

Development and implementation of virtual physics laboratory simulations for enhanced learning experience in higher education

Olena Tsvetkova¹, Olena Piatykop¹, Antonina Dzherenova¹, Olha Pronina¹, Tetiana Vakaliuk^{2,3,4,5} and Irina Fedosova¹

¹*Pryazovskyi State Technical University, 29 Hoholia Str., Dnipro, 49000, Ukraine*

²*Zhytomyr Polytechnic State University, 103 Chudnivska Str., Zhytomyr, 10005, Ukraine*

³*Institute for Digitalisation of Education of the NAES of Ukraine, 9 M. Berlynskoho Str., Kyiv, 04060, Ukraine*

⁴*Kryvyi Rih State Pedagogical University, 54 Universytetskyi Ave., Kryvyi Rih, 50086, Ukraine*

⁵*Academy of Cognitive and Natural Sciences, 54 Universytetskyi Ave., Kryvyi Rih, 50086, Ukraine*

Abstract

Computerization of all levels, branches and areas of higher education today is a key issue for the research of all scientists in the world. An actual task is to organize a computer learning environment at the university in accordance with the needs of users. Part of this environment is virtual labs. In particular, an important issue is the conduct of laboratory work in physics. Thanks to the creation of virtual laboratory works, experiments are available to students that are not possible in the educational laboratory. The transition to a remote form of the educational process during the pandemic prepared all levels of education in Ukraine for work in war conditions. The article describes the experience of fully providing the course "Physics" with high-quality virtual laboratory work for students of technical specialties. The developed laboratory reproduces the actions of real experiments (selection of conditions and initial parameters, observation of the phenomenon, appropriate measurements and processing of results) of both traditional workshops and scientific research.

Keywords

virtual laboratory, physics education, online learning, simulation, computer-based experiments, higher education, technical university

1. Introduction

Achievements in the field of computer technology, mass computerization and the development of information technology have led to qualitative changes in the information component of the spheres of production, business, science and social life. The development of information technology has increased human capabilities in various spheres of life several times. Therefore, the use of computer technologies in the educational process is a necessity in the development of the modern information world as a whole [1, 2].

An important factor in the preparation of students of technical specialties, engineers, specialists in the field of exact and natural sciences is the study and knowledge of physics.

Physics is a science that most fully demonstrates the ability of the human mind to analyze any incomprehensible situation, to identify its fundamental, qualitative and quantitative aspects. Thanks to physics, the level of understanding of the theoretical prediction of the nature and results of its development over time is growing.

Therefore, it is very important to constantly improve the teaching system, strengthen traditional teaching methods, apply new modern information technologies in training and organization computer-based educational and research environment of the university for the needs of its users.

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✉ tsvetkova_577@outlook.com (O. Tsvetkova); piatykop_o_ye@pstu.edu (O. Piatykop); antoninadzherenova@gmail.com (A. Dzherenova); pronina.lelka@gmail.com (O. Pronina); tetianavakaliuk@gmail.com (T. Vakaliuk); fedosova_i_v@pstu.edu (I. Fedosova)

🆔 0000-0001-5216-6641 (O. Tsvetkova); 0000-0002-7731-3051 (O. Piatykop); 0000-0002-4249-4147 (A. Dzherenova); 0000-0001-7085-8027 (O. Pronina); 0000-0001-6825-4697 (T. Vakaliuk); 0000-0003-3923-8270 (I. Fedosova)



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In a technical university, one of the forms of teaching physics is a laboratory workshop, which undoubtedly plays a significant role in the formation of a system of knowledge, skills and abilities. Laboratory workshop in physics allows you to:

- introduce methods of measuring physical quantities,
- penetrate deeper into the world of physical phenomena,
- develop skills and abilities to work with devices,
- experimentally test some of the theoretical provisions of the course, more consciously assimilate them,
- repeat and summarize the material covered.

The level of development of information technologies made it possible to supplement and expand the traditional methods of conducting a laboratory workshop in physics. The first step was the creation of computer models of physical phenomena. Further, visualizations of these models began to appear for demonstration. Today it is already relevant to conduct full-fledged virtual laboratory work [3, 4]. A virtual laboratory is a computer software that allows computer simulation of a physical process, including taking into account the simulation of laboratory equipment.

The relevance of virtual laboratory work is caused by the following factors:

- software models allow you to simulate work with objects, processes and equipment, the use of which is problematic or impossible due to process safety,
- the possibility of students' access to unique equipment, technical objects, scientific and technological experiments, mass access to which presents a certain problem;
- software models allow you to arbitrarily change the time scales of the processes under study and make it possible to conduct laboratory work simulating long-term processes in a reasonable time,
- allow you to solve the problem of loading laboratory equipment - virtual laboratory work can be performed at any time, in any place, at any number of workplaces;
- make it possible to carry out research with critical and supercritical parameters, which is impossible on real equipment;
- the cost of developing, acquiring and operating a virtual laboratory is usually significantly lower compared to organizing a real laboratory workshop.

Universities that had a sufficient laboratory base, and had not previously expanded it with virtual laboratory work, were not ready for the conditions of distance education. And the development, organization of the computer educational and research environment of the university is a very important task.

The development, organization and use of virtual laboratory work is part of the learning environment of the university, which is available to the user from almost anywhere and at any time. This provides open learning processes, supports collaborative learning processes and allows the university environment to be organized in accordance with the needs of its users [5, 6].

Thus, if earlier the task was to expand the capabilities of the laboratory workshop, then in modern realities this has turned into a task – to provide it. An important factor is the quality of virtual laboratory work. These software systems should correspond to the content, level and methods of teaching physics in higher education.

2. Theoretical background

Today, there is already experience in using virtual laboratory work for different levels of education.

