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Combination of Course Teaching and Scientific Research for Plasma Physics Experiment in University Higher Education

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Abstract: As an important branch of physics, plasma physics research has attracted attention worldwide, and major universities around the world offer related courses. Plasma physics experimental courses provide students with an intuitive understanding of the subject. During such courses, students understand and master basic plasma physics knowledge and intuitively understand the research progress and application status of plasma physics in important fields, such as flow control, material processing, and medical hygiene. Students can also participate in relevant experiments to cultivate their hands-on abilities and improve their understanding of plasma physics. Furthermore, the integration of different disciplinary backgrounds and multiple types of experiment can enhance the innovation and teamwork abilities of students. Students are exposed to the latest scientific developments about plasma, which is beneficial for cultivating scientific research interests. The overall course design includes theoretical learning, experimental design, data processing, scientific thinking cultivation, experimental report writing and academic conference presentation. In this article, a plasma physics experimental course offered at the Harbin Institute of Technology that combines experimental course teaching and scientific research is described and analyzed. The specific course process and corresponding course experimental design are detailed description, and the detailed course evaluation results is also analyzed. The results are expected to provide theoretical guidance and valuable suggestions for future teaching.

Keywords: Plasma Physics Experiment, Course Teaching, Scientific Research

1. Introduction

Almost all observable matter in the Universe is in the plasma state. Plasmas comprise freely moving ions and free electrons. They are often referred to as the “fourth state of matter” because their unique physical properties distinguish them from solids, liquids, and gases.

Plasma exists in various forms and can be created in several ways. More than 99% of the visible universe is considered to be in a plasma state. Plasma can be classified in different ways based on the thermodynamic equilibrium, ionization degree, density, etc. Based on the thermal equilibrium between electrons and heavy particles, plasma can be categorized into thermal or high-temperature plasma and nonthermal or cold plasma. The distinction between thermal and nonthermal plasmas is important. In thermal plasma, the electrons and heavy particles (neutrals and ions) reach a local thermodynamic equilibrium state, i.e., the energy transfer from electrons to heavy particles equilibrates the energy transfer from heavy particles to the environment, and all species in the environment remain at almost the same temperature. Therefore, this type of plasma is also called “equilibrium plasma.” Thermal plasma can reach temperatures up to 10^8 K, as in the solar core. However, in nonthermal plasma, the cooling of heavier particles is more efficient than the energy transfer to them from electrons, and the gas temperature remains low [1, 2]. Therefore, nonthermal plasma is also called “nonequilibrium plasma” or “cold plasma."

Atmospheric-pressure plasma is plasma in which the pressure approximately matches that of the surrounding atmosphere — the so-called "normal pressure." Atmospheric-pressure plasmas have prominent technical significance because, unlike low-pressure or high-pressure plasmas, no reaction vessel is needed to maintain a pressure level that differs from atmospheric pressure. Accordingly, depending on the generation principle, these plasmas can be employed directly in the production line. The need for cost-intensive chambers to produce a partial vacuum, as in low-pressure plasma technology, is eliminated. These plasmas play an important role in many current and emerging fields, including plasma medicine, agriculture, plasma processing of materials and surfaces, catalysis, and aerospace engineering [3].

As a basic subject, plasma physics is of great significance to physics learners. The main significance of a plasma physics experimental course is reflected in the following aspects. Academic vision is broadened because, by studying plasma physics, students can expand their academic vision and understand the basic composition and macroscopic effects of plasma. In addition, students must master theoretical knowledge, develop scientific thinking, and learn experimental techniques [4-7]. The study of plasma physics can also improve scientific research and help solve problems. Plasma physics experimental courses can help students understand and master relevant experimental techniques and methods and provide support for their future scientific and technological work.

2. Plasma Physics Experimental Course Teaching

2.1. Teaching Objectives of the Plasma Physics Experimental Course

The teaching objectives of the plasma physics experimental course are as follows.

