

Development and Application of Virtual Simulation Teaching Platform for the Transcritical CO₂ Two-Stage Compression Refrigeration System Based on LabVIEW

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Abstract. Based on the principle of transcritical CO₂ two-stage compression refrigeration system, a virtual simulation teaching platform was developed. Two operation modes can be selected which are practice mode and test mode. According to questions and tips about experiments, students can do simulation experiments by open required valves, running the refrigeration system, adjusting pressure control valves and so on. When these operations are completed, students can save the file of the simulation experiment and exit the system. Then, test marks of students can be exported to Excel for teachers to view. In addition, some risks of operational errors can also be avoided, such as equipment damage. Moreover, if there is a computer, the simulation experiments can be done by this virtual simulation teaching platform, which is very convenient. The virtual simulation teaching platform is innovative and practical. The application of this virtual simulation teaching platform can improve the quality of the traditional teaching in the refrigeration field.

Keywords. refrigeration, LabVIEW, virtual simulation teaching platform, CO₂, simulation experiment

1. Introduction

Nowadays, various refrigeration systems are utilized in cold chain. In order to meet the society trend of rapid development, improving the performance of refrigeration systems has become a research focus. There are many refrigerants used in refrigeration systems, such as R22, R134a, R404a, R290 and CO₂ [1-5]. Different refrigerants can make different cooling effects and different environmental impacts. Due to some artificial refrigerants used can make bad phenomena like greenhouse effect, more natural refrigerants put into use [6]. CO₂ is one of excellent natural refrigerants. GWP and ODP

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of CO₂ are 1 and 0, respectively [7,8]. Moreover, the thermomechanical property of CO₂ is also very good. Transcritical CO₂ two-stage compression refrigeration system is a kind of widely applied refrigeration system which can make higher energy efficiency [9]. In terms of students whose majors are refrigeration, learning the theory of this refrigeration system in detail is beneficial for the development of the refrigeration field in the future.

The application of virtual simulation teaching platform can avoid the large cost of actual experiments, so it is necessary to conduct teaching the theory of transcritical CO₂ two-stage compression refrigeration system by virtual simulation teaching platforms. Moreover, the Ministry of Education proposed that the deep integration of information technology and education laboratory teaching in universities should be taken seriously [10,11]. In order to support this view of the Ministry of Education, many universities actively combine virtual simulation teaching platforms with teaching laboratory courses [12]. LabVIEW is a kind of graphical programming language which can be used to establish virtual simulation experiments [13]. In the refrigeration field, this software is utilized for virtual simulation experiments of various refrigeration systems [14,15]. A virtual simulation teaching platform for the transcritical CO₂ two-stage compression refrigeration system based on LabVIEW was developed by Shanghai Ocean University. Students can intuitively learn the theories of transcritical CO₂ two-stage compression refrigeration system and do relevant simulation experiments by this virtual simulation teaching platform. This virtual simulation teaching platform provides a powerful aid to the education of students whose specialty is refrigeration.

2. Principle of Transcritical CO₂ Two-Stage Compression Refrigeration System

The system schematic diagram of transcritical CO₂ two-stage compression refrigeration system is shown in Figure 1 (a). There are eight main components in this refrigeration system which are compressor in the low-pressure stage, compressor in the high-pressure stage, gas cooler 1, gas cooler 2, intercooler, electronic expansion valve 1, electronic expansion valve 2 and evaporator. The pressure-enthalpy diagram matching this system schematic diagram is shown in Figure 1 (b).

As shown in Figure 1 (b), there are ten processes in one transcritical CO₂ two-stage compression refrigeration cycle which are as follows.

(1) Point A to point B: CO₂ is compressed for the first time in the compressor in the low-pressure stage.

(2) Point B to point B': CO₂ is cooled in the gas cooler 1 at constant pressure.

(3) Point C to point D: CO₂ is compressed for the second time in the compressor in the high-pressure stage.

(4) Point D to point E: CO₂ with high temperature is cooled in the gas cooler 2 at constant pressure.

(5) Point E to point F: in electronic expansion valve 1, CO₂ is throttled and the pressure of CO₂ is decreased.

