Momentum: Physics Education Journal
8 (2), 2024, 249-260
Available at: ejournal.unikama.ac.id/index.php/momentum
ISSN 2548-9127(print) | 2548-9135 (online)

Enhanced learning: Designing bifocal modeling practicum tools with ESP32 for exploring kinetic theory of gases

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Received: 13 May 2024; Revised: 7 June 2024; Accepted: 11 June 2024

Abstract: This research was conducted to obtain an initial design for a laboratory practical tool based on bifocal modeling assisted by an ESP32 microcontroller for kinetic gas theory. This study was conducted to obtain an initial design for a practical laboratory tool based on bifocal modeling assisted by the ESP32 microcontroller on the kinetic theory of gases. This study was conducted descriptively through a literature review of various book articles and materials. Interviews were conducted with students and physics teachers in high schools (9 students and two teachers in Malang, 15 students and three teachers in Bandung) in Indonesia. Interviews were conducted to obtain an overview of the application of physics learning and reveal other potential problems students and teachers face. The design of the bifocal modeling tool developed has been consulted with physics and ICT learning experts. The results are that it needs to be further developed and maintained until the manufacturing stage. Bifocal modeling based on the design developed in this study has the potential to facilitate students to conduct scientific experiments related to the kinetic theory of gases. Based on the equipment to be developed, it is expected that students will be able to observe macroscopic gas phenomena through actual experiments, monitor microscopic phenomena visualized through computer models, collect data in actual experiments and computer simulations, and compare data. Students' understanding of the concept of the kinetic theory of gases has the potential to be improved by conducting practical work using bifocal modeling-based tools.
Keywords: bifocal modeling; ESP32; simulation; kinetic theory of gases; inquiry

How to Cite: Sujito, S., Sulur, S., Hudha, M. N., Winarno, N., & Sunardi, S. (2024). Enhanced learning: Designing bifocal modeling practicum tools with ESP32 for exploring kinetic theory of gases. *Momentum: Physics Education Journal*, *8*(2), 249-260. https://doi.org/10.21067/mpej.v8i2.10046

Introduction

Life in the 21st century is the application of advanced technology and science across many fields. This is called the information age, in which efforts to meet the needs of human life are based on information-based, global network knowledge (Wijaya, Sudjimat, and Nyoto 2016; Triling and Fadel 2009). Therefore, 21st century teachers must help students learn new skills to navigate 21st century education and the 21st century workplace. These skills are commonly known as 21st century skills (Siddiq et al., 2017). 21st century skills have four main areas of skills, namely skills related to ways of thinking (creativity and innovation, critical thinking, problem solving, decision making, learning to learn and metacognition); work methods, skills (communication and cooperation); tools for professional skills (literacy and ICT / digital culture); and Life Skills (How students can live as active citizens with personal and social responsibility and cultural awareness). Today's education system should adequately prepare students with the 21st century knowledge and skills necessary for success in life, work, and citizenship (Chakraborty & Aithal, 2023).

Physics, as an important part of the education system, plays an important role in preparing students, so that they can acquire the knowledge and skills of the 21st century. It is important for all aspects of human life. As a basic science, physics has scientific characteristics in the form of facts, concepts, principles, laws, postulates and theories (Fischer et al., 2014; Legresley et al., 2019). Due to the 21st century education, the Indonesian government wants the educational system to be influenced by the science and knowledge process, through which students can do the work of observation, inquiry, experiment, d association and communication (BSNP, 2010; Pratiwi et al., 2018). By doing such activities, students can gain a variety of practical experiences, guide what scientists do, and understand the basics of physics as a scientific product (knowledge), scientific method (method of research) and scientific attitude (method of thinking) (Devy Alvionita et al., 2020; Sutrisno, 2006). Internship is one of the ways to study physics that gives students the opportunity to gain valuable experience. By teaching physics, students can understand the basics of science (physics) and gain the knowledge, experience, practical skills and advanced thinking skills necessary to face life in the 21st century. The teaching method also allows students to be more motivated in learning and can improve their learning outcomes. Physics internships can also allow students to implement scientific methods. A physics internship can be used to demonstrate the basic principles of physics and introduce students to laboratory equipment, tools and devices, so that students can apply them for specific purposes and develop a variety of useful skills (Branchetti et al., 2019; Gupta, 2013; Hofstein & Lunetta, 2004).