1) Students should become familiar with the basic concepts and theories of plasma physics, including the composition, interactions, and properties of different types of particle (electrons and ions).
2) Students should understand and master plasma physics experimental methods and technologies, including experimental design, U–I signals, and plasma characteristic measurement.
3) Students should Cultivate scientific research and problem analysis abilities, such as scientific thinking and experimental-data analysis.
4) Students should improve their scientific research and academic abilities, including academic data retrieval, academic paper writing, academic discussions, and academic achievement presentation.

2.2. Design of Plasma Physics Experimental Course

The plasma physics experimental course includes different types of plasma mode, such as corona, dielectric barrier discharge (DBD), and arc discharge, and applications that combine different fields, such as flow control, material treatment, and plasma disinfecting technology. It also demonstrates the interactions between plasma and airflow, those between plasma and water, and other related scientific issues. The details of the plasma physics experimental course design are as follows.

A. Corona discharge and ionic wind for flow control

The corona discharge is a typical atmospheric discharge mode that can be applied in various fields. Corona discharge is an electrical discharge caused by the ionization of a fluid, such as air, surrounding a conductor carrying a high voltage. This represents a local region in which the air has undergone electrical breakdown and becomes conductive, allowing the charge to leak off the conductor into the air continuously. Corona discharge occurs at locations where the strength of the electric field (potential gradient) around a conductor exceeds the dielectric strength of the air.

Corona discharges have many applications. For flow control, the corona discharge causes ionic wind. Ionic wind is the airflow induced by electrostatic forces linked to the corona discharge arising at the tips of sharp conductors. Understanding and mastering the characteristics of ionic wind has learning and scientific research value for the application of corona discharge [8, 9].

A schematic diagram of the corona discharge/ionic wind and the corresponding experimental device is shown in Figure 1.

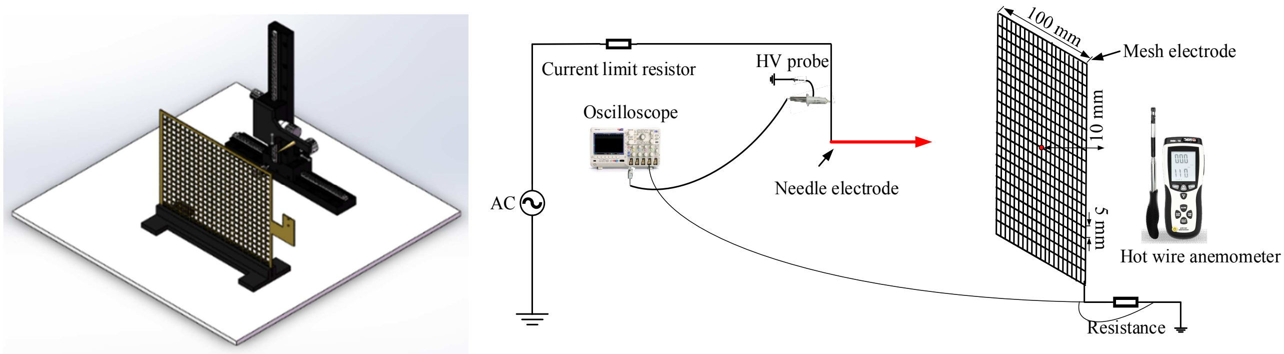


Figure 1. *Experimental setup of ionic wind thruster.*

B. Dielectric barrier discharge, uniformity and material handling

DBD is characterized by inserting one or more dielectrics between the high-voltage and the ground electrodes, and there are two common DBD reactor configurations: panel and cylinder. Because DC cannot pass through an insulating dielectric, the power applied to the DBD should be AC or pulsed high-voltage power. The gas discharge characteristics between the two electrodes change because a dielectric is present. An intact dielectric can limit the amount of charge accumulated and prevent the formation of sparks or arcs in the discharge gap. The material commonly used as a dielectric barrier is glass or silica glass, and, in some special cases, ceramics or polymer layers are also used. It has been more than 150 years since the invention of the DBD by Siemens in 1857. The first DBD device focused on ozone generation and was the earliest environmental application of a nonthermal plasma. It has many applications, such as ozone production, air pollution control, material treatment, and airflow control [10-13].

