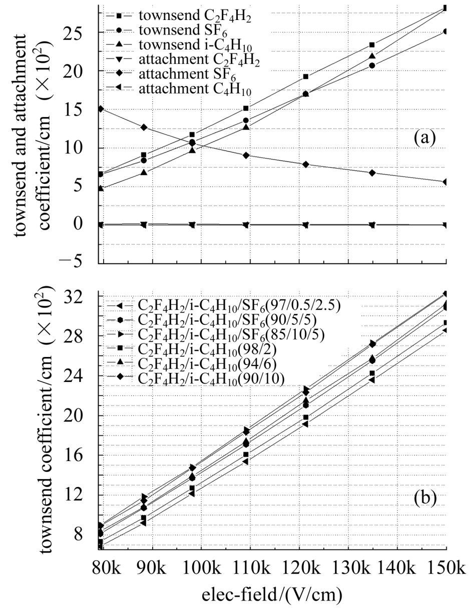

Fig. 2. Townsend and attachment coefficient calculated by Magboltz for pure gases: $C_2F_4H_2$, SF_6 and i-C_4H_{10} (a) and for gas mixtures with different proportion (b).

2.2 Longitudinal and transverse diffusion coefficient

The longitude and transverse diffusion coefficient in pure gases of $C_2F_4H_2$, SF_6, i-C_4H_{10} and gas mixture with different proportion is shown in Fig. 3(a), 3(b), 3(c) and 3(d) respectively.

The longitudinal diffusion coefficient for the pure gases of $C_2F_4H_2$, SF_6 and i-C_4H_{10} is a bit smaller than the transverse diffusion coefficient. Meanwhile the longitudinal or transverse diffusion coefficient of i-C_4H_{10} is lower than that of pure $C_2F_4H_2$ and SF_6 in strong electric field (see Fig. 3(a) and 3(c)).

Indeed the trend of the longitudinal and transverse diffusion coefficient for gas mixture with different proportion is declining (in Fig. 3(b) and 3(d)), but it is impossible to select the minimum longitudinal diffusion coefficient in these gas mixtures. At the same time, as for the transverse diffusion coefficient, the value of the gas mixture of $C_2F_4H_2$/ i-C_4H_{10} (90%/ 10%), shown in Fig. 3(d) is less than others.

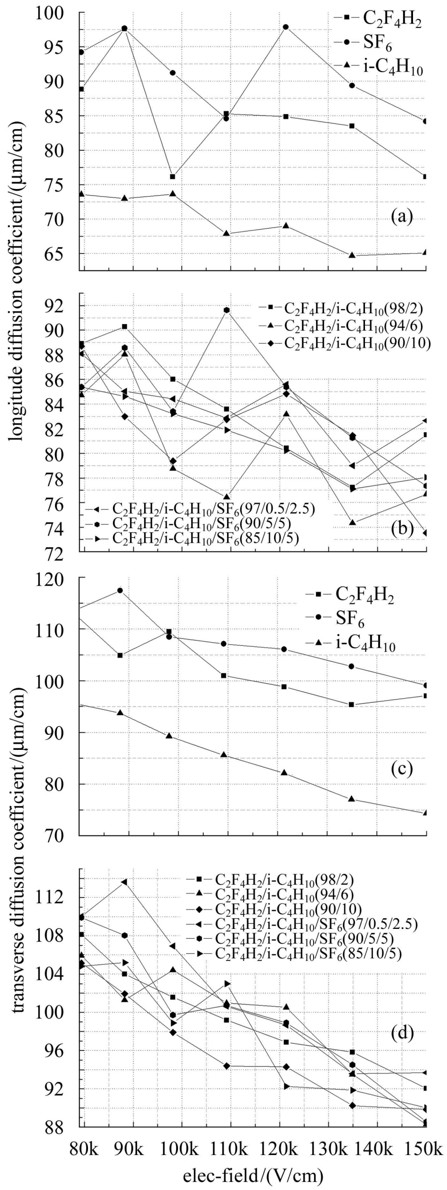

Fig. 3. Longitudinal and transverse diffusion coefficient simulated by Magboltz for the pure gases of $C_2F_4H_2$, SF_6, i-C_4H_{10} (a, b) and gas mixture with different proportion (c, d).