There are computer simulations of physical processes (subject-oriented environments) in accordance with the school curriculum. Software products on the resource "Physics" [3] ensure the performance of laboratory work in accordance with school curricula in physics. The works are decorated colorfully,

accompanied by animation, offered by the authors on a fee basis. The authors state that “current developments in virtual labs provide interactive simulations that are becoming increasingly important as a means to explore and understand complex processes and create the illusion of working on real equipment...”. Similar works are presented in the public domain on the PhET resource [4]. A textbook by Dementiievska and Sokoliuk [7] was developed for their use.

The authors note that the works do not provide for the calculation of absolute and relative errors due to the impossibility of their calculation by the standard procedure for interactive computer models. The authors also point out that virtual laboratory work does not replace a real physical experiment, but is a support and support for such an experiment in cases where real devices and materials are not available or harmful. The authors recommend the use of such virtual work during distance and blended learning, as well as to increase the motivation and interest of students. The use of the PhET platform is also described by Faour and Ayoubi [8].

The positive experience of using virtual laboratory work is also confirmed by Lestari et al. [9]. The authors determined the impact of the combination of a virtual laboratory with demonstration methods on the ability of elementary school students to be scientifically literate in a science course. Behind their results, the situation of combine demonstration and virtual work showed the best way.

Gunawan et al. [10] describe their experience of using virtual laboratories for students of three different senior classes of secondary school. Their research aims to improve students’ conceptual understanding of physics through a virtual laboratory.

The results of the authors showed that the use of virtual laboratory work had a positive impact on the students’ conceptual understanding of physics. Ultimately, according to the results of control activities, schoolchildren improved such cognitive functions as memorization, understanding, analysis and application, but the cognitive aspects of creating and evaluating processes require further improvement.

Thus, software products for the school curriculum are an “illusion of laboratory” and are more like educational games. Therefore, it is not advisable to use them for higher education.

A better but commercial product is the ROQED PHYSICS LAB resource [11]. ROQED PHYSICS LAB allows independent creation of installations and is as close as possible to the real conditions of execution. The list of proposed works does not go beyond the scope of classical workshops and is more in line with elementary school. This product does not contain instructions and formulation of tasks, which is inherent in the structure of laboratory work in higher education. Also, all these software products are more focused only on observing phenomena. When studying physical phenomena in higher education, it is also important to obtain and process the results of observation with the corresponding conclusions.

Also the experience of using virtual laboratory work for universities is described by the following works. Such studies were carried out in Near East University [12]. Virtual laboratory work was carried out using Circuit lab software. Laboratory work was devoted to the study of the topic “Electricity”. In the program, students assembled electrical circuits. The authors write that the majority of students have a positive attitude towards the activities of the virtual laboratory.

El Kharki et al. [13] presents the experience of using virtual laboratory work in Moroccan Universities to support laboratory activities for first-year undergraduate students. The virtual laboratory was developed by Moroccan universities with the help of European partners using the JavaScript programming language and integrated into an interactive learning environment based on the Moodle platform. This virtual lab includes 12 virtual labs linked to the physics curriculum and can be used online. This virtual laboratory is available only for teachers and students of the faculties of natural sciences of the specified universities.

Development of own software is also described by Kozlovsky and Kravtsov [14]. The authors created a software module “Virtual Laboratory” in the distance learning system “Kherson Virtual University” for the topics of kinematics and dynamics. To display physical models, processes and phenomena, the authors used the graphical tool Unity3D together with C#. According to the authors Using this software will allow teachers to create labs and use them in their online courses. Students, in turn, will be able to conduct research by performing virtual laboratory work.

The relevance and interest in virtual laboratory work does not stop, as evidenced by recent publications [15, 16, 17].

Today, innovations in the field of information technology and artificial intelligence are developing very quickly, so there are more and more new tools. Thus, the increase in computing power of computers, the rapid development of machine learning methods and the large amount of accumulated available data provided the user with a new ChatGPT chatbot assistant.

Of course, the appearance of ChatGPT will affect the processes of education and learning, which is actively discussed in recent scientific publications [18, 19]. Educators need to be prepared that students will be using ChatGPT. Therefore, it is important to prevent the negative impact of ChatGPT on the learning process and use the positive aspects. You can recommend this resource as an auxiliary tool for studying physics, find additional sources of information for laboratory work. For example, the ChatGPT model can help understand complex aspects of the theory or illustrate them with examples. But ChatGPT should not replace the student's personal work, it is necessary to analyze and understand physical concepts. This requires virtual labs to be as close as possible to real processes and equipment, and not just perform a demonstration.

So, the authors have set a goal for themselves: to provide a laboratory workshop with unique virtual laboratory work providing the course of "General Physics" of the higher school program. These laboratories should reproduce the process of doing work in a real laboratory as much as possible, make it possible to control and monitor the real process, and reproduce dynamic processes in real time.

The purpose of the article is to demonstrate the possibility of providing a high-quality educational process for studying the physics of technical specialties of a university on the basis of a virtual workshop.

3. Experience in developing virtual labs in physics

Work on the creation the e-learning platform of virtual laboratory work at the Pryazovskyi State Technical University was started back in 2013 to expand the list of works on the topic "Molecular physics and thermodynamics".

In classical physics workshops for technical (non-physical) specialties, the section "molecular physics and thermodynamics" does not have such a variety of works as the sections "mechanics, electromagnetism". At the same time, the list contains more laboratory works on studying the properties of liquids, and according to gas laws, the choice is rather limited [20, 21]. In the virtual school workshop, laboratory work is devoted to the laws of isoprocesses in ideal gases. But the difference between the university program and the school program lies in the fact that theories of the next round of the spiral of knowledge are being studied, and this is the theory of real gases. For real gases, there is a work of a school workshop, in which the transition through the critical state of matter is visually observed and the critical temperature is determined (Avenarius's experiment) [22].