Although physics education is important for providing students with the knowledge and skills necessary for 21st century life, their implementation, especially at the second level, is poor. The reasons are various, such as the limitation of laboratory equipment, tools and equipment; a physics laboratory served as a school; the absence of an assistant or a laboratory supervisor affects the time necessary for the organization of the office's work. Poor condition of laboratory equipment, instruments and tools was also identified as another factor (Katili et al., 2013; Nggadas & Ariswan, 2019). The problem of implementing physics education in secondary level is more serious for theoretical concepts, mathematics and ordinary physics. Students generally do not have the opportunity to see the real and virtual physical phenomena that deal with such ideas. As a result, students' understanding of science, mathematics and physics is low (Hermansyah et al., 2015; Sujito, Liliasari, Suhandi, et al., 2021a).

Numerous factors contribute to this, including limitations in laboratory resources, inadequate supervision, and poor maintenance of equipment, as highlighted in various studies. This inadequacy is particularly pronounced in theoretical concepts, mathematics, and everyday physics, where students often lack exposure to real-world phenomena, hampering their comprehension. For instance, the teaching of gas kinetic theory primarily focuses on mathematical problem-solving, neglecting the deeper understanding of physical principles. Studies indicate a significant gap in students' understanding of gas kinetic processes, with low comprehension levels observed across different regions in Indonesia. Despite these challenges, suitable teaching methodologies for imparting gas kinetic theory remain elusive for educators. Study conducted in a high school in Indonesia (Malang and Bandung city) revealed that gas kinetic theory is taught through the curriculum. Learning the kinetic theory of gases is often focused on solving mathematical problems, so students do not have the opportunity to understand the physical nature of the problem. Another study also found that high school students' understanding of the kinetic process of gas in a given area in Indonesia is low, varying between 12% and 59% (Agustina et al., 2018). Teachers have not found a suitable method or method to teach the subject of the kinetic process of gases (Istyowati et al., 2017).

The development of information and communication technology (ICT) is accelerating, especially in the current era of Industrial Revolution 4.0 or the 21st century (Ma'ruf et al., 2020). It transforms the learning process from traditional learning to ICT-enabled learning. As a result, the adoption and adaptation of ICT in the world of education, especially in education, is successful. The use of ICT in education can overcome the problems mentioned above related to the implementation of physics courses, especially for the theoretical, mathematical and abstract concepts of physics, such as the kinetic process of gases. In fact, ICT can be incorporated into the curriculum to enable students to engage in project-based science activities and visualize the concepts of curriculum, mathematics and physics. ICT can be used to make physical examples that bring students to their potential as young scientists (Ma'ruf et al., 2021; Vieira et al., 2018). This type of learning can be organized into a training course using a bifocal model base training method. It incorporates advanced technology, consisting of ICT and sensors (Blikstein, 2014; Hudha et al., 2019). The introduction of bifocal modeling in science education has been shown to improve students' content knowledge and metamodeling. Schwartz defined metamodeling knowledge as knowledge about modeling that allows students to answer questions about how and why scientific models are used, as well as the strengths and limitations of these models (Fuhrmann et al., 2018).

The heart of the bifocal imaging system is the real-time integration or interaction of real-world experiments with digital computer models. It requires students to design, compare and test data collected from real experiments and data generated from computer models. The bifocal imaging system can be modified in this way depending on the characteristics of the object being studied. It can use different computer languages, hardware, and sensors. To build a bifocal imaging device for some physics lessons, we need specific hardware and software. The GoGo Board is an example of hardware used to display visual and digital data in a previously developed bifocal-type device. The software used is NetLogo (Fuhrmann et al., 2018), Raspberry Pi (single board/miniature computer) (Krauss, 2016) and Arduino (controller) (Blikstein, 2014). Projects can be created using this software by modifying several sensors to regulate time or interaction (Krauss, 2016). However, there are weaknesses among the software above, such as Arduino not having an internal wireless connection that allows internet connections. There is a cheap Arduino board known as the NodeMCU. It is a low-cost WiFi chip that combines a TCP/IP stack and microcontroller capabilities (Dahoud & Fezari, 2018). NodeMCU enables wireless connection using an ESP32 based WiFi module. It is an open source software and development tool that can be used to create Internet of Things (IoT) products (Wicaksono, 2017; Dewi et al., 2022; Dahoud & Fezari, 2018).