The experimental setup for DBD in the plasma physics experimental course is shown in Figure 2.

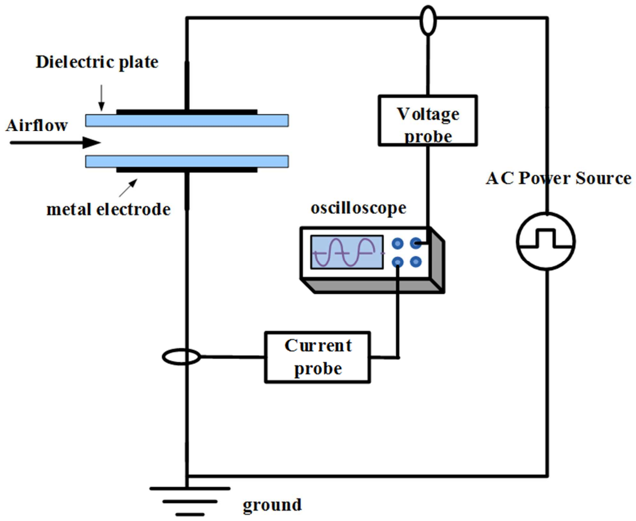


Figure 2. *Experimental setup of dielectric barrier discharge under airflow.*

C. AC arc discharge and generation of plasma-activated water

An electric arc (or arc discharge) is the electrical breakdown of a gas, which produces a prolonged electrical discharge. Current through a normally nonconductive medium, such as air, produces plasma, which may produce visible light. An arc discharge is initiated by either thermionic emission or field emission. After initiation, the arc relies on the thermionic emission of electrons from the electrodes supporting the arc. In the late 19th century, electric arc lighting was widely used for public lighting. Electric arcs can also be utilized for manufacturing processes, such as electric arc welding and electric arc furnaces for steel recycling.

Arc discharge can also be used to generate plasma-activated water (PAW). PAW is a chemically active aqueous medium characterized by the presence of reactive oxygen and nitrogen species created by plasma exposure. This particular chemical composition is the starting point of extensive research in several domains, such as bio-disinfectants in biomedical applications and fertilizers in agricultural applications. These applications require adjustments to the PAW properties and, consequently, require better control of the PAW chemical composition [14, 15].

In the plasma physics experimental course, an arc discharge was applied to generate PAW. The experimental setup is shown in Figure 3.

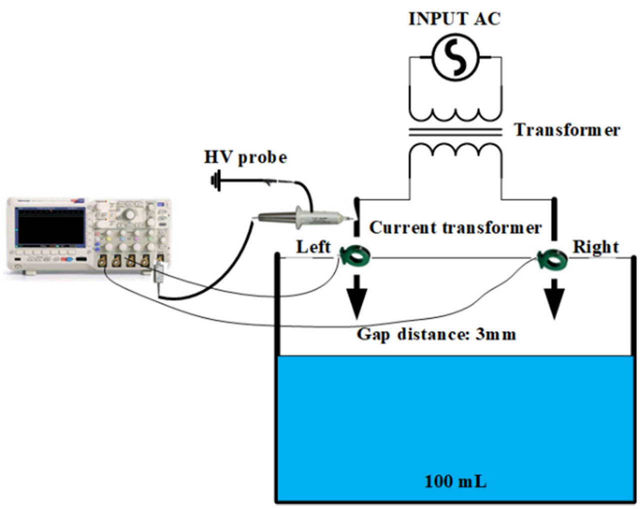


Figure 3. *Experimental setup of plasma-activated water.*

3. Research in Plasma Physics Science

3.1. Ionic Wind: Performance of Corona Discharge

The U–I characteristics and the distribution of ionic wind were measured to demonstrate the performance of ionic wind caused by corona discharge. Different experimental processes were designed to evaluate the performance of ionic wind thrusters in detail. The following experiments were conducted.

