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DEVELOPMENT OF STUDENTS' SKILLS IN MASTERING COMPLEX THERMOPHYSICAL CONCEPTS

The features of skill formation aimed at improving the mastering of thermophysical concepts in the process of studying combined heat transfer with the environment under conditions of free natural convection are considered. Difficulties encountered by students in understanding many provisions of the thermodynamic method for solving technical problems and their practical application have been identified. It has been established that during the experiment, students undergo a restructuring of purposeful and systematically organized actions, which contributes to the development of skills for mastering complex thermophysical concepts. Based on the problem-solving methodology, it is shown that the mastering of complex thermophysical concepts is associated with the forms of information representation. It has been established that the visual representation of experimental data significantly influences the development of skills for mastering thermophysical concepts in the study of various modes of heat transfer, such as thermal conduction, convection, and thermal radiation. At the same time, it is shown that the assimilation of information embedded in the visual representation of thermophysical concepts is related to the representative competencies of the student's personality. It has been established that, during practical classes, particularly in laboratory work, the mastering of complex thermophysical concepts is effectively implemented through collaborative discussion of the obtained results in groups of two or three students. Using the example of studying combined heat transfer within the discipline "Applied Thermophysics", the skills of information assimilation in the process of oral discussion of observed visual relationships are examined, which may improve students' subsequent learning.

Keywords: skills, acquisition of knowledge, thermophysical concepts, problem-solving methodology, visual representation of information, development.

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Студенттердің күрделі жылуфизикалық ұғымдарды меңгеру дағдыларын дамыту

Еркін табиғи конвекция жағдайында қоршаған ортамен біріктірілген жылуалмасуды оқу процесінде жылуфизикалық ұғымдарды меңгеруді жақсартуға арналған дағдыларды қалыптастыру ерекшеліктері қарастырылды. Техникалық сипаттағы есептерді шешуге арналған термодинамикалық әдістің көптеген қағидаларын түсіну және оларды тәжірибеде қолдану барысында студенттердің қиындықтары анықталды. Экспериментті орындау кезінде студенттің мақсатты түрде ұйымдастырылған іс-әрекеттерінің қайта құрылуы жүретіні, бұл өз кезегінде күрделі жылуфизикалық ұғымдарды меңгеру дағдыларының дамуына әкелетіні анықталды. Мәселелерді шешу әдіснамасы негізінде күрделі жылуфизикалық ұғымдарды меңгеру ақпаратты ұсыну формаларымен байланысты екені көрсетілді. Эксперименттік деректерді визуалды түрде ұсыну жылу өткізгіштік, конвекция және жылулық сәулелену сияқты әртүрлі жылу тасымалдау тәсілдерін оқып-үйрену барысында жылуфизикалық ұғымдарды меңгеру дағдыларының дамуына елеулі әсер ететіні анықталды. Сонымен қатар, жылуфизикалық ұғымдардың визуалды ұсынылуында қамтылған ақпаратты меңгеру студент тұлғасының репрезентативтік құзыреттіліктерімен байланысты екені көрсетілді. Практикалық сабақтарда, әсіресе, зертханалық жұмыстарды орындау кезінде, күрделі жылуфизикалық ұғымдарды меңгеру екі немесе үш адамнан тұратын топтарда алынған нәтижелерді бірлесіп талқылау арқылы тиімді жүзеге асатыны анықталды. «Қолданбалы жылуфизика» пәнін оқу барысында қарастырылатын біріктірілген жылуалмасуды зерттеу мысалында студенттердің кейінгі оқуын жақсартуға ықпал ететін, бақыланатын визуалды тәуелділіктерді ауызша талқылау процесіндегі ақпаратты меңгеру дағдылары қарастырылды.

Түйін сөздер: дағдылар, меңгеру, жылуфизикалық ұғымдар, мәселелерді шешу әдіснамасы, ақпаратты визуалды ұсыну, даму.

