Enhanced Virtual Reality Plant: Development and Application in Chemical Engineering Education

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Abstract—Over the past few decades, chemical education has undergone profound changes in teaching modes and styles with the emergence of novel media technologies. As a promising technology, virtual reality plants (VRPs) have attracted increasing attention in education. This study presents the development and application of a VRP for chemical engineering education. The VRP has two main subsystems: a virtual scene and a process control system. The virtual scene provides students with a virtual environment, allowing them to roam freely and observe various pieces of chemical equipment from multiple perspectives. In addition, the students can simulate various operation procedures in the VRP process control system and thus gain practical experience. The effectiveness of the VRP on chemical practice education was evaluated and investigated through surveys of students and teachers. All the results showed that the VRP played a positive role in improving students' practical abilities.

Keywords—virtual reality plant, practical training, teaching methodology, chemical engineering education

1 Introduction

It is an extremely important task to cultivate the practical ability of students majoring in chemical engineering (CEE). However, most local colleges do not pay enough attention to training students' practical skills in China due to the limitation of experimental sites, funds, safety, etc. Therefore, a safe and cost-effective training fashion should be developed to offset the shortage of conventional training approaches. Over the past decades, virtual reality (VR) technology has been successfully used in many fields including education, healthcare, entertainment, etc [1-4]. The technology can render individuals a realistic, interactive, and immersible virtual environment, where the users can gain multisensory stimulation and feelings [5-9]. Extensive studies reveal that the use of VR technology in engineering education may enhance interest in learning [10,11]. Therefore, introducing VR technology into chemical engineering education may be one of the effective ways to solve the above dilemma.

At an early stage, VR in chemical engineering education was primarily used for a single chemical experiment or unit operation [12–14]. Recently, there is a growing interest in pursuing realistic visual experiences based on three-dimensional (3D) visual effects [15–17]. In practice, trainees prefer to experience "real operations and feedback" when using a VR platform. Therefore, it is imperative to develop an enhanced platform, which can provide a 3D immersive environment and interactive learning approaches. Additionally, as an excellent simulation system for chemical training, it should not be limited to an isolated chemical unit operation but should be capable of simulating the entire chemical process. Very recently, virtual reality plants (VRPs) have attracted increasing interest. VRPs can be used to simulate the whole process of a chemical plant. It includes various common unit operations that may be used in the real chemical industry. The simulations must follow basic chemical principles, such as satisfying the heat-, material-, and momentum-balance equations. To fulfill the above simulation requirements, it is necessary to integrate components such as VR, automatic control, artificial intelligence, and graphical representation technology. Therefore, it is still a challenge to develop VRP systems. To our knowledge, limited software is available that can simulate the whole chemical process. Furthermore, detailed investigations of the chemical education impact of this type of software are rare in the literature.

In this study, a VRP was designed and constructed based on the dimethyl ether (DME) production process, and the system was presented to aid students in improving their skills. Moreover, the role of the VRP in chemical practice education was analyzed based on surveys completed by senior students and teachers from ChaoHu University.

2 Devise of VRP system

2.1 Composition of VRP system

A modular design was adopted to simplify the development of the VRP system. The VRP system consisted of two subsystems: the DME process control and the VR scene system. The DME process control system was a platform that could provide trainees with real-time simulation responses by adjusting the DME process conditions. The VR scene system was a virtual environment composed of three-dimensional models of common equipment in a chemical plant. Figure 1 shows the overall block diagram of the VRP.