A. Characteristics of ionic wind under different input voltage

The ionic wind characteristics under different input voltages are studied to evaluate the ionic wind performance. The experimental procedure are as follows.

The discharge gap is fixed at 10 mm. Three input voltage are chosen as −5, −7, and −9 kV. A typical Trichle current pulse is measured to determine the characteristics of corona discharge. In addition, the ionic wind distributions under different input voltages are measured using a hot-wire meter. The distance between adjacent test points is 5 mm. The corresponding U–I signals and ionic wind distributions are shown in Figure 4.

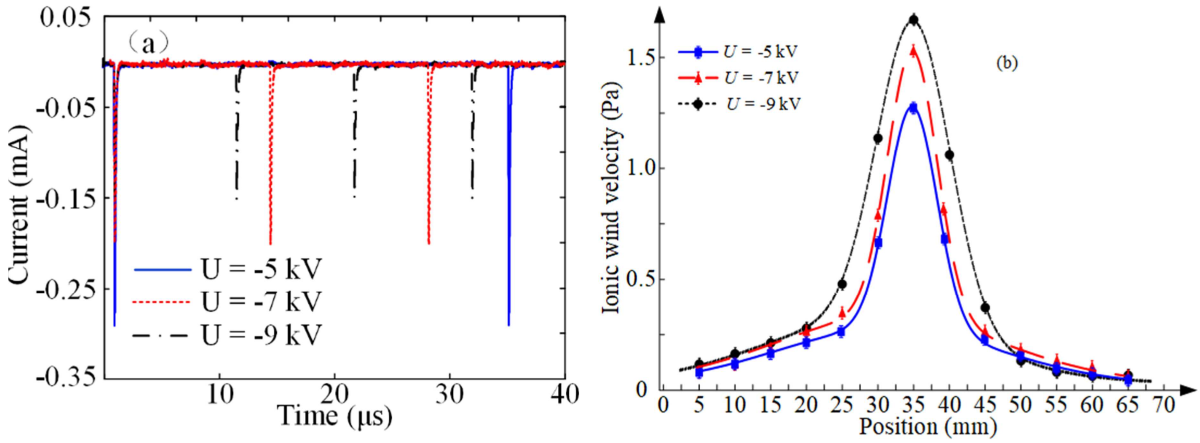


Figure 4. *Characteristics of ionic wind: (a) discharge current and (b) ionic wind distribution.*

B. Characteristics of multielectrode ionic wind thruster

The influence of the electrode distribution on the performance of the ionic wind thruster is also studied. Two electrodes are placed in parallel. The distance between the electrodes is modified accordingly. The ionic wind distribution is measured to illustrate the influence of the electrode distance.

3.2. Uniform DBD Characteristics: Interaction Between Plasma and Airflow

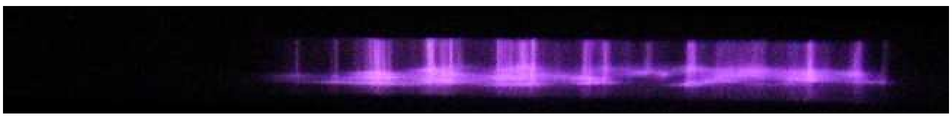
Uniform DBD has many applications, such as material treatment and flow control. To generate a uniform DBD, airflow was applied during the experiment. Different experimental processes were designed to analyze the DBD characteristics. The following experiments were conducted.

A. Discharge mode conversion phenomenon of DBD under airflow

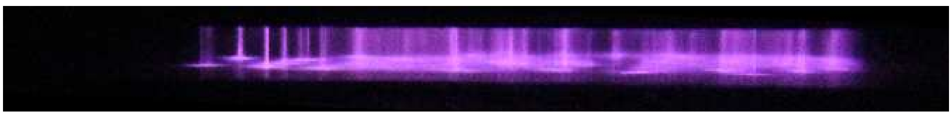
For the experiment, the input frequency is fixed at 40 kHz, and the input voltage is approximately 15 kV. The discharge image is captured with a digital camera with exposure times of 200, 500, and 1 ms. When the discharge is in static air, the discharge is in filament mode. With increasing input airflow rate, the discharge mode is transferred from the filament to the diffuse mode. The discharge is converted into a uniform bulk discharge mode. Moreover, the corresponding U–I signals can be modified from a large current pulse to a uniform current pulse by increasing the input airflow.