2.3 Electron drift velocity

The drift velocity of electrons in working gases for MRPC computed by Magboltz can be seen in Fig. 4(a) (the value for pure gases) and Fig. 4(b) (the value for gas mixtures). It is clear that no matter for the pure gases of $C_2F_4H_2$, SF_6 and i-C_4H_{10} (Fig. 4(a)) or for gas mixture with different proportion (Fig. 4(b)), the electron drift velocity increases linearly with electric field enhancing in strong electric field. For the pure gases, the electron drift velocity in $C_2F_4H_2$ is the fastest, and the drift velocity of electrons in gas mixture without SF_6 increases with the proportion of i-C_4H_{10} falling.

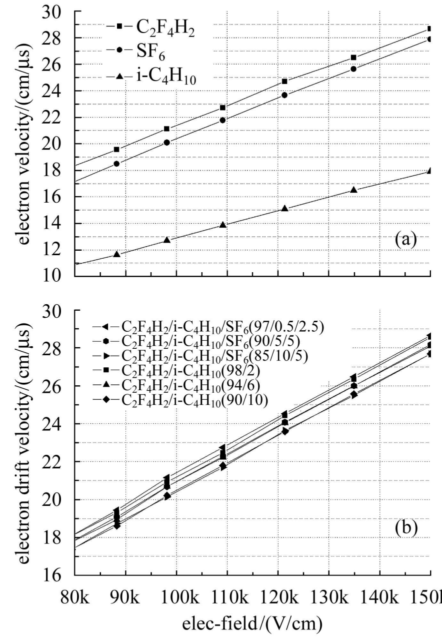

Fig. 4. The electron drift velocity for the pure gases of $C_2F_4H_2$, SF_6, i-C_4H_{10} (a) and gas mixture with different proportion (b) obtained by Magboltz.

3 Relation between gas parameter and MRPC performance

Some references[6, 7] have already simulated the mechanism in RPC and have also presented some mathematical relationship between the working gas parameters and the RPC performances, such as the effective Townsend coefficient versus the gas gain and efficiency, and the electron drift velocity versus the time resolution. Of course there is some disagreement in MRPC when applying those formulas obtained from RPC, but based on those functions, we can analyze the relations between the gas parameters and the MRPC performances, for a lot of experiments have proved that to a great extent, the mechanism in timing RPC is much similar to that in MRPC when working in avalanche mode.

3.1 Effective Townsend coefficient versus the gas gain and efficiency

According to the theory of gas transport that in uniform electric field, the gas gain A is determined by effective Townsend coefficient (α-η), where α is the Townsend coefficient and η the attachment coefficient:

$$A = \mathrm{e}^{(\alpha-\eta)x}, \tag{1}$$

where x is the average drift distance of electrons. From Fig. 2(b), it can be expected that supplied with the same high voltage, the highest gas gain can be obtained with the gas mixture of $C_2F_4H_2$/ i-C_4H_{10} (90%/10%) in MRPC. However almost all the tests on MRPC performances have confirmed that MRPC works in avalanche mode, which has been saturated, so it is not important to select an ideal gas mixture for getting a high gas gain.

As presented in some references[6], the efficiency ε in timing RPC is:

$$\varepsilon = 1-\mathrm{e}^{-(1-\eta/\alpha)d/\lambda}\left[1+\frac{V_{\mathrm{W}}}{E_{\mathrm{W}}}\frac{\alpha-\eta}{\mathrm{e}_0}Q_{\mathrm{t}}\right]^{1/\alpha\lambda}, \tag{2}$$

where d is the thickness of gas gap, λ the average distance between clusters produced by primary ionization in working gas, E_{W} the weighting field in gas gap, V_{W} the potential between anode and cathode electrode, e_0 the charge of an electron and Q_{t} the threshold of the electric system. In MRPC, we select the geometrical parameters, the working voltage and high energy particle as:

$$\begin{aligned} d &= 0.22\mathrm{mm}, \quad N_{\mathrm{d}}=6, \\ V_{\mathrm{W}} &= 14.5\mathrm{kV}, \quad \lambda = 0.1\mathrm{mm}(7\mathrm{GeV\ pion}), \end{aligned} \tag{3}$$

where N_{d} is the number of gas gap in MRPC. Therefore it is reasonable that the efficiency of MRPC should be:

$$\varepsilon_{\mathrm{MRPC}} = 1-(1-\varepsilon)^6, \tag{4}$$

By making use of the program: Ansys[8], the weighting field in gas gaps of MRPC can be calculated. When the working voltage is the typical value of 14.5kV, the weighting field is about 87kV/cm. If the threshold Q_{t} is 20fC, for all the different gas mixtures mentioned above, the efficiency of MRPC can reach almost 100%, which is proved by our experiments. In the next work, we will calculate the efficiency plateau curve versus the working voltage for MRPC with different working gases.