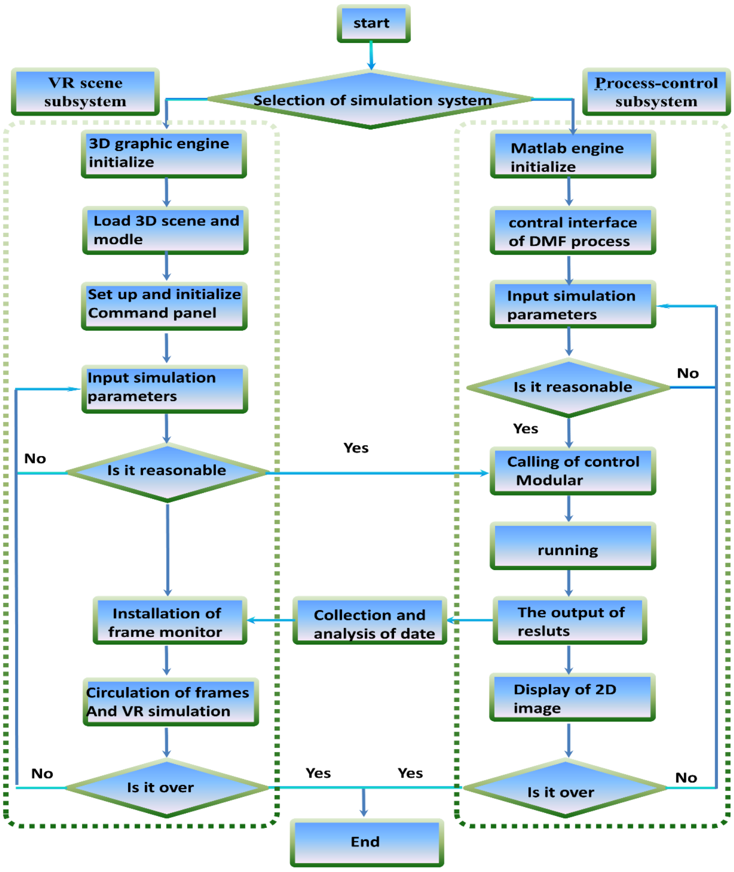

Fig. 1. The VRP system architecture diagram

To implement the control of the DMF production process, many programs were used in the DME process control subsystem. These programs were written in the MATLAB language and then encapsulated into the control modules. The control modules were invoked as follows: a model object was first triggered, and then a MATLAB engine began to drive these compiled programs. Next, the VRP created a command panel to receive the control parameters entered by the users to emulate the DME production process. Finally, the simulation results were fed back to the students in the form of pictures, tables, and virtual animations.

To realize the virtual scene, a 3D graphics engine was driven to generate VR graphics and animations. Additionally, the programs in the control subsystem could also be called in the virtual scene subsystem. The detailed invocation process was as follows. First, the reasonability of instruction was evaluated in the virtual scene subsystem. The control instructions were transmitted to the corresponding control modules in the DME process control subsystem. After calculation, the results were re-feed-backed to a frame detector, in which data is converted into virtual reality animations in the VR scene subsystem.

2.2 Hardware architecture of VRP

Figure 2 shows the hardware architecture of the VRP, which was mainly com-posed of a stereo projection system, numerous control terminals, and several servers. To improve the VRP immersion sense, a three-dimensional projection display system was employed with three-channel cylinders. These control terminals were equipped with man-computer interaction windows, through which trainees could input the instructions and operating parameters to control the DME production process. There were three types of servers: a computing server, a database server, and a graphics workstation server. The computing server was composed of several blades servers (HP ProLiant BL460c Gen9), which were used to calculate and monitor the DME production process in the VPR. The graphics workstation server was mainly used to generate and render 3D graphics in real-time. The large quantities of static and dynamic data were all stored in the database server, which was managed by an oracle relational and PHD real-time database management system.

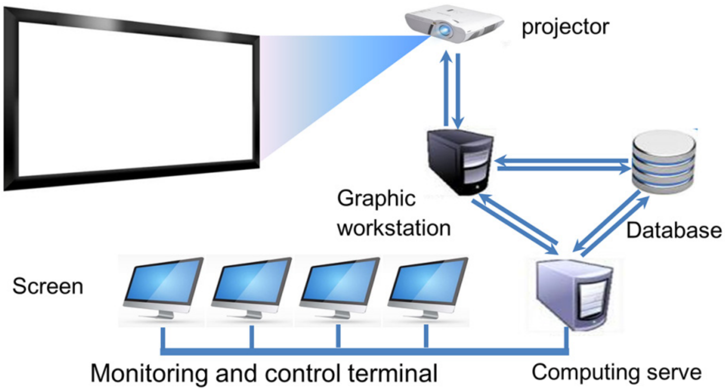

Fig. 2. The VRP's hardware composition diagram

2.3 Logical level s and data channel of VRP

Figure 3 shows the four VRP logical levels: a user interface layer, an application support layer, a core layer, and an information-storage layer.