B. Data processing and programming

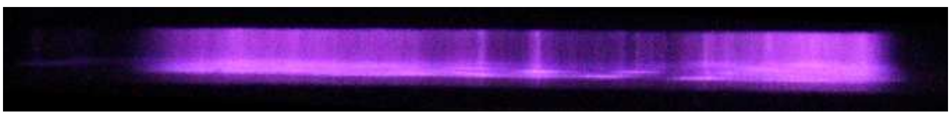
To understand the changes in the discharge characteristics better, the U–I signals and discharge images under different input airflow rates are processed. Using this software, the discharge images and U–I signals are transferred to the data mode and treated by a data-processing program, finally forming data with contrast for display. The corresponding characteristics of DBD under airflow are demonstrated in Figure 5 and Figure 6.



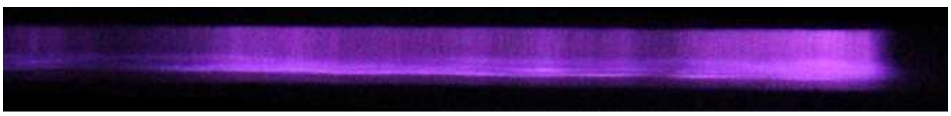
(a) 0 m/s



(b) 30 m/s



(c) 60 m/s



(d) 90 m/s

Figure 5. *Images of dielectric barrier discharge under different airflow rates.*