3.2 Time resolution versus electron drift velocity

The key factor that the time resolution of MRPC can be excellent is the fast drift velocity of electrons, to a great extent, which can cut down the time fluctuation caused by random primary ionization position in MRPC gas gaps.

According to the formula deduced out in Ref. [6], for timing RPC, the intrinsic time resolution σ_t is:

$$\sigma_{\mathrm{t}} = \frac{1.28}{(\alpha-\eta)v}, \tag{5}$$

where v is the drift velocity of electrons in RPC. In the reference quoted above, we can believe that because of serious space charge effect in MRPC, the number of total multiplied electrons mainly depends on the strongest avalanche in any gas gap of MRPC, not the sum of all the avalanches in each gas gap of MRPC, and accordingly we can also adopt Eq. (5) to estimate the time resolution of MRPC. Therefore the time resolution of MRPC with different gas mixtures can be estimated by Eq. (5) as shown in Fig. 5. The calculated time resolution of MRPC with such gas mixtures as $C_2F_4H_2$(100%), $C_2F_4H_2$/i-C_4H_{10} (94.7%/5.3%) and $C_2F_4H_2$/i-C_4H_{10}/SF_6 (90%/5%/5%) is in Table 1. Compared with the experimental results in some reference[9] in Table 2, the estimated time resolution agrees with the experiment well. Of course, in the next work, in order to describe the mathematical relation between time resolution and electron drift velocity in MRPC precisely, we need to correct Eq. (5) by simulating the mechanism carefully in MRPC.

Table 1. The estimated time resolution of MRPC with different gas mixtures when working voltage is 14.5kV.

gas mixture	time resolution/ps
$C_2F_4H_2$ (100%)	74
$C_2F_4H_2$/i-C_4H_{10}(94.7%/5.3%)	64.5
$C_2F_4H_2$/i-C_4H_{10}/SF_6(90%/5%/5%)	68.5

Table 2[9]. The experimental time resolution of MRPC with different gas mixtures when working voltage is 14.5kV.

gas mixture	time resolution/ps
$C_2F_4H_2$(100%)	77
$C_2F_4H_2$/i-C_4H_{10}(94.7%/5.3%)	63
$C_2F_4H_2$/ i-C_4H_{10}/SF_6(90%/5%/5%)	67

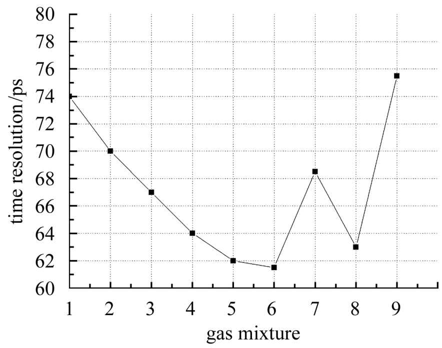

Fig. 5. The simulated time resolution versus different gas mixtures. The serial number along the horizontal coordinate represents different working gases in MRPC as
1: $C_2F_4H_2$ (100%);
2: $C_2F_4H_2$/i-C_4H_{10}(98%/2%);
3: $C_2F_4H_2$/i-C_4H_{10}(96%/4%);
4: $C_2F_4H_2$/i-C_4H_{10}(94%/6%);
5: $C_2F_4H_2$/i-C_4H_{10}(92%/8%);
6: $C_2F_4H_2$/i-C_4H_{10}(90%/10%);
7: $C_2F_4H_2$/i-C_4H_{10}/SF_6(90%/5%/5%);
8: $C_2F_4H_2$/i-C_4H_{10}/SF_6(85%/10%/5%);
9: $C_2F_4H_2$/i-C_4H_{10}/SF_6(97.5%/2.5%/0.5%).

4 Discussion and conclusion

4.1 Electron multiplication mode in MRPC

Indeed larger signals can be obtained in MRPC when working in streamer mode, which can loosen the requirements for front-end electronics system, but at the same time larger signals will reduce the counting rate limit in MRPC, because a larger signal often leads to longer dead time in gas detectors. Therefore MRPC usually works in avalanche mode. For MRPC, there are three candidate gases: $C_2F_4H_2$, i-C_4H_{10} and SF_6 with different proportions and it has been proved that SF_6 has a function on suppressing streamer. However SF_6 has been abandoned by RHIC-STAR for its heavy green house effect. According to some data-base on materials, i-C_4H_{10} also has the function of suppressing streamer. Fig. 6[10] shows the mass attenuation coefficient curve of i-C_4H_{10} for photons ranging from 0.001 to 0.1keV. It is clear that i-C_4H_{10} has an absorption peak when the energy of a photon is near 20eV, so for MRPC, by increasing the ratio of i-C_4H_{10} in working gas can suppress streamer, too. However because of its flammability, the proportion of i-C_4H_{10} should not exceed 10% in working gas.