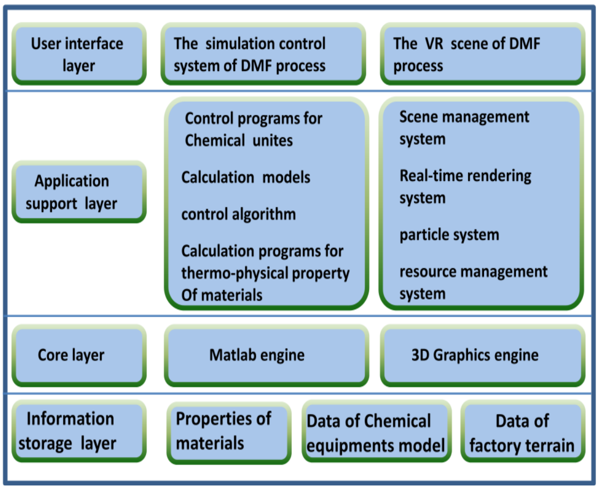

Fig. 3. Diagram of the VRP logic layer

The top layer of the VRP was a user interface layer (UIL), which was used to call the process control and VR scene of the DME system. Under the UIL, there was a corresponding process control application layer and a virtual scene application layer. The process control modules were used to implement the simulations of the DME production process, which included control programs, algorithms, calculation models, and thermo-physical properties of the materials. In addition, the VR scene modules were composed of a scene management system, a real-time rendering system, and a particle and resource module management system. All the above application modules were based on the core layer, which consisted of a MATLAB engine and a 3D graphics engine. In the VRP core layer, the 3D graphics engine was developed by Vega Prime (VP) based on the framework of Vega Scene Graph (VSG). Moreover, the MATLAB engine was a set of functions to realize the simulation of the DME production process in the VR environment. The bottom layer of the VRP was an information storage layer that contained various components, including the physical parameters of the materials, chemical equipment models, and terrain data.

A data stream is an information path formed in the transmission process of output and reception of data. Figure 4 shows the data flow of VRP. When the VRP system is running, it will generate massive data. As one of the sources and destinations of data, a database plays a significant role in data transmission and storage.

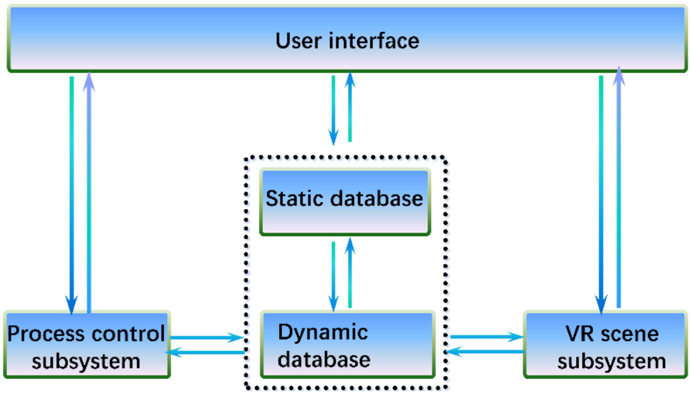

Fig. 4. Diagram of the VRP data flow

The database of the VRP system consisted of a static and a dynamic database, which were used to store static and dynamic data, respectively. Information could be delivered between the static and dynamic databases. Additionally, the users could directly retrieve information from the database, process control subsystem, and virtual scene subsystem through a user interface.