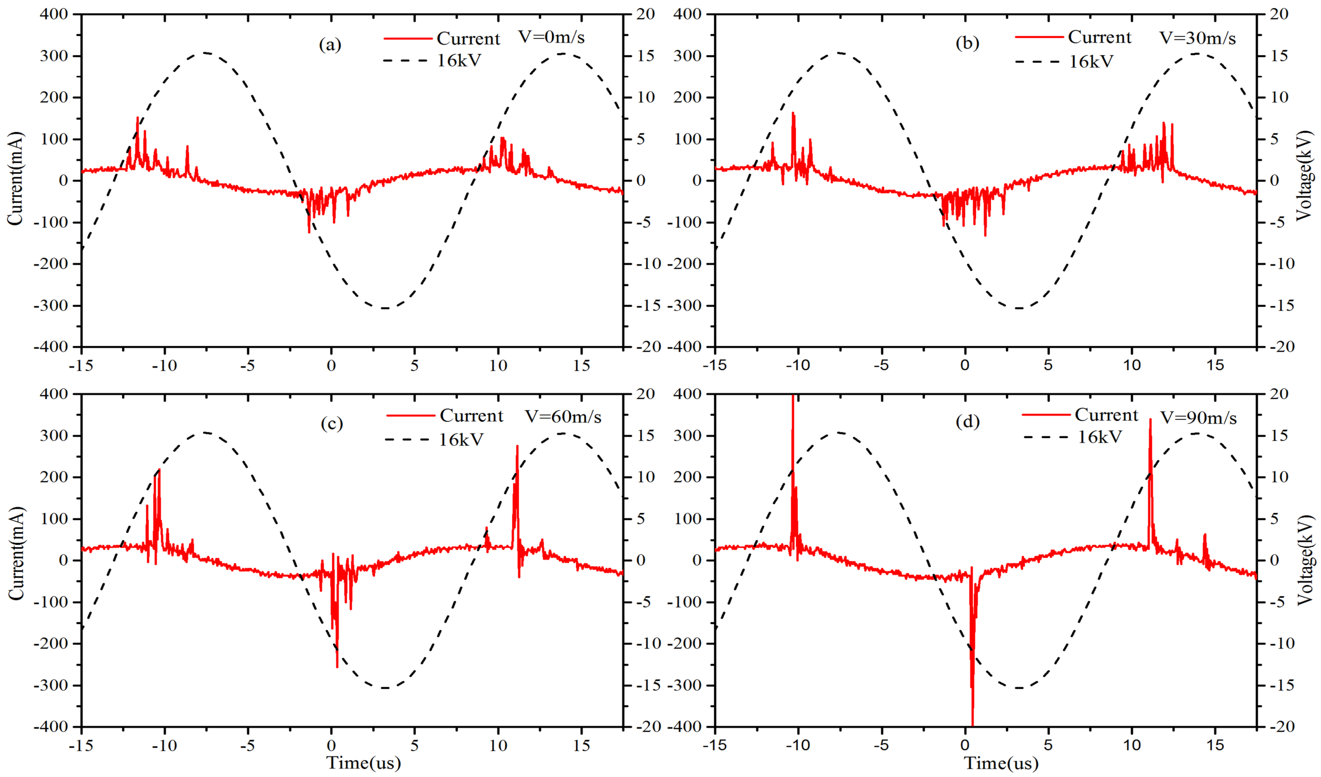


Figure 6. U–I characteristics of dielectric barrier discharge under different airflow rates.

3.3. Plasma-Activated Water: Interaction Between Plasma and Water

PAW is generated by the effect of plasma on water. To understand the interaction between them, the characteristics of PAW were studied experimentally as follows.

A. Characteristics of plasma-activated water

To determine the performance of PAW, the characteristics of PAW, such as pH, conductivity, and concentration of NOx, are measured. The student acquires an overall understanding of the characteristics of PAW.

B. Effect of treatment time on the plasma-activated water

As an important parameter influencing the performance of PAW, the treatment time of plasma-treated water is studied. Surface AC arc discharge is applied to generate plasma-treated water, and the discharge mode conversion phenomenon is studied. The U–I signals and discharge images for different treatment times are studied experimentally. The characteristics of plasma activated water are shown in Figure 7 and Figure 8.

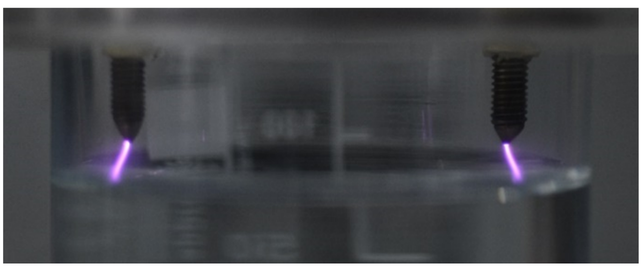


Figure 7. Discharge images of plasma-activated water.

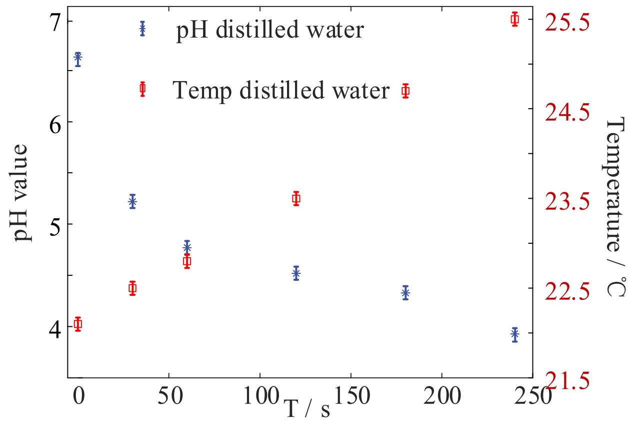


Figure 8. Characteristics of plasma-activated water.

4. Combination of Course Teaching and Scientific Research

4.1. Challenges and Solutions

The combination of the teaching of the plasma physics experimental course and scientific research is an important teaching model that can improve learning interest. However, there are some challenges in the teaching and scientific research processes. The corresponding challenges and solution methods are as follows.