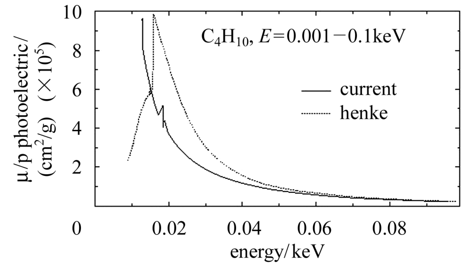

Fig. 6. The mass attenuation coefficient of i-C_4H_{10} for photons ranging from 0.001 to 0.1keV.

4.2 Mechanism of electron attachment in MRPC

According to the simulated results of attachment coefficient for $C_2F_4H_2$, i-C_4H_{10} and SF_6, in strong electric field, the attachment coefficient of $C_2F_4H_2$ and i-C_4H_{10} is so little that we can ignore the attachment effect. But actually as shown in Fig. 2(b), for gas mixture of $C_2F_4H_2$ and i-C_4H_{10}, the effective Townsend coefficient is higher with a larger ratio of i-C_4H_{10}, which implies that $C_2F_4H_2$ is a kind of electronegative gas. Perhaps this electron attachment of $C_2F_4H_2$ stems from hydrofluoric acid (HF) produced by dissociation of $C_2F_4H_2$ in the course of avalanche which has been found in some experiments[11] and Fig. 7 illustrates the F^- ions gathered vs. time for two different i-C_4H_{10} concentrations: 5% and 30%, which indicates that the $C_2F_4H_2$ dissociation exists in the course of avalanche in MRPC, so for MRPC, in order to get a lower "knee" voltage in efficiency plateau curve, it is better to reduce the ratio of $C_2F_4H_2$. However the reduction of $C_2F_4H_2$ is limited by the strength of electric field, because we have to supply

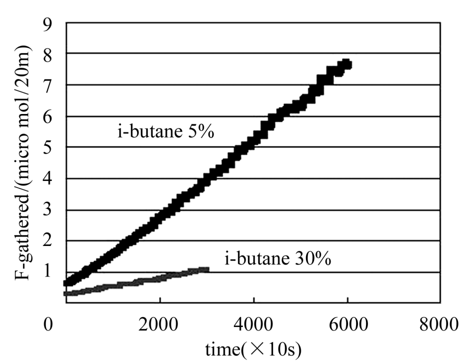

Fig. 7. F^- ions gathered vs. time for two different i-C_4H_{10} concentrations: 5% and 30%. The operating current was kept constant at about 15μA in both cases.

a high voltage on MRPC electrodes to get a strong field for fast electron drift velocity, and the high proportion of $C_2F_4H_2$ can also play an important role in reducing the discharge probability for MRPC.

4.3 Conclusion

The most important performance of MRPC is its time resolution. According to Eq. (5) in Section 3, the time resolution of MRPC has an inverse proportion relationship with the product of the electron drift velocity and the effective Townsend coefficient. As shown in Fig. 5, we may expect a better time resolution in MRPC with a higher ratio of i-C_4H_{10} in $C_2F_4H_2$/i-C_4H_{10} gas mixture, and the time resolution is almost near the "bottom" of the time resolution curve when the proportion of i-C_4H_{10}i-C_4H_{10} is close to 10%.

According to the simulated parameters of working gas by Magboltz, the estimated performances with different gas mixtures and the discussion on the main performances of MRPC as mentioned above, if we consider the main performances of MRPC synthetically, the gas mixture of $C_2F_4H_2$/ i-C_4H_{10} with the proportion near 90/10 will be an appropriate working gas for MRPC.

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多隙阻性板室(MRPC)的性能和工作气体关系的模拟研究

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摘要　多气隙阻性板室(MRPC)以其优良的时间分辨率在粒子物理实验中被用作飞行时间(TOF)探测器. 国际合作项目RHIC-STAR采用MRPC作TOF. 我们已成功地制作出30多个MRPC, 并安装在RHIC-STAR上. 通过模拟计算软件Magboltz, 计算了MRPC常用工作气体的物理参数, 并根据气体探测器物理机制, 重点分析了MRPC性能与其工作气体之间的相互关系, 此分析对优化RPC与MRPC混合气体组分是有益的.

关键词　多气隙阻性板室　工作气体　气体参数　性能

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