3 Virtual scene roaming and process control simulation

Figure 5(a) shows a panoramic overview of the VRP, which consisted of vaporization towers, condensation reactors, tanks, heat exchangers, and distillation columns for separation and purification in the DME production process. Figures 5(b) and 5(c) show partial views of the tanks and heat exchangers. The three-dimensional models of the chemical equipment were all constructed with the 3Dmax software based on real prototypes. Users could log into the VRP scene subsystem with their own avatars for a "roaming" exercise, in which they were allowed to walk freely and observe various kinds of equipment from multiple perspectives. The roaming exercise was essential because it allowed students to gradually learn about and become familiar with the platform. Additionally, after the roaming exercise, the students could be recommended to undertake simulation tasks for the process control of the VRP.

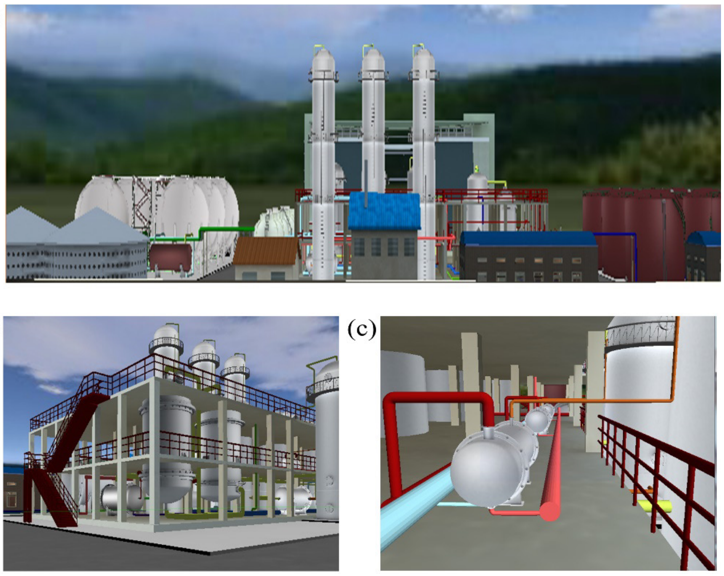

Fig. 5. Virtual reality scenes of the DME production process

In the VRP system, there were six simulation missions for the DME process control, which are listed and described in Table 1.

Table 1. Simulation tasks of the DME process control

Number	Training task	Depiction
1	Methanol tank operation	The trainee is required to operate the outlet valve of the methanol tank and regulate the discharge flow.
2	Methanol reactor operation	The trainee must learn to start and shout down the reactor.
3	Methanol preheater operation	The trainee is required to operate and adjust the parameters of the methanol preheater.
4	Methanol recovery tower operation	The trainee must learn to manipulate recovery tower
5	DMF tank operation	The trainee is required to operate the inlet valve of the DMF tank and regulate the inflow.
6	DMF distillation column operation	The trainee is required to regulate the condition of the distillation column.

To improve the emulation efficiency, both dynamic and static simulations were used in the process control of the DME. Dynamic simulations are chiefly adopted in chemical engineering units with frequent changes in the energy and material phases, while static simulations are mainly used in other chemical equipment units. For instance, a DME rectification tower is a crucial piece of equipment for DME production. In the DME rectification tower, there is a frequent conversion of gas and liquid phases with the change of energy. Therefore, the DME distillation was simulated by a dynamic simulation method based on material-balance, phase-equilibrium, mole-fraction-summation, and heat-balance (MESH equations) equations. Figure 6 shows the dynamic simulation process. The operation parameters were entered on a command disk. The bottom, top, and feeding temperatures of the tower, as well as the pressure, were set to 140 °C, 35 °C, 65 °C, and 0.9 MPa, respectively (Figure 6(a)). Figures 6(b)–(d) depict the changes in DME molar ratios, methanol concentration, and water concentration over time-based on the calculation of corresponding modules.