(6) Point F to point G: the heat exchange process between low-temperature CO₂ and high-temperature CO₂ in the intercooler (the thermal energy of low-temperature CO₂ is raised).

(7) From point B' and point G to point C: CO₂ from the gas cooler 1 and the intercooler are mixed.

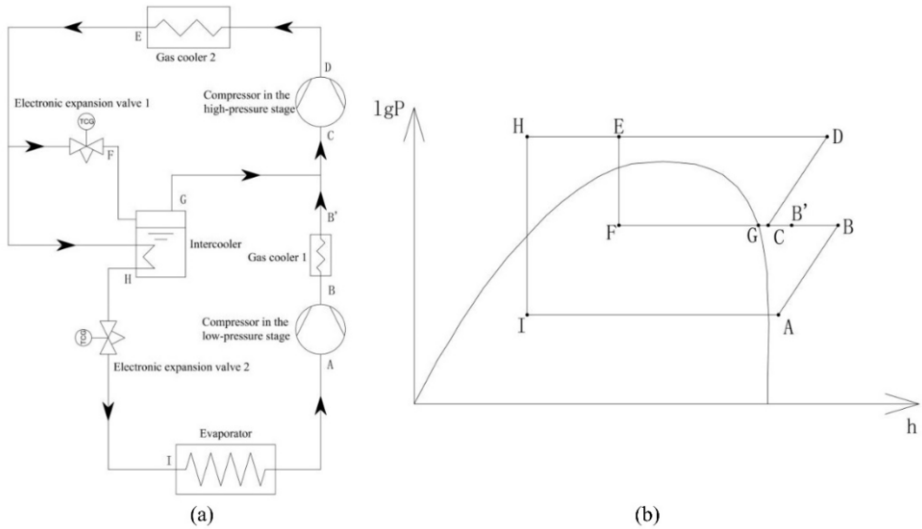


Figure 1. transcritical CO₂ two-stage compression refrigeration system, (a) system schematic diagram, (b) pressure-enthalpy diagram.

(8) Point E to point H: the heat exchange process between high-temperature CO₂ and low-temperature CO₂ in the intercooler (the thermal energy of high-temperature CO₂ is declined).

(9) Point H to point I: in electronic expansion valve 2, CO₂ is throttled and the pressure of CO₂ is decreased.

(10) Point I to point A: CO₂ absorbs the heat and is evaporated in the evaporator at constant pressure.

According to the principle of transcritical CO₂ two-stage compression refrigeration system, the virtual simulation teaching platform for the transcritical CO₂ two-stage compression refrigeration system based on LabVIEW is designed by Shanghai Ocean University. This virtual simulation teaching platform can be used in the teaching of refrigeration-related courses, and students can study knowledge about transcritical CO₂ two-stage compression refrigeration system by this virtual simulation teaching platform.

3. Design of the Virtual Simulation Teaching Platform for the Transcritical CO₂ Two-Stage Compression Refrigeration System

3.1. Basic Information of the Virtual Simulation Teaching Platform for the Transcritical CO₂ Two-Stage Compression Refrigeration System

The virtual simulation teaching platform for the transcritical CO₂ two-stage compression refrigeration system was designed by LabVIEW 2016 with the Windows 10 operation system. Many illustrations like compressor, gas cooler and evaporator were provided by the image gallery of LabVIEW. Some special illustrations could be drawn by AutoCAD and be imported to LabVIEW. Based on these illustrations, clear and intuitive front panels were created. On the basis of this virtual simulation teaching platform, opportunities for students to operate experiments about the transcritical CO₂ two-stage

compression refrigeration system can be increased. In addition, this virtual simulation teaching platform is positive to the improvement of teaching effectiveness.