The reason for the lack of work on real gases lies in the fact that a real gas is a gas under certain parameters. According to the theory (the van der Waals equation of state), the transition from an ideal gas model to a real one occurs under strong compression, when the pressure is orders of magnitude greater than atmospheric pressure. The process is temperature dependent. If the gas temperature is less than the critical one, then during compression, a phase transition to the liquid state will be observed. If the temperature is higher, then under no circumstances can the gas be obtained in a liquid state of aggregation, and its state will be described by the equation of the ideal gas model. However, for atomic and chemically pure gases, the critical temperatures are in the low temperature range. For example, for air, the critical temperature is 132K, for high molecular weight hydrocarbon compounds, these are room temperatures. But at atmospheric pressure, they are already in a liquid state. To the above problems, we can add safety issues related to the use of bottled gas in a training laboratory: toxicity and explosiveness of gas. It also requires a special technique for its use in the installation, the procedure for reproducing gas with repeated use, and more.

It is in this case that virtual laboratory work is simply necessary to provide a workshop on this topic. To study this topic, initially (2013), the authors created and used a computer simulation (figure 1), which reproduced real isotherms corresponding to the van der Waals equation (taking into account the two-phase state).

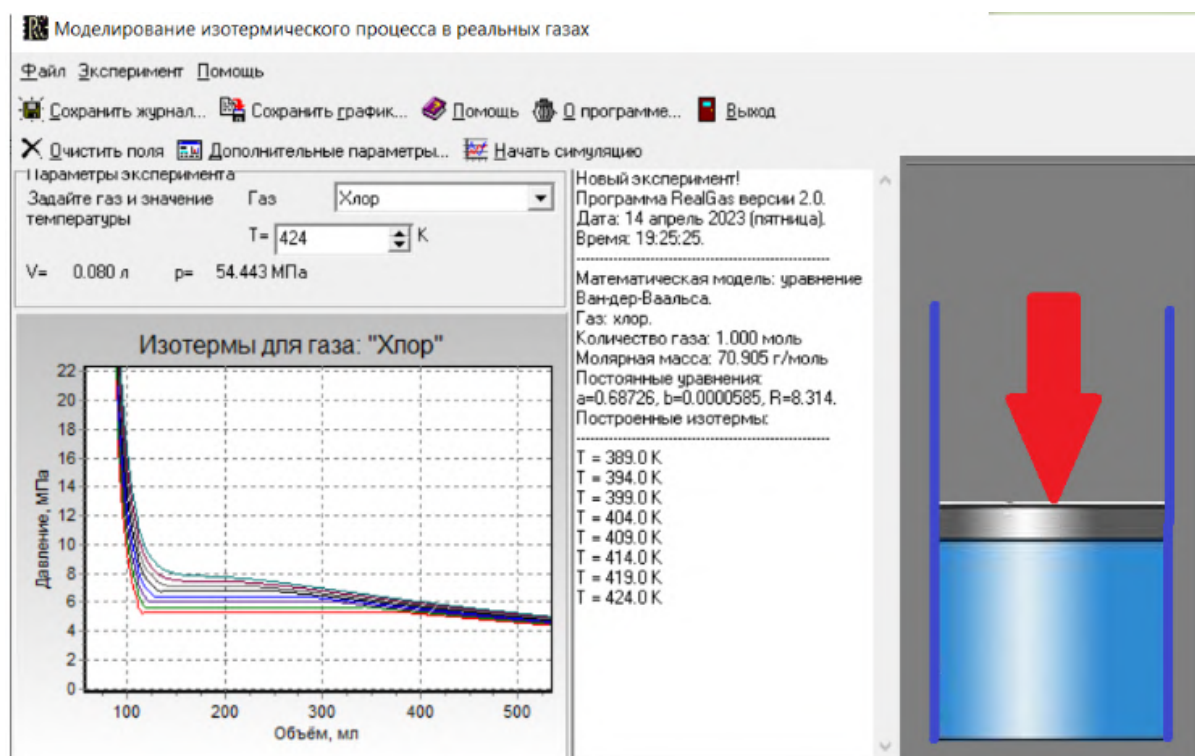


Figure 1: The window of virtual laboratory work “Real gases”.

At the initial stage of computerization, the work played a positive role, but in this form it did not correspond to the spirit of the laboratory: instead of real actions with the device (turn on the device, select the temperature interval, to see the piston stroke during compression, to observe the readings on the pressure gauge), the student pressed the button “start simulation” and at the same time saw isotherms, the same as in the textbook. It was this primitive simulation that led to the idea of creating virtual lab, in which the course of the experiment is reproduced as much as possible, actions are performed with devices and natural results are demonstrated.

The use of modern information technologies has made it possible to put such ideas into practice. Two methods were created for determining the parameters of a real gas in the van der Waals equation: for the isochoric gas heating process (figure 2) and for isothermal compression (figure 3).

The virtual laboratory program (figure 2) was written in the Delphi 7 programming language using the Alpha Skins visual components in the Delphi XE development environment. The program uses a photo of equipment for determining the parameters of a real gas by isochoric heating, which was made in a real classroom of the Pryazovskyi State Technical University.

The virtual lab program (figure 3) is written in C# on the Microsoft Windows Forms platform. This virtual lab also uses a photo of the actual equipment. In the figures we see the settings, on which the active controls are indicated by arrows; there is a choice of objects of study. It should be noted that these works were carried out by students in the classroom on computers on an equal footing with other works in molecular physics.

Later added another virtual laboratory work on molecular physics. It is devoted to the study of the Boltzmann distribution and the determination of the Avogadro number by the Perrin method (figure 4). This work belongs to static physics, then particle counting is carried out several times and it is guaranteed that there will be no repeated results. Under normal laboratory conditions, real experiments are represented by only two kinds of particles in the corresponding solvents. The developed virtual laboratory work makes it possible to study 6 types of particles: gum in water, mastic in water, kaolin in honey, flour dust in glycerin, carbon dust in glycerin, white soot dust in honey.