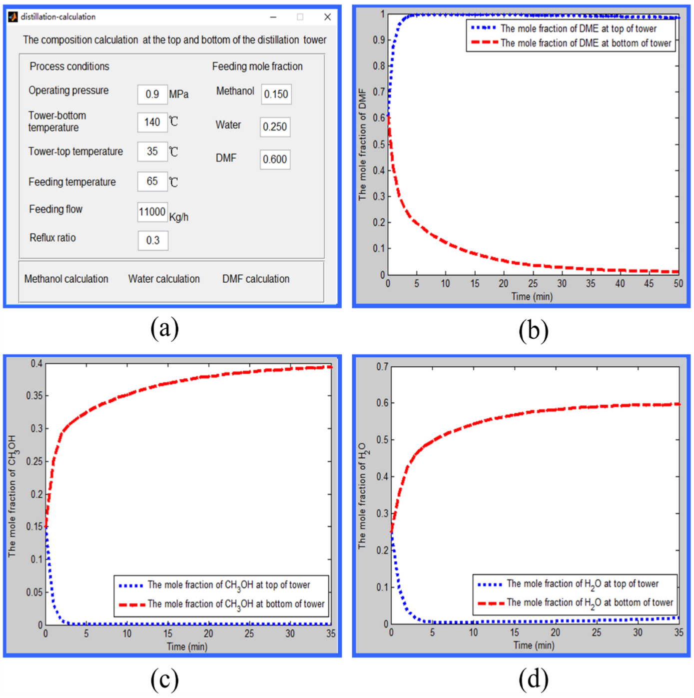

Fig. 6. Calculation of the DME distillation

The feedback results are displayed in tabular form in Table 2. The mole fractions of the reactants at the top and bottom were calculated separately. All the parameters were the same except for the reflux ratio.

Table 2. Molar fractions of the reactants with a different reflux ratio

Reflux ratio	Mole fraction of gas phase at top of the tower			Mole fraction of liquid phase at bottom of the tower		
	DMF	***Methanol***	***Water***	***DMF***	***Methanol***	***Water***
0.1	0.9793	0.0139	0.0078	0.0019	0.3977	0.6014
0.2	0.9863	0.0128	0.0009	0.0015	0.3972	0.6013
0.3	0.9878	0.0101	0.0021	0.0009	0.3984	0.6007
0.4	0.9902	0.0090	0.0008	0.0008	0.3985	0.6007
0.5	0.9922	0.0051	0.0027	0.0007	0.3986	0.6007
0.6	0.9932	0.0049	0.0029	0.0006	0.3987	0.6007

Taking DME rectification as an example, we further elaborate on how the process control simulation was called in the virtual scene system. When the users clicked anywhere on the virtual interface (Figure 7(a)), a process control panel appeared (Figure 7(b)). The command panel consisted of various control modules for the chemical unit operations in the DME production. The users could select the button labeled "DME distillation" and click on it to enter the simulation system for DME refining. In the DME distillation, the sensitive plate temperature (SPT) indirectly reflects the separation efficiency of DME. To obtain a high-purity target product, the SPT should be controlled within a suitable range (about 84 °C). Figure 7(c) shows the interference factors of the SPT, i.e., fluctuations in the feeding volume, temperature, and pressure in the distillation tower. For instance, when the feed volume suddenly increased by 0.3 tons per hour at the 1000th second, the SPT then deviated from the normal temperature of 84°C (a significant drop in the SPT). The VRP could provide the students with three types of controllers—classical proportional–integral–derivative (PID), fuzzy PID, and Smith compensation controllers—to tune the distillation SPT. Figure 7(d) shows control parameters input for the classical PID controller (proportional regulation coefficient: Kp = 1, integral regulation coefficient: Ki = 0.4, and differential regulation coefficient: Kd = 0.3). After 500 s, the SPT was modulated to a constant temperature of about 84°C. The trainees could try to input different parameters into the VRP system to obtain the desired results, thereby gradually accumulating regulation experience for DME production.