Based on the description above, a set of activities for the implementation of a bifocal modeling framework allows students to easily communicate macroscopic and microscopic physics quantities as well as gain valuable knowledge and skills from the perspective of the kinetic theory of gases, available important. Therefore, a teaching tool will be developed based on the bifocal model for teaching the subject of the kinetic theory of gases. The aim of this study is to obtain the first set of teaching tools implemented in the bifocal model system of the microcontroller ESP32 that helps for the teaching of the subject on the kinetic process of gases.

Method

This research used descriptive method through literature review. Literature review is a structured, clear and repeatable process for conducting research, analysis and synthesis of the results of studies conducted by researchers (Creswell, 2017). It seeks to analyze and integrate existing knowledge on a subject to identify opportunities for further study. The steps of literature review include selecting topics, collecting and selecting relevant topics, comparisons, analyzing and organizing literature, and organizing research findings (Ulhaq et al., 2020).

This research is conducted by interviewing students and physics teachers to better understand the implementation of physics lessons for gas theory. These interviews are also conducted to reveal other problems that may occur to students and teachers due to the kinetic teaching of gas education (Marton & Pong, 2017). Based on the literature review process, this research continued by choosing research topics, namely Kinetic Theory of Gas Properties, Concepts and Learning, Bifocal Modeling Framework, and ESP32. In addition, physics books published in high schools are also analyzed to get an explanation of the concept of the kinetic process of gas (Walsh et al., 2019). The important articles were then selected based on the concept of gas kinetic system, bifocal imaging system and ESP32. After that, all relevant articles and primary literature were discussed and the results of this research were used and organized to create a tool that was implemented in the ESP32 microcontroller bifocal modeling system that helps in gas kinetic education. Experts or those who do it, including experts or experts in physics and ICT education, carefully calculate the plan (Docktor & Mestre, 2014; Walsh et al., 2019; Williams, 2018).

Results and Discussion

Characteristics of Kinetic Theory of Gases Concepts

Interviews with physics teachers and 11th and 12th grade students in a high school in Bandung revealed that physics subjects related to the process of gas have never been taught. According to the teachers, there are no internships that work to study the kinetic theory of gases for some reasons, including the weakness of the physics internship equipment and the short time spent to achieve the purpose of the study. This discussion with students shows that it is difficult for students to solve mathematical problems because of the kinetic process of gases. They cannot fully understand the physical phenomena involved in the gas production process. Among other physics chapters, understanding the concept of kinetic theory of gases can be considered as the worst.

The number of articles searched in Harzing's Publish and Purish using the keyword "kinetic theory of gases" is about 2,080,000 articles and papers selected by the criteria "from the last fifteen years (2008 - 2023)". Physics is based on the Indonesian curriculum (commonly known as Kurikulum 2013). The analysis of the articles and the parts of the literature focused on the distribution of materials, the general characteristics of materials, the presence of work instructions, the review of teaching instructions and the general type of work implemented. According to the Law of the Minister of Education and Culture 24/2016 on the basic skills and the main topics of the 2013 curriculum for the main and elementary schools, the topic of the kinetic theory of gases is taught in class 11. All chapters of the children's physics book Secondary education in Indonesia, which is controlled by the Minister of Education and Culture, presents the topic of the gas system in a chapter that has several chapters, that is, chapters that talk about it. concept of real gas, law of gas, real gas equation and quantitative relationship between physical quantities of gas, such as pressure, volume, temperature, kinetic energy, effective speed and internal energy.

Many of the chapters that cover the process of gas plants and physics textbooks used by Indonesian high school students and regulated by the Minister of Education and Culture did not serve as teaching instructions. However, there is one novel aimed at practical teaching, that is, teaching that deals with Boyle's law in which students can only see and analyze the macroscopic aspects of physical appearance and thoughts. In this case, the macroscopic phenomena of the kinetic theory of gases deal with physical measurements, such as pressure, temperature and volume of gases, which can be easily seen and measured using some examples. However, students can't see the things that are represented by macroscopic figures.