On the screen, the student observes in real time the Brownian motion of particles and counts their

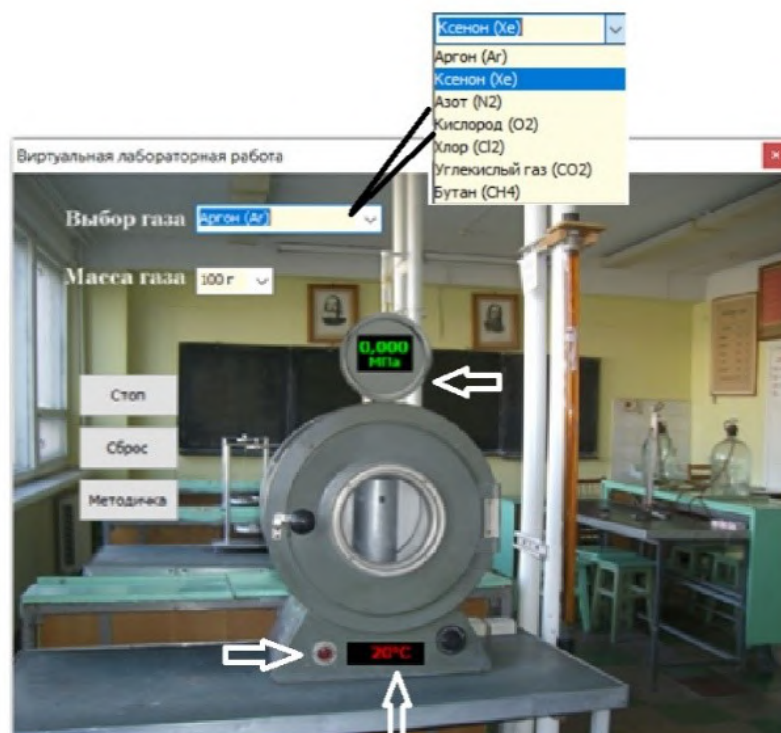


Figure 2: The window of virtual laboratory work on determining the parameters of a real gas by isochoric heating.

number by layers depending on the depth of focusing of the microscope eyepiece. The undoubted advantages of this work is the multivariance of particles. Brownian motion occurs not only in a plane, and particles in the process of motion can disappear from visibility, passing from layer to layer. Therefore, an important advantage of virtual work is the ability to make a “freeze frame” during the process. This allows the field of observation to be divided into smaller areas and the particles to be counted without much difficulty. This virtual lab was developed using the Godot Engine for PCs running Windows, Linux and macOS.

Such a work as Perrin’s experiment allows us to formulate the thesis about “historicism in science”, showing what path scientists took from hypothesis to theory through experiment.

So the next step was also reproduction of fundamental experiments as virtual laboratory work, but already for the section “Electricity and magnetism”.

So, in the topic “Electric field” one of the fundamental experiments is R. A. Millikan’s experiment to determine the charge of an electron, and in the topic “Quantum optics” its version is complicated – these are the experiments of A. F. Ioffe and M. I. Dobronravov on the elementary photoelectric effect, in which experimentally confirmed the propagation of radiation in the form of individual photons and the quantum nature of the interaction of radiation with matter. In the above experiments, the observation of the smallest ($d \sim 1 \mu\text{m}$) charged dust particles in an electric field was carried out using a microscope; the electric field was created by a high voltage source; in addition, in the Ioffe-Dobronravov experiment, a dust grain was irradiated with X-rays, as a result of which it lost its elementary charge and began to move. For the authenticity of the results obtained, it was not enough to carry out one cycle of measurements. It follows from the above reasons that these fundamental experiments cannot be reproduced in a teaching laboratory. Therefore, due to their complexity, laboratory work was not previously included in the list of physics workshops at universities.

At the same time, modern software products make it possible to create virtual laboratory works that, both visually and in terms of execution methodology, are as close as possible to a real physical experiment.

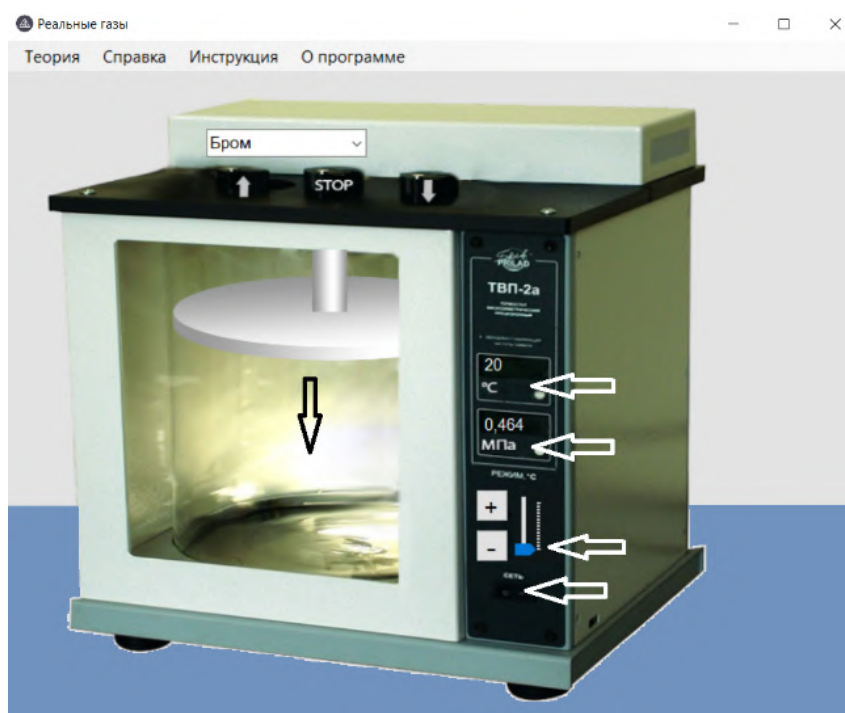


Figure 3: The window of virtual laboratory work to determine the critical parameters of gas under isothermal compression.