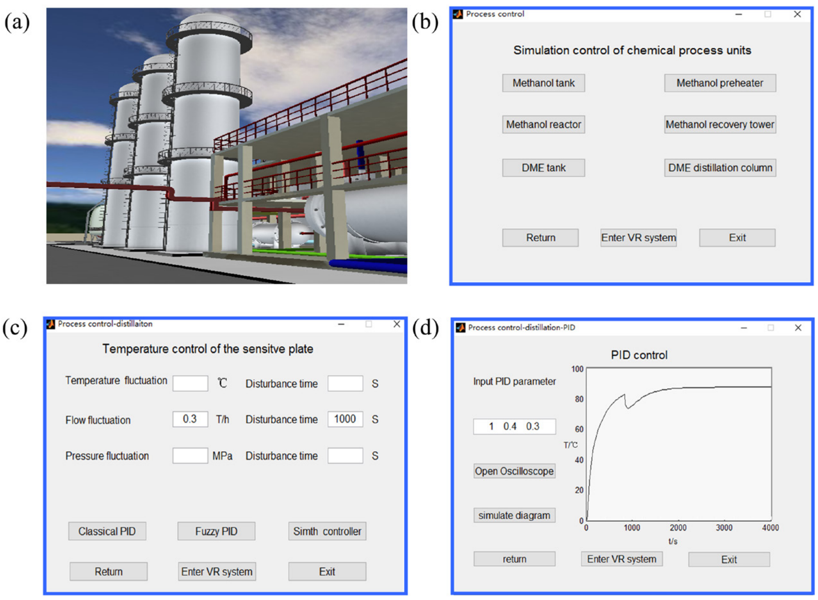

Fig. 7. Calling of DME rectification process control

4 Implementation and evaluation of VRP system in chemical practice course

The VRP system was used in a professional practice course in the last semester of the third year of a bachelor's degree specializing in chemical engineering and technology at ChaoHu University. This was a six-credit, compulsory course that consisted of two parts: a theoretical part (24 h) and an experienced part (60 h). The experimental part included computer simulations (24 h) and hands-on experience in factories (36 h). The VRP first became operational in the 2018–2019 academic year. The VRP mainly involved the following operations: fluid transport, solution stirring, liquid distillation, liquid extraction, gas separation, and heat transfer. Our VR platform could accommodate about 36–40 students simultaneously in a process simulation.

It is also important to explore the role of the VRP in chemical engineering education, which is conducive to the improvement of the VRP and the cultivation of the practical abilities of students. A survey was conducted with 120 senior students at Chao Hu University in the 2019–2020 academic year, and 114 questionnaires were collected.

Figure 8 shows the frequency distribution of the VRP utilization, in which 10.5%, 73.7%, and 11.4% of the students used the system 4–7, 8–12, and over 12 times per month, while only 4.4% of the students utilized the system less than 3 times per month. This indicated that the VRP was highly popular, and most students used it for self-regulated learning.

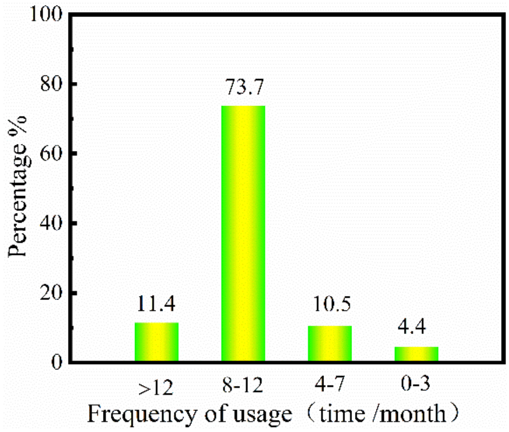

Fig. 8. Frequency distribution of the VRP utilization

To improve the VRP quality, it is necessary to further search for the deficiencies that may affect its usage. Hence, a survey was conducted on 114 students who had utilized the VRP system. A questionnaire was designed for the survey, which consisted of six questions classified into three categories: realism (Q1 and Q2), interactivity (Q3 and Q4), and immersion (Q5 and Q6) (Table 3).