Learning physics from the kinetic theory of gases rarely affects the teaching process. However, efforts have been made to improve the quality of education through topics related to the biology of gas, including the production of educational materials for the biology of gas using more technology (Gusmida & Islami, 2017), developing electronic modules (Astra et al., 2020; Nurmayanti et al., 2015), inquiry-based computer simulation (Sujito, Liliasari, & Suhandi, 2021), and virtual laboratory (Sofi'ah, 2017). Kinetic theory of gases concepts are relatively mathematical, theoretical, and abstract. They deal with microscopic phenomena which cannot be directly observed by students. Hence, the conceptual understanding of senior high school students due to the kinetic theory was relatively low (Agustina et al., 2018). Moreover, based on a study dealing with level of understanding on kinetic theory of gases, it was revealed that most students have partial understanding and other students have partial understanding with a specific misconception (Nurhuda et al., 2017). Students are also difficult to make a scientific connection between what is microscopically happening to the gases' particles when the gases condition changes and what students macroscopically observe.

Bifocal Modeling Framework

The number of articles searched through Harzing's Publish and Purish by using keyword "bifocal modeling" was about 17.900 articles. The articles were chosen based on the criteria "the last fithteen years (2008–2024)" and its relevance to the framework of bifocal modeling experiment. Analysis of articles was focused on scheme of bifocal modeling activities, students' activities in a bifocal modeling learning, hardware and software potentially utilized for designing a bifocal modeling device/ tool. The following paragraph summarized the results of the analysis.

Bifocal modeling framework (BMF) is an inquiry-driven science learning approach which links student's physical experimentation with computer modeling in real time. The BMF challenges students to design, compare, and examine the relationships between physical experiments and computer or theoretical models. As part of BMF activities, students explore natural phenomena through physical experimentation, the design of computer models, and the comparison of the measured and simulated data gathered from these distinct empirical and virtual modalities (Sujito, Pratiwi, et al., 2021). Bifocal modeling approach involves students in investigating a natural phenomenon through synchronization of a real experiment and a digital computerized model. It requires students to design, compare, and test the data gathered from a real experiment and the data generated from computerized model (Blikstein, 2014; Fuhrmann et al., 2018; Sunardi et al., 2023).

Bifocal modeling learning is different from a learning by using a computerized model or simulation. It is because in the bifocal modeling learning, students have an opportunity involve in designing both the real experiment and computerized experiment. Moreover, in the bifocal modeling learning, students are able to "revise" a scientific model based on the results of their observation and comparison between the data gathered from the real experiment and the data generated from the computerized experiment. In a bifocal modeling practicum, students design and do a real physics experiment connected with a sensor system to a virtual model. Students then compared the data generated from the real experiment and the data from the virtual model (Fuhrmann et al., 2018). Generally, the bifocal modeling framework is shown in Figure 1.

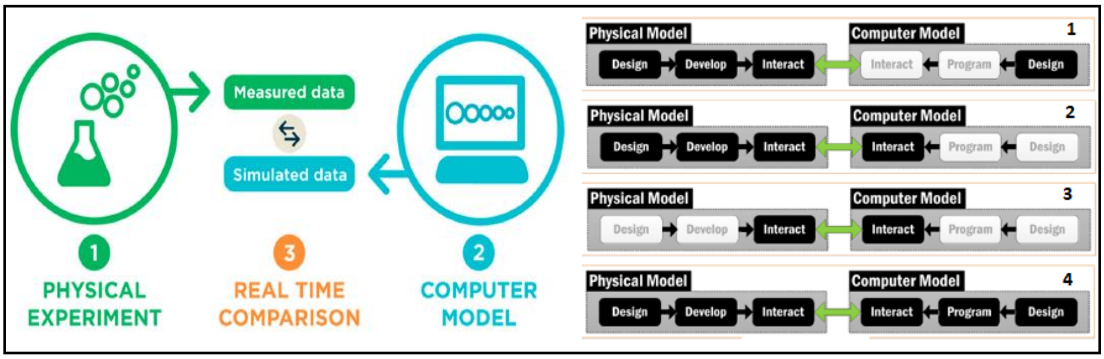

Figure 1. Bifocal modeling: (a) framework, (b) Variations

Bifocal modeling framework is not rigid but flexible and adaptable. It can be adjusted to the circumstances and the needs of learning contained in the lesson plans made by the teacher. Figure 6 shows the variation of bifocal modeling frameworks (Fuhrmann et al., 2018). The types of bifocal modeling frameworks are determined by a set of activities which can be done by students are involved in designing, developing, and doing real experiment.