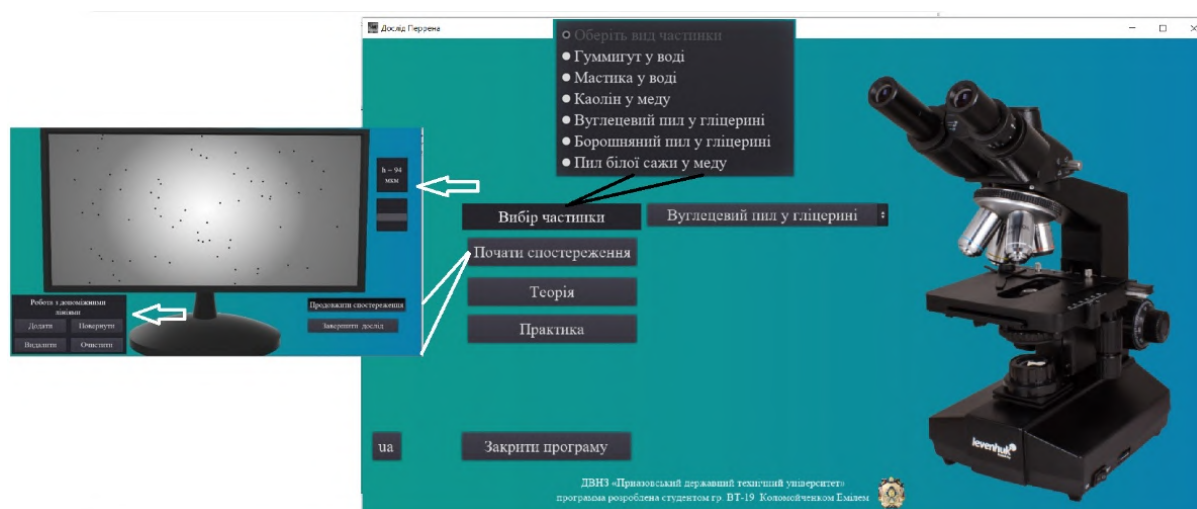


Figure 4: The window of virtual laboratory work “Experience Perrin”.

The technique was developed and programs for virtual laboratory work “Determination of the electron charge in the Millikan experiment” (figure 5) and “Determination of the electron charge in the Ioffe-Dobronravov experiment” (figure 5) were created [23]. The program code is written in C++ using the cross-platform Qt framework. All controls are visible in the figures. The programs provide for the generation of particles with different numbers of electrons and masses. The movement (calm) of a charged dust particle is monitored in real time.

In these works, the student observes charged microdroplets in real time, and also, for example, for the Ioffe experiment, controls devices to create equilibrium. In this case, the student must collect enough experimental data to see patterns, make calculations and draw conclusions. Thus, the student will be able to feel what incredible work has been done by scientists to discover the discreteness of the charge, determine the charge of the electron, or confirm Planck’s hypothesis.

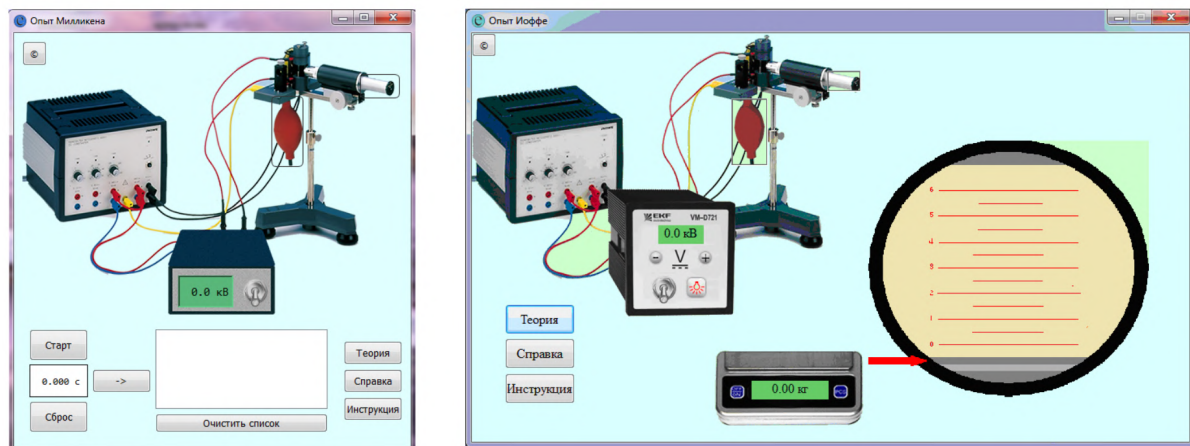


Figure 5: The window of virtual laboratory work of determining the charge of an electron.

The advantage of such a computer simulation is its simplicity: there is no need to maintain a laboratory bench, select its parameters, and no special personnel are required to assist the student in carrying out the work. In addition, in a computer model, you can change the method of work without changing the essence of the experiment. For example, in the developed Ioffe Experiment program, the photoelectric effect manifests itself instantly with the irradiation of a dust particle, and not with an interval of 30 minutes, as was the case in a real experiment.