Table 3. The VRP performance questionnaire

Question	Disagree n (%)	Agree n (%)
Q1. Is it realistic and visual?	9 (7.9)	105 (92.1)
Q2. Can it afford feedback fitted objective law?	6 (5.3)	108 (94.7)
Q3. Do you quickly find what you want to learn?	3 (2.6)	111 (97.2)
Q4. Can it help you to control learning progress?	5 (4.4)	109 (95.6)
Q5. Are you totally immersed in the virtual scene of the VR system?	19 (16.7)	95 (83.3)
Q6. Are you completely engrossed in training tasks, when using the VR system?	22 (19.3)	92 (80.7)

[n: people number (percentage, %)]

Based on the results from Q1 to Q4, most students gave highly positive feedback on the authenticity and interactivity of the VRP system, and the satisfaction ratings were 92.1%, 94.7%, 97.2%, and 95.6%, respectively. This may have been because of the high interactivity of the VRP system, namely, the friendly human–computer interface, interactive 3D scene, and intelligent interactional response. Nevertheless, the positive responses to questions 5 and 6 were not as high, with percentages of 83.3% and 80.7%, respectively. Hence, there is still room for improvement in the immersion of the VR system.

To evaluate the impact of the VRP on chemical practice education, a test on the DME production process was taken by the trainees before and after the VRP training. In total, 18 questions were designed based on three aspects: chemical production theory, chemical equipment, and DME operating procedures (Table 4). In chemical production theory, seven questions were proposed about the basic principles of chemical production. In chemical equipment, seven questions were designed to investigate the understanding of the types and functions of common chemical equipment. Finally, four questions were used to examine students' operation abilities of the chemical machinery and facilities in the DME plant.

Table 4. The test for the evaluation of the VRP on chemical education

Question	Section	Question description
1	chemical production theory	What are the flow types of fluid in a pipeline and how do define them?
2		How is evaluated the mixing effect of stirring?
3		What is heat the transfer coefficient?
4		What is the Henry's Law?
5		What is the Fourier law of heat transfer?
6		How is evaluated the separation efficiency of a distillation column?
7		What is the concept of the theoretical board in a distillation tower?
8	chemical equipment	Elaborate the effect of the sensitive board in a distillation tower.
9		Elaborate the effect of reflux tower in a distillation tower.
10		Describe the type and shape of the heat exchangers in a DMF plant.
11		Describe the type and shape of the pumps in a DMF plant.
12		Describe the type and shape of the condensers in a DMF plant.

13		Describe the type and shape of trays in a distillation column.
14		Describe the type and shape of the flowmeters of the pipelines in a distillation column.
15	Operation procedure	How is the pump started in a DMF plant? What will you do when the “air-binding” phenomenon occurs?
16		How is adjusted the temperature of the distillation tower?
17		How is the reactor started in a DMF plant?
18		If there is a leakage in the distillation tower? How do you deal with it?

The students were asked to independently complete the open-ended problems. Each question in the test was graded with a score of 0 points for no answer, 20 points for an incorrect answer, 40 points for a partially adequate answer, 60 points for a correct answer, 80 points for a good answer, and 100 points for an excellent answer. The feedback on each question was evaluated by the scoring criteria. Additionally, the total average score based on the mean of every answer was also calculated. The test was conducted before and after the VRP training, and all the results are shown in Figure 9.