A. Cross-disciplinary knowledge

The plasma physics experimental course includes plasma physics, electrical engineering, fluid mechanics, signal testing, and other related topics. This is a typical interdisciplinary characteristic. It also requires participating students to have multidisciplinary backgrounds and good learning abilities. At the same time, students are required to do a good job of previewing the course in advance to ensure the smooth progress of the experimental course.

B. Complexity of teaching

The different multidisciplinary backgrounds present a problem for teaching. Multimedia teaching methods are commonly used in teaching courses. By viewing experimental simulation animations and experimental procedures, students can master the inner mechanism of the experiment, and further explanations can guide them to discuss and discover difficulties in their understanding of the course. In an actual experimental process, the focus is on the difficulties in theoretical understanding and detailed analysis associated with the experimental process. Students can learn the internal mechanisms of plasma physics through practical experiments.

C. Safety of the experimental process

Plasma physics experiments involve high-voltage power supplies that can be dangerous if not handled properly. During the actual experiment, students are first given safety explanations and training, and operational demonstrations are conducted to master the experimental methods in detail. Safe low-voltage areas and dangerous high-voltage areas are designed, and warning signs, sounds, and lights are designed simultaneously. Alarms are installed to ensure operational safety. Furthermore, the class has a dedicated safety officer who is responsible for the overall experimental safety.

4.2. Teaching Improvement Methods

Plasma physics is a frontier field in modern physics, and it is important to cultivate student innovation and scientific literacy. To enable students to understand the relevant experimental processes better, the following improvements were made to the teaching methods.

A. Application of multimedia teaching and online learning platform

Recording experimental videos and experimental operation procedures and posting them on the course shared online platform enabled students to watch them repeatedly, helping them master the experimental equipment and procedures in detail.

B. Collaborative learning in groups with multidisciplinary backgrounds

Because of the multidisciplinary nature of plasma physics experiments and the complex subject backgrounds of course selectors, the design of learning/experimental groups includes students with backgrounds in different subjects who perform the experiments together. Through cross-collaboration involving multiple disciplines, the relevant theoretical and experimental knowledge is learned more effectively.

C. Encouraging laboratory visits, academic exchange, and participation in scientific research

Students are guided to participate in various seminars, forums, competitions, and other activities. By designing visiting classes and symposia, students are invited to experience specific plasma application scenarios, form an intuitive understanding of the application of plasma physics, and gain a deeper understanding of the intrinsic mechanisms of plasma physics experiments.

4.3. Examples and Efficiency

The teaching effects of the plasma physics experimental course are evaluated using a teaching evaluation system. Fifty students took the course. The major distribution of students who chose the course covers six professional directions. Twenty percent of the students are from Aerospace College, with majors in aircraft power design. Eleven students are majoring in energy and power. There are also eight students from electronic information majors: communication engineering and intelligent measurement and control, and the corresponding research directions. Furthermore, several students are majoring in physics and mechanical engineering.

Students also participate in academic conferences and competitions in China. For example, Ren et al. and Liang et al. won second prize in the 2022 and 2023 National College Student Plasma Technology Innovation Competition, respectively. Zhou et al. won the prize of the Second "Pioneer Cup" Future Technology Innovation Competition in 2022. Gong et al. won first prize for the Harbin Institute of Technology's 2022 annual project plan. In addition, students participate in various academic exchanges and seminars and give oral and poster presentations at conferences.

5. Conclusion

A plasma physics experimental course is essential for undergraduates. It is important to understand the experimental mechanism, experimental method, and improvement of the research status. In this article, the design of a plasma physics experimental course is described in detail. The experiments about ionic wind, dielectric barrier discharge and plasma activated water are designed to demonstrated the application of plasma on the fields of aerospace engineering, plasma processing of materials and surfaces, catalysis, plasma medicine and agriculture. The characteristics and corresponding mechanism are detailed studied. Furthermore, students further learned data processing, paper writing, report presentation and other related scientific research methods. Besides, the course teaching approach and scientific research are also discussed. The situation and research process of the plasma physics experimental course at the Harbin Institute of Technology are examined. Based on the current multidimensional course assessment system of the school, an overall evaluation of the course is provided.

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