Speaking about the quality of a laboratory workshop, I would also like to raise the issue of creating such works that would demonstrate that physics is an integral science. There are not many works in which several sections are intertwined. Let's give an example that demonstrates the relationship of 3 different sections: molecular physics, electromagnetism and nuclear physics – this is mass spectrometry. The student is asked questions: why are there chemical elements in the periodic table whose molar mass does not correspond to an integer number of nucleons? The answer is hidden in the “nuclear physics” section when talking about the existence of isotopes. And how to separate them by mass, if they are stable? The answer is mass spectrometry. However, the mass spectrometer is clearly not the equipment of a training laboratory, it is an expensive special-purpose equipment, requiring appropriate maintenance by trained personnel. However, in the topic “Action of the magnetic field” lectures always talk about the use of the Lorentz force in these installations.

Thus, virtual laboratory work was created on the topic “Determination of the composition and molecular weight of a chemical element using a mass spectrometer”. In the virtual setup (figure 6), it is possible to determine the radius of curvature of the trajectory of singly charged ions of stable isotopes moving in a magnetic field, depending on the accelerating voltage, and their concentration (by the signal intensity on the detector). As a result, the molar mass of the test sample is calculated and which chemical element is determined.

According to the authors, such work should form the basis of practicums that provide a physics course with a small number of credits, or for distance learning with a minimum number of hours allocated per practicum. In these cases, the work provides several branches of physics at once.

The Compton phenomenon is one of the key experiments considered as proof of the corpuscular theory of electromagnetic waves. Along with the photoelectric effect, this phenomenon is considered and analyzed in detail in the lecture course. However, there is no corresponding work in the list of classical practicums; it cannot be implemented in the classroom. Through the use of virtual laboratory work, this situation has been changed. Figure 7 shows that there is a real installation for studying this phenomenon, but it uses a source of gamma radiation and an appropriate gamma-ray detector that separates them by energy. It should be noted that the detector operates only at liquid nitrogen temperatures, i.e. The instrument is not intended for use in a teaching laboratory.

The extended capabilities of this virtual laboratory work are that elements that emit gamma quanta

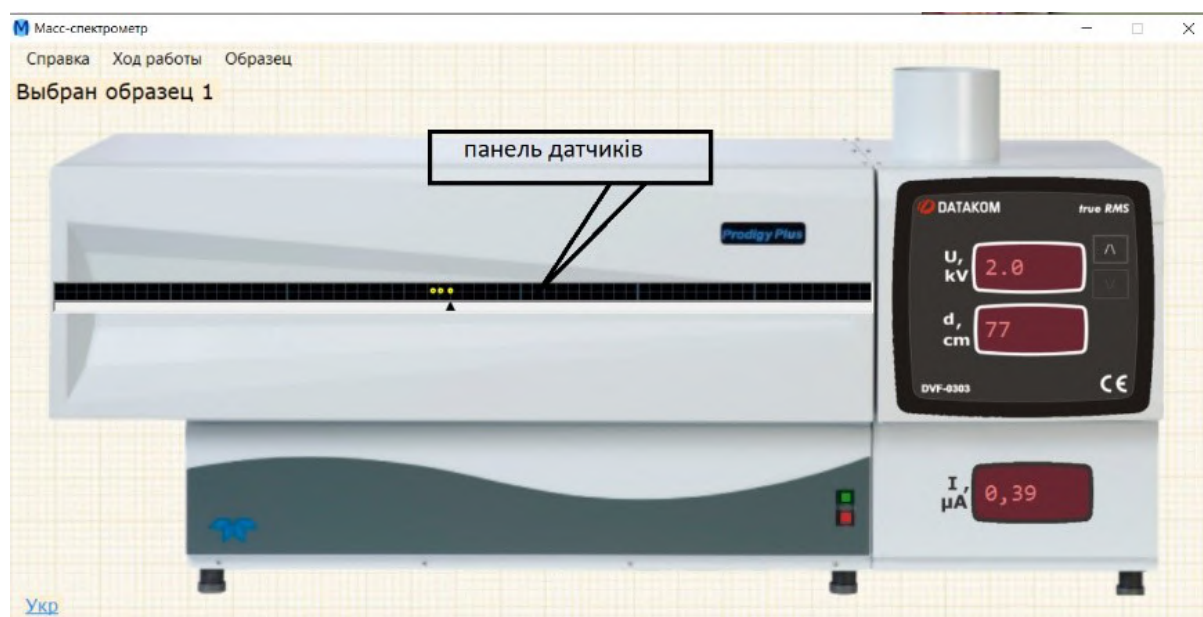


Figure 6: The window of virtual laboratory work “The determination of the composition and molecular weight of a chemical element using a mass spectrometer”.

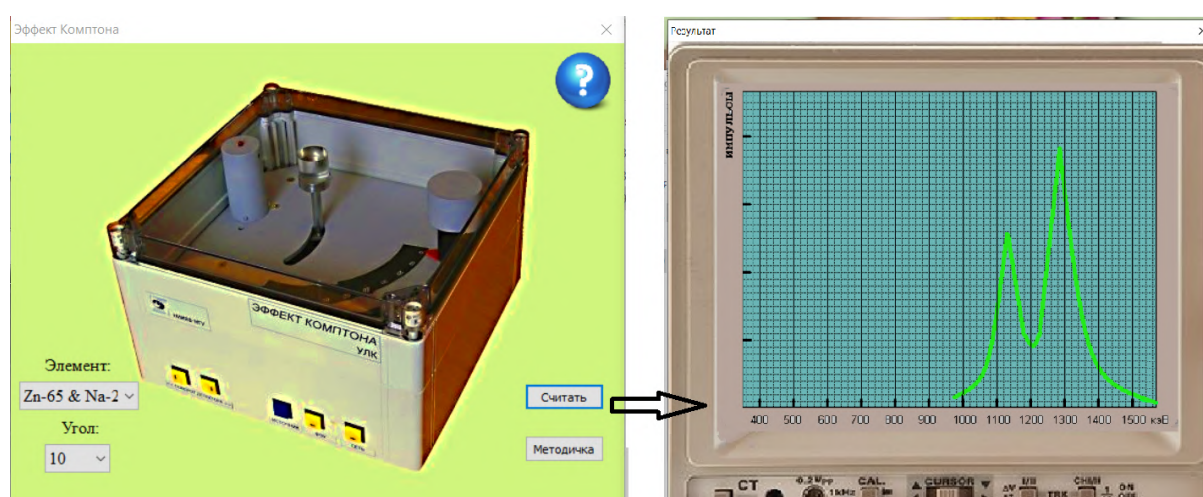


Figure 7: The window of virtual laboratory work of research of the Compton effect.

of two energy values are selected as sources. First, it makes it possible to determine the Compton wavelength of an electron. Secondly, it makes it possible to establish the fact that the effect does not depend on the energy, but is determined only by the scattering angle.