3.2. Teaching Module Design of the Virtual Simulation Teaching Platform for the Transcritical CO₂ Two-Stage Compression Refrigeration System

The processes of the teaching module of the virtual simulation teaching platform for the transcritical CO₂ two-stage compression refrigeration system is disclosed in Figure 2. First, users should import their own academic numbers (students) or work numbers (teachers) and corresponding passwords. If academic numbers (or work numbers) and corresponding passwords are recognized, the login interface of the software will be turned to the selection interface of the operation modes. There are two operation modes can be chosen which are practice mode and test mode. Contents of experiment operation in these two modes are the same, but there is a time limit in the test mode, and the user's experiment operation is scored by the system automatically. In this software, the time set for each test is 600 s. According to the requirements of teaching, teachers can set up questions and tips in this virtual simulation teaching platform. After the selection of operation modes, users can see these questions and tips set in advance first. When these questions and tips are confirmed, users can press the “OK” button. Then, the transcritical CO₂ two-stage compression refrigeration system will be displayed on the screen. Users must operate the equipment in the transcritical CO₂ two-stage compression refrigeration system based on the questions and the tips set in advance. If there is an error in the operation, a matching tip about how to conquer this problem will be shown at once. User can revise error operation after understanding this tip. However, if the error in the operation is too serious, tips names “Serious error occurred” will appear, and the software will end after the exit button being pressed. This setting simulates the emergency shutdown function of the transcritical CO₂ two-stage compression refrigeration system when a serious problem appears. In reality, this function can be carried out by safety valves. When users finish all operation, the submit button can be pressed. Then, all practice or test is over. Moreover, if the operation time is longer than

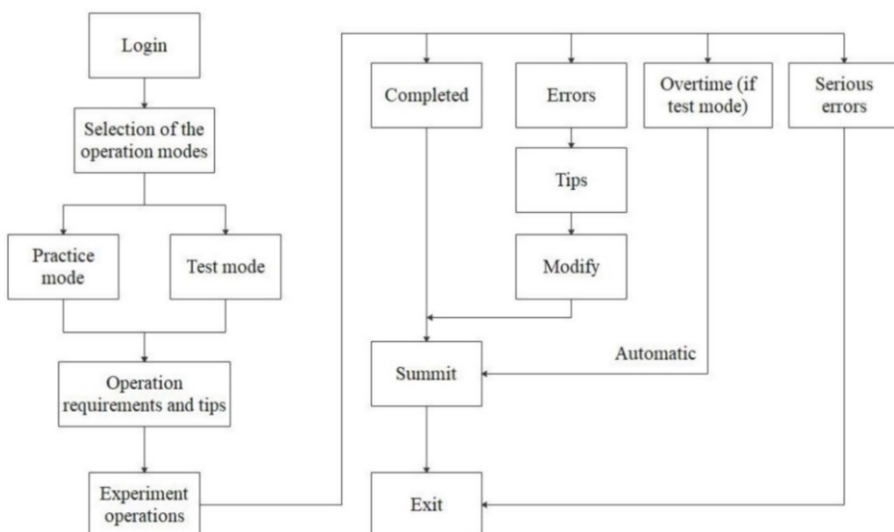


Figure 2. The processes of the teaching module.

600 s in the test mode, test papers will be submitted automatically. Test marks of students can be exported to Excel for teachers to view. Some operation interfaces are shown in Figure 3.

Based on the virtual simulation teaching platform for the transcritical CO₂ two-stage compression refrigeration system, students can pre-learn and revise the experiment operation of the transcritical CO₂ two-stage compression refrigeration system by the practice mode and conduct the test of the transcritical CO₂ two-stage compression refrigeration system by the test mode.