ESP (Espressif Systems Platform)

The number of articles searched through Harzing's Publish and Purish by using keyword "ESP32" was about 22.300. The articles were chosen based on the criteria "the last fiteen years (2008 – 2023)" and its relevance to the sensor technology potentially used for developing a bifocal modeling device. Analysis of articles was focused on working principle of ESP32 in general, sensor modules, output devices (peripherals) potentially utilized for a bifocal modeling device based on the ESP32 working principle. The following paragraph summarized the results of the analysis. Internet of Things (IoT) is a big platform, by which everyday devices are transformed into informative automated system (Patel & Devaki, 2019). It allows connection among devices using internet with ability to gather and exchange data. These devices are usually connected with microcontrollers like Arduino, sensors, actuators, and internet connectivity (Kashyap et al., 2018). One of the best ways to develop IoT devices with fewer integrated circuits is to choose ESP32. ESP32 is an open source firmware and development kit that plays an important role in designing proper IoT products using a few lines of scripts lines (Dahoud & Fezari, 2018). ESP32 is a microcontroller developed by Espressif Systems as a successor to the ESP8266 microcontroller. The difference is, the ESP32 is equipped with a Wi-Fi module on the chip, making it possible to develop IoT application systems effectively. In addition, the ESP32 has pins that can function as input or output to control various devices such as LCD screens, lights, and DC motors (Sujito et al., 2020).

The advantage of the ESP32 compared to other devices is that it is equipped with a dual-core processor which makes it possible to run several tasks simultaneously, increasing system performance and responsiveness; equipped with WiFi and Bluetooth which makes it possible to communicate with other devices via a wireless network; more input/output (I/O) ports to connect more sensors, actuators, and external devices; larger memory capacity makes it possible to run more complex programs and store more data; low power consumption so it is suitable for applications that require energy efficiency; equipped with various additional features such as DAC (Digital to Analog Converter), ADC (Analog to Digital Converter), SPI (Serial Peripheral Interface), and I2C (Inter-Integrated Circuit) (Chakraborty & Aithal, 2023). These advantages make ESP32 a popular and attractive choice for developing electronics-based learning laboratory tools. These applications require wireless connectivity or higher performance offered using sensors. The main parts of the ESP32 device mainly consist of hardware and software components. Following are some of the main parts of the ESP32 device ESP microcontroller, processor, memory (several types of memory to store programs, data and configuration, RAM (Random Access Memory), EEPROM (Electrically Erasable Programmable Read-Only Memory)), WiFi and Bluetooth, Input/output (I/O) port, Connectors and Interfaces, and Software .

A node ESP32 board consist of multiple GPIO (general purpose input/ output) pins that allow us to connect the board with other peripherals and are capable of generating PWM (pulse-width modulation), I2C (inter integrated circuit), SPI (serial peripheral interface), and UART (universal asynchronous receiver-transmitter) communications (Muchlis et al., 2018; Dahoud & Fezari, 2018). The physical form of the ESP32 is shown in Figure 2.