The timely application of modern information technology to expand the laboratory workshop in physics has become a very timely educational resource during the sudden quarantine measures caused by COVID-19.

This forced transition to a distance learning process, along with the creation of new work, has set the task of duplicating existing laboratory work. On figure 8 and figure 9 show virtual laboratory works that fully reproduce experiments on real equipment. For example, in figure 8 shows the spectra of mercury and hydrogen. They were filmed in real time, and in the program they were combined with the scale of the spectrometer. Performing work in this form, the student actually does all the same actions as with laboratory equipment. On figure 9 in the eyepiece of the virtual laboratory work pyrometer, the observations of the pyrometer filament and the incandescence of the object are exactly the same as reproduced by the real device.

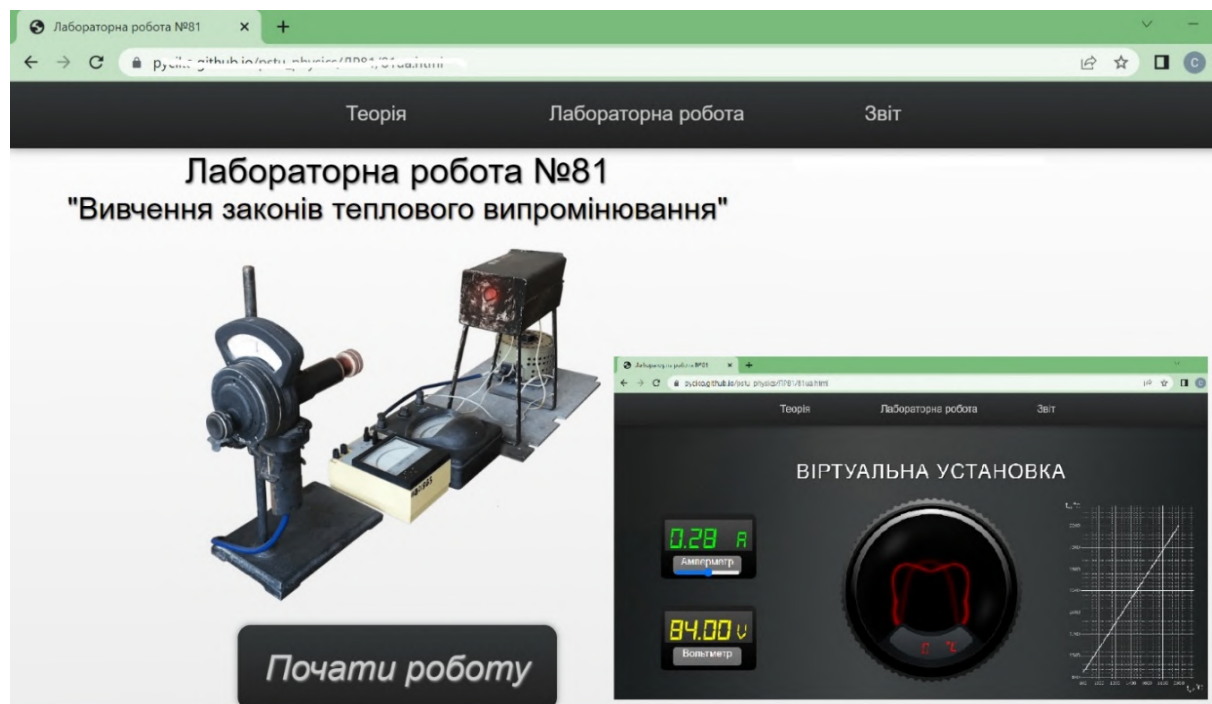


Figure 8: The window of virtual laboratory work “The study of the laws of thermal radiation”.