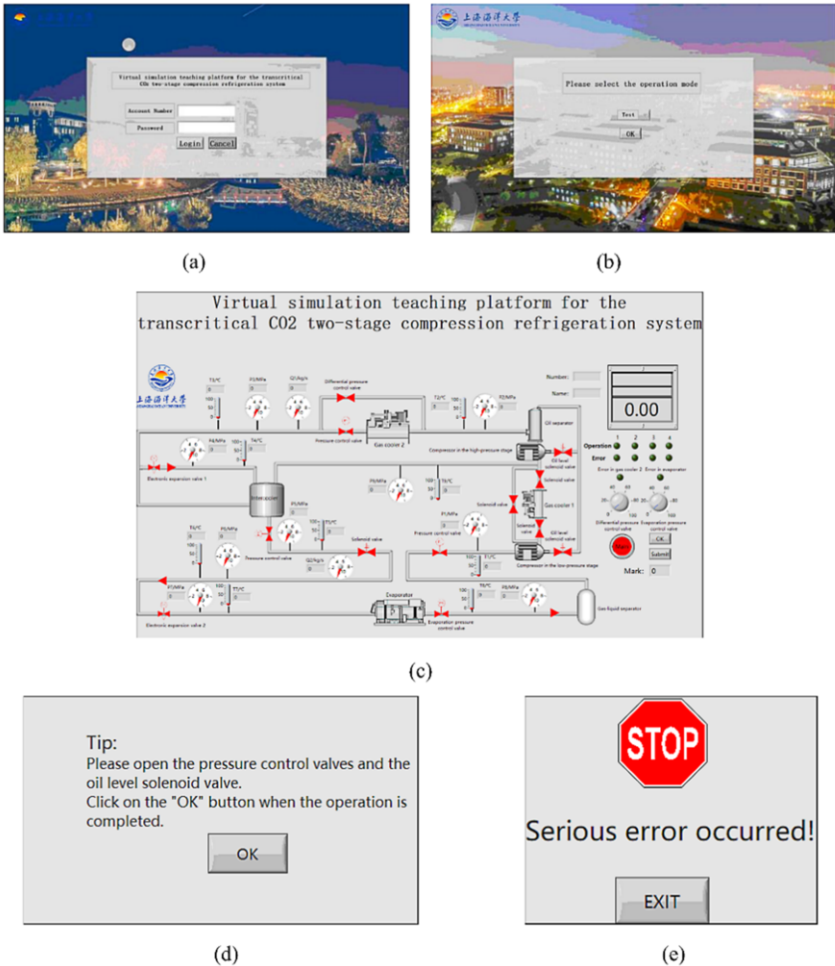


Figure 3. Operation interfaces, (a) login interface, (b) selection interface of the operation modes, (c) experiment operation interface, (d) tip example, (e) serious error report interface.

3.3. Simulation Experiment Design of the Virtual Simulation Teaching Platform for the Transcritical CO₂ Two-Stage Compression Refrigeration System

The interface of the simulation experiment design of the virtual simulation teaching platform for the transcritical CO₂ two-stage compression refrigeration system is shown in Figure 3 (c). The refrigeration system for the experiment operation is designed based on the principle of transcritical CO₂ two-stage compression refrigeration system. Besides eight main components in the transcritical CO₂ two-stage compression refrigeration system, an oil separator, a gas-liquid separator, various regulating valves, temperature sensors, pressure sensors and flow meters are added. The extra equipment is used to control the refrigeration system and observe the parameter changes at each state point in the refrigeration system. The operation conditions of the transcritical CO₂ two-stage compression refrigeration system is controlled by various valves which are on the right of the interface, like the differential pressure control valve and the evaporation pressure control valve. The number of these valves can be added or be subtracted based on the teaching requirements.

If users want to know whether the experiment operation is accurate, they can observe the indicator lights on the interface. There are two rows of indicator lights which represent whether the experiment operation has done and whether it is correctly, respectively. If the experiment operation has done, the indicator lights in the first row will be switched on. If there is a mistake in any experiment operation, the corresponding indicator lights in the second row will be switched on. If all experiment operations have been finished, the main switch can be pressed. Then, the refrigeration system will start running. In addition, if there are deviations in the parameters, users should adjust valves until parameters meet requirements.

The operation time is displayed in the top right corner of the interface. If the time is displayed to 600 s, the experiment operation will be interrupted automatically and the test paper will be submitted automatically. In addition, the test time can be changed by teachers. Furthermore, the test marks of users can be seen from the test mark box. The test mark in the test mark box changes with the variations of experiment operations.

4. Application and Characteristics of the Virtual Simulation Teaching Platform for Transcritical CO₂ Two-Stage Compression Refrigeration System

4.1. Application of the Virtual Simulation Teaching Platform for Transcritical CO₂ Two-Stage Compression Refrigeration System

The experimental data are obtained from the refrigeration system shown in Figure 4. The data is input in the software during the course of software writing. In the process of teaching, users can carry out simulation experiments by the virtual simulation teaching platform.