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Развитие у студентов навыков усвоения сложных теплофизических понятий

Рассмотрены особенности формирования навыков для улучшения усвоения теплофизических понятий в процессе изучения комбинированного теплообмена с окружающей средой в условиях свободной естественной конвекции. Выявлены затруднения студентов в понимании многих положений термодинамического метода для решения задач технического характера и их практического применения. Установлено, что в ходе выполнения эксперимента, у студента происходит перестройка действий, целенаправленных и определенным образом организованных, которая приводит к развитию навыков усвоения сложных теплофизических понятий. На основе методологии решения проблем показано, что усвоение сложных теплофизических понятий связано с формами представления информации. Установлено, что визуальное представление экспериментальных данных существенно влияет на развитие навыков усвоения теплофизических понятий при изучении различных способов переноса тепла, как теплопроводность, конвекция и тепловое излучение. При этом показано, что усвоение информации, заложенной в визуальном представлении теплофизических понятий, связано с репрезентативными компетентностями личности студента. Установлено что, на практических занятиях, в частности при выполнении лабораторных работ, усвоение сложных теплофизических понятий эффективно реализуется при совместном обсуждении полученных результатов в группах по два или три человека. На примере изучения комбинированного теплообмена, рассматриваемого при изучении дисциплины «Прикладная теплофизика», рассмотрены навыки усвоения информации в процессе устного обсуждения наблюдаемых визуальных зависимостей, которые могут улучшить последующее обучение студентов.

Ключевые слова: навыки, усвоение, теплофизические понятия, методология решения проблем, визуальное представление информации, развитие.

Introduction

Undergraduate students in Technical Physics often encounter difficulties when studying thermophysical disciplines that are based on the fundamental concepts of thermodynamics. This field of science is closely associated with practical challenges related to the design and operation of modern thermal engineering and power-generation equipment, the investigation of the thermophysical properties of substances, and the development of reliable methods for the calculation and analysis of thermal systems and devices [1–3]. Therefore, students must acquire the skills necessary to apply the thermodynamic approach when studying the laws governing processes occurring in thermal power installations, the properties of working fluids and heat-transfer media, as well as certain physical and mathematical models of heat and mass transfer in thermal engineering and thermal technological systems. In addition, they should become familiar with current technological advances in thermal power engineering and heat engineering. The complexity of this learning process arises from the fact that heat and mass transfer phenomena occurring within the working space of engineering devices take place simultaneously and are closely interconnected [4–6].

This study examines, using the course "Applied Thermophysics" as an example, information presentation skills that facilitate students' understanding and assimilation of abstract and complex thermophysical concepts during laboratory work.

Research Methods

The most comprehensive understanding of the physical characteristics of the phenomena under investigation is achieved through the independent performance of scientific experiments during laboratory practice. Participation in experimental work not only helps students deepen and consolidate the theoretical knowledge they have acquired, but also enables them to develop essential skills in operating laboratory equipment and measurement instruments, processing experimental data, analyzing experimental results, and drawing appropriate conclusions. Thus, during the execution of an experiment, students should undergo a restructuring of actions previously formed through repetition. This process is purposeful, systematically organized, and characterized by a high degree of mastery of the material. As a result, methods of action become reinforced and transformed into stable practical skills [7,8].

This paper examines the development of skills aimed at improving students' understanding of thermophysical concepts during the study of combined heat transfer with the environment under conditions of free natural convection. Laboratory experiments were carried out using modern automated educational laboratory equipment within a collaborative learning environment, in which individual activity occupies a clearly defined role. As one of the key components of professional competencies, a system of skills ensures an individual's readiness for practical work in new conditions, as well as the capacity for self-development. Therefore, the organization of individual work during the performance of measurement and computational tasks is designed to engage students in situations that closely resemble their future professional activities.

Many researchers have highlighted the difficulties associated with understanding fundamental thermodynamic processes, such as heat transfer, in which thermal energy is transported through space and time by conduction, convection, and radiation. Students experience particular difficulties in understanding the concepts of thermal equilibrium and the nature of steady-state thermal conditions [9–12]. According to the authors of [13–15], the abstract nature of thermodynamic processes is one of the main reasons for students' difficulties in comprehending thermodynamic concepts such as equilibrium, non-equilibrium, steady-state, and convective processes. These difficulties are often related to insufficient prior knowledge of thermodynamics and to misconceptions, for example, regarding the relationship between the rate of heat transfer and the amount of energy transported by convection. Students frequently transfer everyday (colloquial) interpretations of thermodynamic concepts into the scientific context, leading to incorrect interpretations of their mathematical foundations and an inability to apply these concepts at the microscopic level. Although students must understand concepts such as heat and temperature, thermal equilibrium, heat transfer, and mechanisms of energy transport in order to successfully master the core topics of thermodynamics, traditional teaching methods often fail to identify and address the underlying causes of students' misconceptions. These misconceptions hinder their ability to understand and effectively apply thermodynamic concepts [16–18].