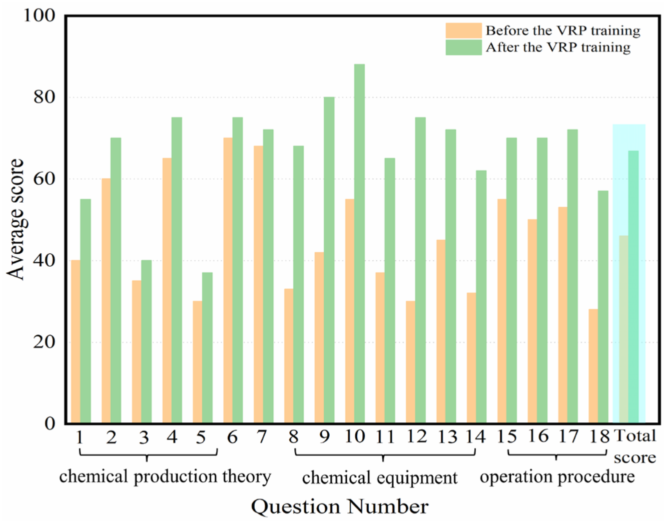

Fig. 9. Test results before (natural yellow) and after (green) the VRP training

After the students underwent the VRP training, there was a significant improvement in the quality of the answers. The average grade was 46 points before the VRP training, while it reached 66.8 points after the VRP training. The scores for almost every question increased to some extent after the VRP training. In particular, the student’s knowledge of the chemical equipment and operating procedures increased more than that of chemical production theory. This was because it was very difficult to give the participants a clear understanding of the physical structure, arrangement, and operating procedures of the chemical equipment in a chemical plant with the traditional teaching model. It is difficult for undergraduates on campus to have an opportunity to improve their chemical practice skills. Moreover, it is not practical for students to have long-term internships at a chemical plant due to various factors, such as cost and safety. To some extent, the use of VRP in chemical practice education can make up for such shortcomings [18]. In particular, the trainees using VRP can break through the limitations of the traditional physical boundaries of equipment and operations. For instance, in the VRP system, students can enter into or fly above the chemical equipment to observe its structure and shape, which is impossible in a real situation. Additionally, students can conduct multiple training sessions on the virtual platform without being limited by space and time, which is also impossible with a traditional internship in plants. These factors may help students to improve their knowledge and skills related to chemical equipment and production procedures [19].

The level of chemical production theory understanding of students was also somewhat improved after the VRP training. This may be related to the increase in fundamental knowledge of students during the VRP exercise. For instance, setting the parameters of a controller (such as a PID, fuzzy PID, or Smith compensation controller) is an important exercise in the VRP. Only when students have a certain understanding of the chemical process and control theory can such tasks be completed.

Another survey, in which eight teachers participated, was conducted to further assess the role of the VRP in chemical education. Table 5 shows the questionnaire, which consisted of six questions. Questions 1 and 2 were used to investigate the teachers' attitudes toward the changes in the students' learning interests and enthusiasm. Questions 3 and 4 were aimed at investigating teachers' views on the teaching effect of the usage of VRP in chemical teaching. The teachers' evaluation of students' practical skills was investigated through questions 5 and 6. According to the feedback results from questions 1 to 4, all the teachers felt positive about using the VRP to improve the learning interest and teaching effectiveness (the support rate was 100%). In addition, 87.5% of the teachers agreed that practice skills could be increased by the VRP exercise. The above results revealed that the VRP played a positive role in increasing the students' practice ability.

Table 5. The survey of the tutors' attitudes towards the VRP system

Question	Disagree n (%)	Agree n (%)
Q1. Is it useful to increase students learning enthusiasm?	0(0.0)	8(100.0)
Q2. Is it useful to increase the interest in learning?	0(0.0)	8(100.0)
Q3. Is it useful to improve the teaching effect?	0(0.0)	8(100.0)
Q4. Is it useful as a teaching aid means?	0(0.0)	8(100.0)
Q5. Is it useful to improve the ability to analyze problems?	1(12.5)	7(87.5)
Q6. Is it useful to improve the ability to solve problems?	1(12.5)	7(87.5)

[n: people number (percentage, %)]

5 Conclusions

In engineering practice education, on-site internships are often constrained by various factors, such as funding, site availability, and safety, especially for local colleges that lack resources. To address this deficit, we have designed and developed a virtual reality plant for chemical engineering practice education. This enhanced platform system integrates full-process control and virtual scene simulation, and it is intended to replace on-site training and assist students in improving their practical skills.

The role of the VRP in chemical practice education was investigated and discussed in detail through questionnaires completed by students and teachers at ChaoHu University. The quantitative analysis of teacher and student questionnaires indicated that the VRP system is an effective tool for practical teaching. After the VRP training, students' knowledge and skills significantly increased, especially those related to chemical equipment and operating procedures. Furthermore, 87.5% of the teachers believed that the VRP exercise could improve the practical skills of the students.

In the future, we plan to explore the mobile version of the VPR which can provide the functions of course announcements, communicating with other users, and downloading course notes through an interactive 3D environment. The mobile version of the VPR will not only ensure students have continuous access to the course but also help maintain their interest and keep them engaged and motivated in learning.

6 Acknowledgments

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