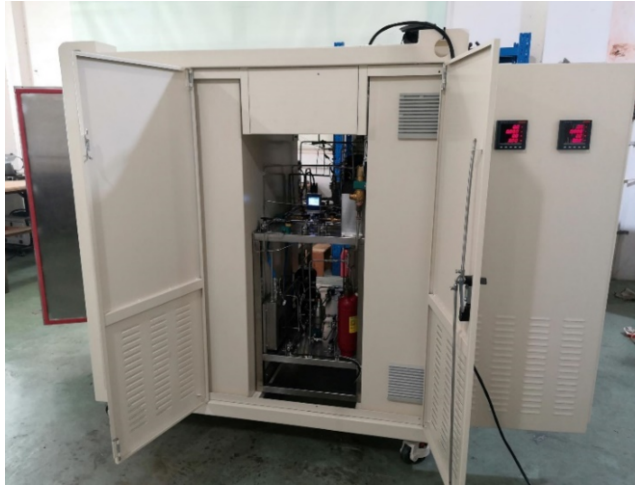


Figure 4. Transcritical CO₂ two-stage compression refrigeration system.

A simulation experiment is conducted in this paper, which is to adjust the refrigeration system in the operation condition of Table 1. The refrigeration system used for this experiment is transcritical CO₂ two-stage compression refrigeration system with auxiliary gas cooler. The auxiliary gas cooler is the gas cooler 1 in the refrigeration system.

Table 1. Parameters of the simulation experiment.

State point	T (°C)	h (kJ/kg)	s		P (MPa)
			(kJ/(kg · K))		
A	-20.00	440.70	1.98		1.79
B	42.28	482.21	2.00		4.06
B'	13.88	442.04	1.86		4.06
C	10.90	436.76	1.85		4.06
D	78.00	476.05	1.86		9.20
E	32.00	282.92	1.26		9.20
F	5.90	282.92	1.30		4.06
G	5.90	426.75	1.81		4.06
H	4.99	207.08	1.00		9.20
I	-23.00	207.08	1.04		1.79

It is assumed that the operator of the experiment is a student. First, the student should import his academic number and the corresponding password. Next, the practice mode is chosen. Then, the experiment operation interface is displayed on the screen. The processes of this simulation experiment are described as follow.

(1) Open the oil level solenoid valves which are next to compressors, and click on the "OK" button when the operation is finished.

(2) Open all pressure control valves and electronic expansion valves, and click on the "OK" button when the operation is finished.

(3) Open all solenoid valves except for the solenoid valve on the line in parallel with gas cooler 1, and click on the "OK" button when the operation is finished.

(4) Press the main switch to start the refrigeration system. The parameters at each state point will be gradually stable at a pre-set operation condition.

(5) Parameters (temperature, pressure and so on) at each status point should be adjusted by adjusting pressure control valves, such as the differential pressure control valve and the evaporation pressure control valve. PA should be 1.79 MPa and PE should be 9.20 Mpa, which represent evaporation pressure and condensation pressure, respectively. Other parameters can be adjusted by the same method. After these adjustments, parameters can meet the requirements of the simulation experiment.

(6) Save the file of the simulation experiment and exit the system.

Based on the above-mentioned operations, a simulation experiment about the transcritical CO₂ two-stage compression refrigeration system is completed, which can be seen from Figure 5. Many other simulation experiments also can be done with this virtual simulation teaching platform. Doing experiments with this virtual simulation teaching platform can reduce the experimental costs and avoid the damage to the equipment due to operator errors. In addition, according to the course schedule, teachers can set up the requirements of simulation experiments and some operation tips in advance in the virtual simulation teaching platform according to the course schedule.