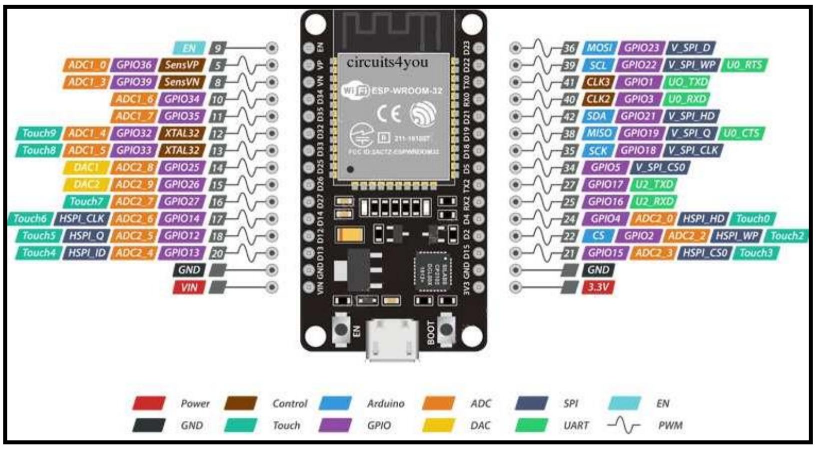

Figure 2. The board of ESP32

ESP32 is potentially used as the sensor-based device in developing a bifocal modeling-based tool. It is because, ESP32 is programmable by C++ language by using Arduino IDE (Efendi & Chandra, 2019; Muchlis et al., 2018; Wicaksono, 2017). Hence, it can be connected to a physical experiment, from which the values of physical quantities are able to be simulated and the physical phenomena due to the experiment can be visualized on output peripherals, such as computer and smartphone screens.

Discussions

Early study results showed that students' understanding of the kinetic theory of gases ranged only by 15%. This suggests that teachers have not yet had the right method of teaching the kinetical theory of gases accurately. It's a joint challenge to prepare students for the challenges of the 21st century. Life in the 21st century epitomizes the fusion of advanced technology and scientific knowledge across multiple domains, marking the era as the information age. In this epoch, addressing human needs revolves around a global network of information, emphasizing the significance of 21st-century skills essential for navigating education and the workforce. These skills encompass critical thinking, problem-solving, communication, and digital literacy among others, pivotal for active citizenship and professional efficacy. Consequently, contemporary education must equip students with these competencies to ensure their success in life, work, and societal engagement (Sujito, Liliasari, Suhandi, et al., 2021a). Physics, as a fundamental discipline, assumes a crucial role in this educational paradigm, imbuing students with scientific fundamentals, methods, and attitudes essential for 21st-century life. The Indonesian government, recognizing the importance of integrating science into education, emphasizes observational, investigative, and communicative skills in students (Aji et al., 2018). Experimental methods are emerging as a powerful avenue for physics education, providing experiential learning opportunities in which students engage with scientific principles, methodology, and equipment. Through experiment, students not only deepen their understanding of physics but also cultivate practical skills and advanced thinking vital for thriving in the contemporary landscape (Mumba et al., 2023).

The topics in the kinetic theory of gases are theoretical, mathematical, and physical. They deal with both macroscopic physical quantities, such as pressure, volume and temperature, and microscopic physical quantities, such as the kinetic energy and velocity of gas molecules. The kinetic theory of gases is best learned through lectures without giving students the opportunity to observe physical phenomena in the laboratory. As a result, students will face difficulties in understanding the concept of kinetic theory of gas (Sunardi et al., 2022). In addition, it is difficult for students to compare macroscopic and microscopic physical figures. ICT can be used to create physics teaching tools, in which students can see invisible objects, interact with computers, find scientific models, compare experiments with computer data and, in the end, students able to create a critical concept of the scientific type (Grapin et al., 2023; Pratiwi et al., 2019).

Based on the results of aforementioned analyses, a practicum tool for facilitating kinetic theory of gases learning is needed. The tool should be developed in such a way so it can facilitate students to conduct a scientific experiment and enable students to easily understand concepts due to kinetic theory of gases. Moreover, the tool should enable students to do a set of activities, by which students can scientifically connect macroscopic physics variables of gases such as pressure, temperature, and volume to microscopic physics variables such as kinetic energy and effective speed of gases' particles, so the conceptual understanding and the conceptual understanding level of students can be improved (Sujito, Liliasari, Suhandi, et al., 2021b).