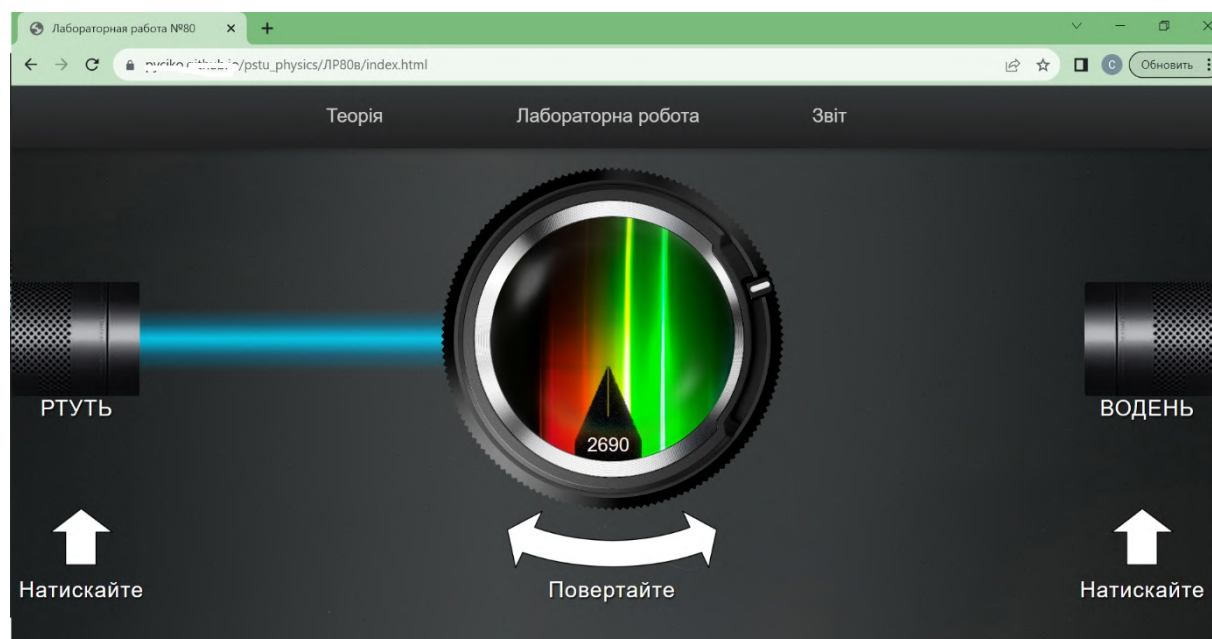


Figure 9: The window of virtual laboratory work “Studying the spectrum of the hydrogen atom and determining the Rydberg constant”.

As can be seen from figure 8 and figure 9, these works already created as web pages that are displayed in the browser. They were created with HTML, CSS, JavaScript. Thanks to the use of JavaScript, the animation is fast, for example, compared to Flash. This version of the software product is dictated by the ease of use during distance education. Since the use of programs with executable files (exe - files) may require additional software.

Therefore, further virtual laboratory works were developed as web pages. For example, figure 10 shows the work of observing interference and determining the wavelength of light using a Fresnel biprism. The possibilities of the virtual laboratory work have already been expanded in comparison

with the real analogue. So the audience was limited to the use of two light filters. In virtual laboratory work, you can choose 4.

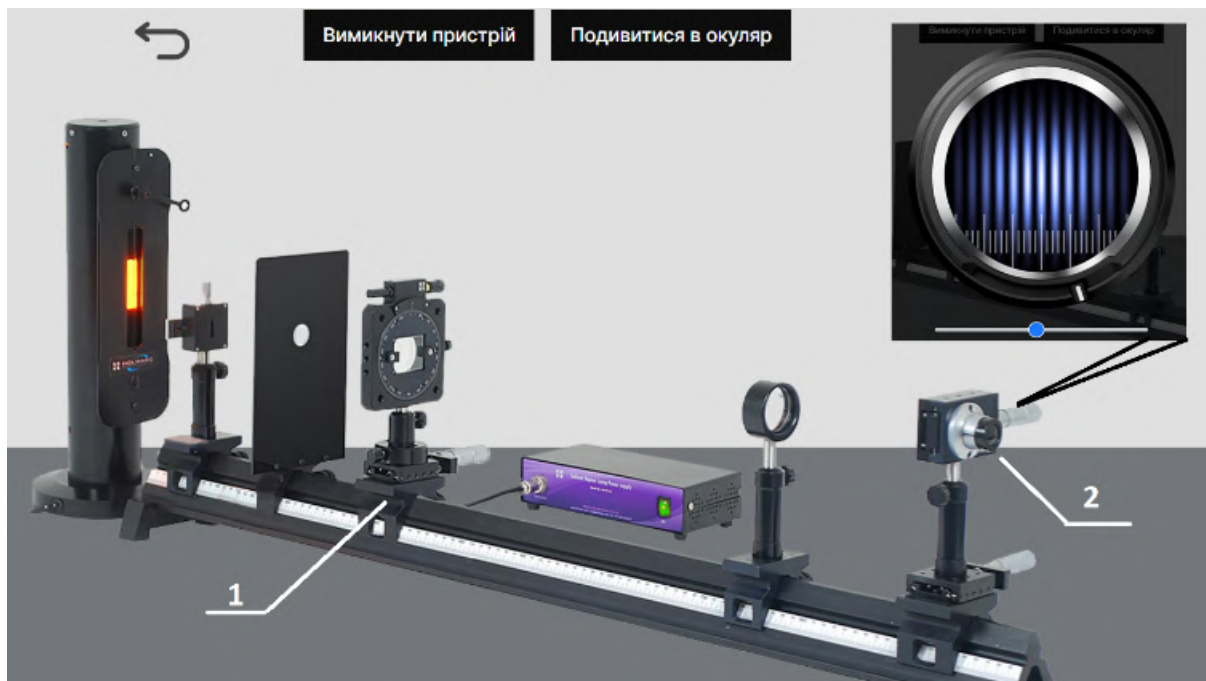


Figure 10: The window of virtual laboratory work “The Determining the wavelength of light using a Fresnel biprism”.

4. Conclusions

The production of a quality software product should reduce skepticism about the use of virtual laboratory work.

To date, the computer educational environment of the Pryazovskyi State Technical University consists of 27 laboratory works. This number of works provides the course “Physics” for technical specialties in sufficient volume. The works were tested in the educational process and gained interest and support from students.

It should be noted that only one virtual laboratory work reproduces the circuit diagram with conditional devices. The rest of the labs contain information with real lab equipment. There are no boundaries for perfection. Some laboratory works have video fragments of real experiments. These real observations and measurements provide statistical processing of measurement results, but their drawback is the lack of multivariance of the initial data. Unfortunately, at the time of writing, the own laboratory facilities of the Pryazovskyi State Technical University are not available due to the military aggression of the Russian Federation against Ukraine and the conduct of hostilities in the territory of Mariupol, but the university was evacuated to the Dnipro. Therefore, work on the creation and expansion of virtual laboratory work will continue.

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