We have also observed that many aspects of the thermodynamic approach to solving engineering problems and its practical applications present difficulties for students in understanding the fundamental principles of the theory [8,19,20]. Many years of experience in teaching engineering disciplines have shown that students often find it challenging to analyze the system of differential equations describing convective heat transfer processes. Therefore, before students perform laboratory work, it is necessary to provide them, through explanation and demonstration of the forthcoming procedures, with a clear understanding that the flow regime of a fluid plays a crucial role in heat transfer processes, since it determines the mechanism of heat transport. Consequently, students must recognize that the intensity of heat transfer in the operation of various heat-exchange systems is governed both by the hydrodynamic conditions of fluid flow and by the thermophysical properties of the fluid. In this way, conditions are gradually created for students to understand the mathematical description of the heat transfer process as an integrated system consisting of the heat conduction equation, the equation of motion, the continuity equation, and the heat transfer equation together with the corresponding boundary and initial conditions. These elements should be perceived as parts of a unified whole, whose various aspects are interconnected and mutually dependent.

Due to the limited possibilities for obtaining analytical solutions to the differential equations governing convective heat transfer, experimental investigation becomes particularly important [7,21]. Modern automated educational laboratory equipment, such as the "Laboratory Setup for Investigating Combined Heat Transfer from a Horizontal Tube to the Surrounding Environment under Free Convection Conditions", manufactured by "Measlab" (www.measlab.ru), enables students to study convective heat transfer and to measure the parameters of the process under consideration. In the present experiment, the primary measured parameters are temperature and time. During the experiment, these parameters are measured automatically, while the experimental process is simultaneously monitored and controlled. Performing laboratory work using this setup requires the registration and processing of a substantial amount of information concerning the temperature distribution over the surface of horizontal tubes made of different materials under natural convection conditions. The system provides real-time acquisition and display of data from sensors (thermocouples), as well as real-time presentation of control information on a computer screen. In addition, it offers visual representations of manually specified numerical parameter values. All experimental data can be recorded, stored, and processed on a computer at any time.

By observing the visual representation of experimental data displayed on the computer, students can monitor the onset of the transient regime through changes in the temperature of the investigated surfaces. In doing so, they learn that the flow regime of the heat-transfer medium (air) plays a crucial role in heat transfer processes, as it determines the mechanism of heat transport. This understanding of the heat transfer mechanism is essential for students' comprehension of the various modes of heat transfer, including conduction, convection, and thermal radiation.

While examining the characteristic stages of temperature variation from the beginning of tube heating, students observe that the temperature initially remains unchanged for a certain period and then begins to change gradually. Since methods for calculating convective heat transfer are based on Newton's law for steady-state heat flow, it is necessary to determine the time required for the experimental setup to reach a steady-state operating condition. Visual representations of the data can be regarded as a means of enabling students to observe the corresponding process and develop meaningful interpretations of the mathematical description of heat transfer. Moreover, in this context, visual representations serve as a tool for thinking and reasoning about heat-transfer problems and about methods for calculating convective heat transfer based on boundary-layer theory. To help students acquire the skills necessary for assimilating the information obtained—in this case, analyzing the observed heat-transfer regimes—the learning process should support their engagement in explicit analytical activities that contribute to the construction of coherent verbal explanations of the observed phenomena.

Research results

In heat engineering experiments, it is often necessary to work with a large amount of experimental data, which are subsequently used either to calculate specific quantities or to construct graphs. Consequently, supporting students' information representation skills can significantly influence their understanding and assimilation of abstract and complex thermophysical concepts.

Our scientific-methodological and pedagogical research is conducted on the basis of the problem-solving methodology [22–24].