Adopting bifocal modeling framework which utilizes sensor-based low-cost microcontroller (ESP32), an initial design of bifocal modeling-based practicum tool aided by ESP32 for kinetic theory of gases topics, has been developed. The tool design is depicted in Figure 3. This design has been consulted with validators, consisting of physics learning experts and ICT experts. All physics learning validators recommended that the design can be continued to the creation step. However, they made a note that safety aspects of the tool should be considered. All physics learning validators gave score 4 (Agree) in Likert's scale dealing with the statements "Bifocal modeling-based practicum tool aided by ESP32 based on the design can be an alternative solution for overcoming problems of kinetic theory of gases learning, developing scientific and practical skills, scientific attitudes, dan ICT literacy". Like the physics learning experts, the ICT experts also recommended that the tool design can be potentially continued to the creation step

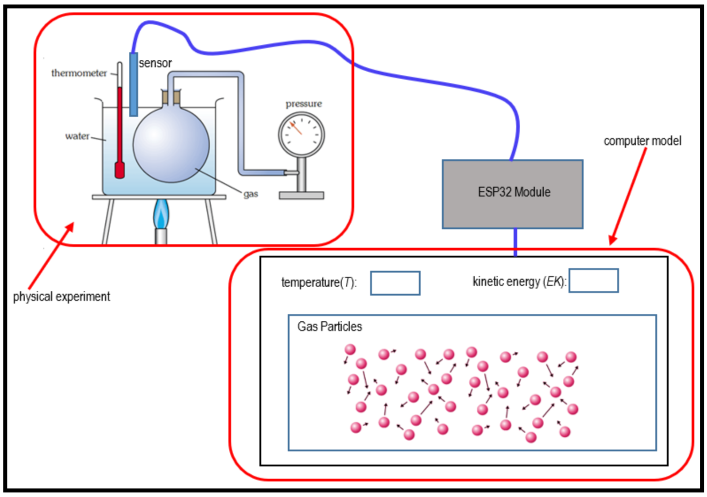

Figure 3. Design of bifocal modeling tool aided by ESP32 for kinetic theory of gases practicum.

Generally, a bifocal modeling-based practicum tool for kinetic theory of gases learning as depicted in Figure 3 consists of three main parts, i.e. real experiment devices, ESP32 module, and computer model devices. Real experiment devices enable students to observe macroscopic physics phenomena. When the water in the beaker glass is warmed up, the temperature of both water and gas in the flask rises. This temperature is measured by the thermometer. The volume of the gas in the flask is constant, so the change in temperature of the gas will increase the pressure of the gas. This value of gas pressure can be observed by students by pressure gauge. In this case, the real experiment devices are utilized for facilitating students to identify the relationship of macroscopic physics quantities of gases, i.e. temperature (T), pressure (P), and volume (V). These three physics quantities can be easily measured by students.

The ESP32 module as in Figure 3 is a microcontroller that can be directly programmed and functions to control input data (water temperature) obtained from a temperature sensor placed in the water. In this case the water temperature is the same as the gas temperature because the water and gas are considered to be in a state of thermal equilibrium. This temperature data can be processed as input for simulating gas particles and kinetic energy which will be displayed by computer modeling tools. Based on temperature data (T), the kinetic energy of gas particles (EK) can also be simulated digitally using the equation EK = 3/2 kT, where k is Boltzmann's constant = 1.38 × 10-23 J/K. This data can also be used to visualize the condition of gas particles, namely the higher the temperature of the gas, the faster the motion of the gas particles and the greater the distance between the particles.

Computer model devices can be laptops, personal computers (PCs) and even Android smartphones (Sujito, Liliasari, Suhandi, et al., 2021a). The ESP32 can be easily connected to computers and laptops using a USB cable or WiFi connection and even smartphones using a WiFi connection (Muchlis et al., 2018; Dewi et al., 2022). Computer modeling tools allow students to observe microscopic physical phenomena (the behavior of gas particles) when the temperature changes and also allow students to identify the relationship between macroscopic and microscopic physical quantities, namely between temperature and kinetic energy of gases. Therefore, students have the potential to increase their level of conceptual understanding through the kinetic theory of gases.

Conclusion

The development of a bifocal model-based learning device for the kinetic theory of gases developed in this study can be continued. The device can help students experiment with the kinetic theory of gases to see the macroscopic physics of gases when the gas conditions change in an experimental device. Students can collect accurate data from real devices and see small physical phenomena related to gases. The display on the monitor screen using computer-assisted software helps students collect simulation and computational data. Actual and simulated data can be used simultaneously so that students can understand what happens microscopically in gases represented by macroscopic quantities. Thus, students' conceptual understanding of the kinetic process of gases can be improved. Further researchers can develop bifocal modeling practicums for other physics materials.

Conclusion

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