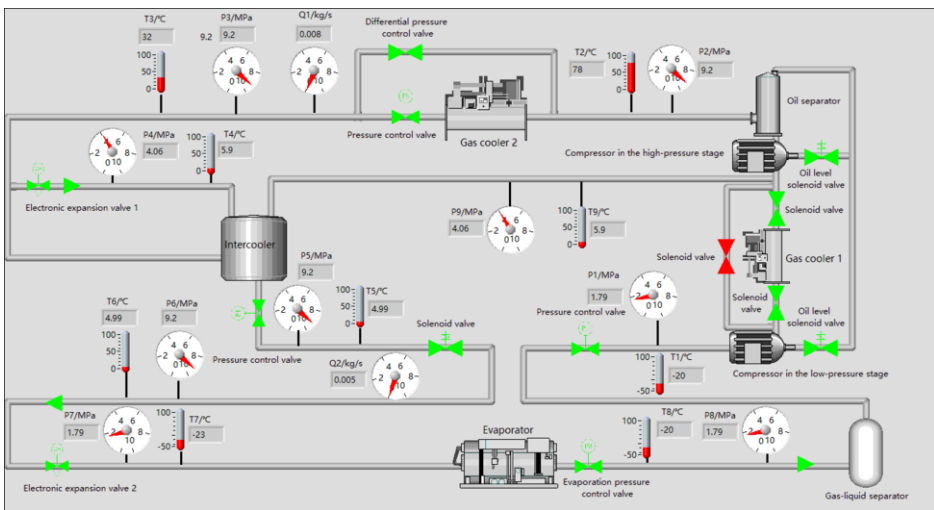


Figure 5. Simulation experiment.

4.2. Application of the Virtual Simulation Teaching Platform for Transcritical CO₂ Two-Stage Compression Refrigeration System

Characteristics of the virtual simulation teaching platform for transcritical CO₂ two-stage compression refrigeration system are as follows.

(1) This virtual simulation teaching platform can be combined with traditional teaching. The transcritical CO₂ two-stage compression refrigeration system can be displayed in the virtual simulation teaching platform intuitively which is helpful for students to better understand the composition and operation of this refrigeration system.

(2) If there is a computer, the simulation experiments can be done by this virtual simulation teaching platform, which is very convenient. In addition, the running memory of this virtual simulation teaching platform is only 5.32 MB.

(3) Users can do simulation experiments by this virtual simulation teaching platform repeatedly. In addition, the costs of doing simulation experiments are much smaller than those of doing real experiments.

(4) Perform experiments by this virtual simulation teaching platform can avoid risks of operational errors, such as equipment damage.

(5) Experiment operation tests can be held by this virtual simulation teaching platform. This method is more efficient than using actual experiment equipment to conduct experiment operation tests.

On the basis of the above-mentioned characteristics of the virtual simulation teaching platform, it is obvious that the virtual simulation teaching platform is both innovative and practical and has a positive impact on teaching in the refrigeration field.

5. Conclusions

A virtual simulation teaching platform for the transcritical CO₂ two-stage compression refrigeration system based on LabVIEW is disclosed in this paper. This virtual simulation teaching platform can be combined with traditional teaching about transcritical CO₂ two-stage compression refrigeration system. In addition, if there is a computer, the simulation experiments can be done by this virtual simulation teaching platform, which is very convenient.

Moreover, students can train more times of simulation experiments by this virtual simulation teaching platform than by real experiments. And, the costs of doing simulation experiments are much lower. Some risks of operational errors can also be avoided, such as equipment damage. In addition, the running memory of the virtual simulation teaching platform is small.

Furthermore, the practice mode and the test mode can be selected in this virtual simulation teaching platform. Tips about experiment operations can also be set up in the software which can help students understand experiment operations about the transcritical CO₂ two-stage compression refrigeration system.

Finally, the virtual simulation teaching platform can be used for the simulation of many studies about the transcritical CO₂ two-stage compression refrigeration system, which is beneficial to the investigation of the transcritical CO₂ two-stage compression refrigeration system in the future.

Nomenclature			
Temperature	T (°C)	Pressure	P (MPa)
Enthalpy	h (kJ/kg)	Entropy	s (kJ/(kg·K))
Subscripts			
State point	A, B, B', C, D, E, F, G, H, I		

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