Therefore, before the experiment begins, students are introduced to the specific features of the process under investigation. For example, they should understand which thermophysical properties and thermodynamic parameters need to be measured, what methods and instruments will be used, how long the measurement process will take, for what purposes the measurements are being conducted, and under what conditions they will be performed. The next step is to determine the actual initial situation before starting the experiment. To solve the problem correctly and successfully, it is necessary to understand the characteristics of the measured process and its expected results, including the temperature measurement range, the choice of measurement mode, accuracy requirements, measurement duration, heating power consumption, thermocouple placement, and other relevant parameters. In addition, attention should be paid to possible software malfunctions and other issues that may arise during the measurement process. It is also important to identify all possible causes of convection, since natural convection processes are widely encountered in many areas of modern engineering and technology. Observations of the heat-transfer process further confirm its complexity. For engineering calculations, the primary quantity of interest is the heat transfer coefficient, which students are required to determine through their calculations. The calculated heat transfer coefficient is a combined coefficient because heat is transferred from the tube surface not only by natural convection but also by thermal radiation. In this way, information is transformed from one representation (or conceptual framework) to another, facilitating a deeper understanding of the heat-transfer process. Mastering the complex phenomenon of heat transfer involves multiple transformations of information, enabling students to progress from an initial vague and undifferentiated understanding toward an increasingly clear, precise, and differentiated comprehension. This process also promotes the development of skills necessary for understanding abstract heat-transfer concepts. Thus, students independently analyze various features of heat transfer and identify the most significant among them, particularly the temperature field. Having identified the problems that need to be solved, they must then determine possible solution methods and select the most appropriate approach. Based on this analysis, a plan of further actions can be formulated for implementing and investigating the chosen heat-transfer regimes.

In the present study, this includes selecting a time interval sufficient for the experimental setup to reach a steady-state condition, when the temperature stabilizes at a certain level, identifying the characteristic stages of the non-stationary process associated with tube heating (the initial stage, the regular regime, and the final stage), establishing the heating regimes, and determining the procedure for conducting the experiment.

The development of computational skills and the ability to analyze heat-transfer processes requires a close integration of spatial, temporal, and quantitative representations. The formation of a strong connection among these three types of representations depends on the interaction of data obtained from calculations and graphical visualizations. Therefore, experimental data should be systematically organized in the form of tables and graphs. The process of constructing tables involves a detailed quantitative analysis of changes in surface temperature over time, as well as the synthesis of the resulting experimental data. Such analysis promotes the understanding of functional relationships that are subsequently represented graphically, where abstract characteristics of thermal processes are visualized through spatial representations. Thus, the experimental studies described above allow us to conclude that visual representations of experimental data have a significant impact on students' understanding of thermophysical concepts, including temperature-change regimes at surfaces (non-stationary, steady-state, and regular regimes), natural convection, forced convection, heat transfer, the heat-transfer coefficient, the heat-transfer medium, and related concepts.

During the learning process, information assimilation skills become evident when students explain the results of their measurements, identify the establishment of a steady-state thermal regime, and use these data to calculate the heat-transfer coefficient [21]. At the initial stage of the measurements, students often have only a vague understanding of how to determine the onset of a steady-state thermal regime. Therefore, the visual representation of temperature variations over time, unfolding through a sequence of distinct stages, helps them develop a clear understanding of the complex heat-transfer process.

As a result of this activity, students develop practical subject-specific skills that enable them to master the corresponding system of competencies and acquire knowledge of how to perform particular tasks and procedures. These competencies and skills, in turn, facilitate a more effective understanding and assimilation of new learning material.

At the same time, students are required to carry out preliminary work that includes the following components:

a) some initial theoretical understanding of the physical reality of heat exchange being studied, expressed as a brief introduction to the theory of the issue;

b) an experimental procedure outlined in the form of a general plan;

c a description of the requirements for conducting the investigation, including both the research procedure itself and the organization of the work;

d) a description of the experimental setup and the necessary measuring instruments;

e) a description of the primary processing and presentation of the experimental data.

It should be emphasized that each stage of observation, orientation, execution, and motivation places specific demands on the corresponding personal qualities of the student.

In summary, the processes of information acquisition, storage (memory), and repeated processing (transformation), as well as decision-making and the implementation of decisions in practical learning activities, are inherently linked to personal characteristics and to the development of students' representational competence. As a result, students become capable of taking initiative and engaging in active learning, while the skills and abilities they acquire prepare them to solve assigned tasks independently and play a significant role in their subsequent learning, particularly when applying knowledge in new situations. Over time, specific skills are developed that can be interpreted both as outcomes of the learning process and as indicators of the degree to which learning objectives have been achieved.

Practical classes increasingly demonstrate a trend toward active learning, in which students engage in collaborative activities that foster a closer exchange of ideas, perspectives, and interests among students and instructors, as well as among members of the student group. Within such an interactive environment, students actively formulate, discuss, and refine their judgments. According to our observations, processes of self-monitoring develop more rapidly among all participants in the discussion, and those aspects of the material that none of the participants can accurately reproduce become more clearly recognized. The search for correct or forgotten definitions and procedures, together with self-assessment during practical activities, proceeds more intensively and promotes the development of creative skills. Such a combination of collective effort and its outcomes leads to a fundamental rethinking not only of many traditional approaches to teaching methodology but also of broader conceptions regarding the structure of disciplinary knowledge, its sources, and its purpose. Therefore, each additional step taken in preparing students in this direction appears particularly important and timely.

The effectiveness of collaborative learning in such educational environments depends on the improvement of information assimilation skills and perceptual fluency in the following ways. During collaborative learning, when two or three students perform the same task, cooperation often requires verbal discussion of the observed measurements. In the course of these discussions, students express their ideas and critically evaluate different viewpoints regarding the observed graphical dependence displayed on the computer screen, that is, the visualization. In this case, information assimilation skills (in particular, the mental rotation of the represented object) enable students to explain how visual cues represent information relevant to the task under consideration.

On the other hand, collaborative activity often requires high perceptual fluency. The ability to quickly extract information based on visual cues can improve subject discourse [25,26].

It should be noted that providing support and managing cognitive load during laboratory work is based on the preliminary study of the theoretical material related to the topic and on mastering, that is, assimilating, thermophysical concepts. At the same time, the process of assimilating these concepts takes place under conditions of student interaction, since the laboratory work was performed jointly by two or three students. In such collaborative and dynamic activity, knowledge is corrected, supplemented, refined, discussed, and debated, while inaccuracies are identified. Such communication during the experiment has a significant influence on the process of assimilating thermophysical concepts.

The effectiveness of collaborative activity during practical work often requires students to assimilate the observed visual relationships through verbal discussion, during which they express their thoughts and critically evaluate the various viewpoints of the participants. Information assimilation skills are also manifested when students explain experimental results and translate, or transform, spatiotemporal patterns into differential equations.

Thus, our studies show that supporting the development of information representation skills can potentially improve subsequent student learning using new visual means.

Conclusions

The studies conducted have shown that mental rotation skills play an important role in teaching students using visualization. Analysis of the research results shows that collaborative learning may be more effective for students, helping them to make sense of visualizations together with their classmates.

The procedure for obtaining measurement information is cognitive in nature; in this process, previously perceived information about modes of activity and accumulated individual experience are actively reproduced and recalled: the ability to compare an unknown quantity with a known one, the use of physical instruments, the ability and skills to systematize the results of observations, to present them in tabular and graphical forms, and so on. At the same time, the processing of experimental observations constantly requires the incorporation of newly acquired knowledge into the procedures of measurement and theoretical calculations. In these activities, the knowledge, abilities, and skills assimilated by the student are transformed and become a means for constructing other new knowledge (i.e., knowledge that is new only for the student) and for expanding the scope of its application.

Considering the prevalence of visualizations in modern education and the shift toward more collaborative formats of active learning, the research conducted has broad application not only in the assimilation of complex thermophysical concepts by students.

Author Contributions

M.S. Moldabekova: Conceptualization, Methodology, Formal Analysis; **O.V. Fedorenko**: Methodology, Resources, Writing-Original Draft. **M.K. Asembaeva**: Methodology, Writing & Editing.

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