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Exploring university students' misconceptions of the kinetic molecular theory of gases: A study from Kazakhstan

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Abstract

This study investigates university students' conceptual understanding and misconceptions about the kinetic molecular theory of gases (KMTG) in Kazakhstan. A sample of 223 students from two universities was assessed using the KMTG concept inventory. The sample consisted of 54.3% females and 45.7% males, with participants primarily in their first year of study (64.1%) and aged 17-18 (79.8%). The findings reveal significant misconceptions of molecular motion, gas pressure, entropy, and temperature changes in thermodynamic systems. For instance, 81.2% of students demonstrated incorrect conceptions about entropy, while 80.3% misunderstood temperature behavior during adiabatic processes. Statistically significant differences were observed in performance based on university affiliation and grade level, with Abai Kazakh National Pedagogical University students and first-year students outperforming second-year students. However, no significant gender-based differences were identified. This research points out the persistence of misconceptions in molecular and thermodynamic physics, indicating the need for localized and interactive instructional strategies. These findings contribute to the growing body of literature on physics education in Central Asia, providing recommendations for curriculum development and teacher training in the region.

Keywords: concept inventory, kinetic molecular theory of gases, misconceptions in physics, physics education in Kazakhstan

INTRODUCTION

Understanding foundational physics concepts is a cornerstone of scientific education, essential for equipping students with critical thinking and problem-solving skills applicable across disciplines. However, due to its abstract and mathematically intensive nature, students often grapple with misconceptions that hinder their ability to integrate this knowledge effectively (Erceg et al., 2016; Mulford & Robinson, 2002). These include misconceptions related to gas pressure, temperature, and molecular collisions, which have been observed across diverse student populations (Hestenes et al., 1992; Lin & Cheng, 2000). While misconceptions in physics have been widely researched globally, including in molecular and thermodynamic physics (e.g., Clement, 1982; Hestenes et al., 1992), there is limited localized research focusing specifically on Kazakhstani students. Recent works in the broader Central Asian context, such as those by Japashov et al. (2024) and Ospanbekov et al. (2024), have primarily addressed misconceptions in other areas of physics education, leaving the conceptual understanding of kinetic molecular theory of gases (KMTG) largely unexamined. Conceptual understanding refers to the ability to grasp and apply scientific principles accurately, integrating them into a cohesive mental framework. Misconceptions, on the other hand, represent deeply ingrained, often intuitive

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Contribution to the literature

- This study fills a gap in the literature by identifying misconceptions about the Kinetic Molecular Theory of Gases among university students in Kazakhstan, a context previously underexplored in physics education research.
- The study shows how cultural and institutional factors influence conceptual understanding, offering localized understandings that can inform curriculum development and teaching strategies.
- The findings contribute to global discussions on physics education by indicating the importance of context-specific interventions to address persistent misconceptions.

but incorrect beliefs that conflict with scientific explanations. Furthermore, studies like those by Nurhuda et al. (2017) indicates the importance of cultural and educational contexts in shaping misconceptions, pointing to the need for more research in Kazakhstan.

This study is significant because it addresses the unique educational context of Kazakhstan, a country undergoing extensive educational reforms aimed at aligning with global standards while preserving local cultural and educational values (Zhumabay et al., 2024). These reforms focus on inquiry-based learning and international collaborations to enhance science education (Yakavets et al., 2023). However, misconceptions about the KMTG among Kazakhstani students remain underexplored, limiting our understanding of how localized factors affect conceptual learning. Findings from this research extend beyond Kazakhstan, offering models for adapting science education in other countries undergoing similar reforms or with diverse educational needs. For instance, studies have shown that addressing culturally influenced misconceptions can improve conceptual understanding globally, as seen in Treagust et al.'s (2010) cross-national research on particle theory misconceptions. By bridging the gap between global best practices and regional challenges, this study contributes to the improvement of science education within Kazakhstan and internationally.

Research Questions

1. What is the level of conceptual understanding of the KMTG among university students in Kazakhstan?
2. How does students' performance differ on KMTG concept inventory across gender, intuition and grade level
3. What are the most common misconceptions related to KMTG in this student cohort?

LITERATURE REVIEW

Misconceptions in Physics Education

Addressing misconceptions in physics education is a critical component of global efforts to enhance scientific literacy and improve learning outcomes. Research indicates that students often enter physics classrooms with deeply ingrained misconceptions, typically stemming from common intuition and everyday experiences. These misconceptions present significant challenges for educators, as students are often resistant to information that conflicts with their preconceptions. By identifying and addressing these misconceptions, educators can align with international educational standards and contribute to the global advancement of physics education (Clement, 1982; Posner et al., 1982).

Misconceptions in physics education have long been recognized as significant barriers to effective learning. Students often arrive in the classroom with deeply ingrained intuitive beliefs derived from everyday experiences, which can conflict with scientifically accurate concepts. These misconceptions, if not addressed, can persist and hinder the development of a robust understanding of physics (Clement, 1982). For example, in the context of thermodynamics, misconceptions often arise around topics such as the relationship between pressure and volume, temperature changes in gases, and molecular behavior under varying conditions (Erceg et al., 2016).

Misconceptions in physics arise when students' intuitive beliefs or prior experiences conflict with scientific principles. These intuitive understandings, often termed "alternative conceptions" or "preconceptions," are formed from everyday observations that may lead to incorrect generalizations (Clement, 1982). For example, students may believe that heavier objects fall faster than lighter ones, a misconception rooted in everyday experiences but inconsistent with Newtonian physics. Such misconceptions are not merely knowledge gaps; they represent deeply held beliefs that are resistant to change through traditional instructional methods (Vosniadou, 1994).

Misconceptions in Molecular Physics

Understanding molecular physics, particularly the kinetic molecular theory (KMT), is foundational to comprehending concepts such as thermodynamics and energy transfer. However, numerous studies have documented persistent misconceptions among students, which hinder their ability to grasp and apply these principles effectively.

A common area of confusion involves the differentiation between heat and temperature. Studies indicate that students often view heat as a substance that flows between objects rather than as a transfer of energy due to a temperature difference (Harrison et al., 1999). This misunderstanding leads to challenges in applying concepts such as thermal equilibrium and adiabatic processes. Research by Jasien and Oberem (2002) revealed that both college students and K-12 teachers struggle with elementary concepts in thermodynamics, such as the relationship between heat, temperature, and internal energy.

Students also face difficulties in understanding the fundamental laws of thermodynamics. Kautz et al. (2005) documented significant challenges among students in relating to the macroscopic and microscopic perspectives of the ideal gas law. These difficulties often manifest in an inability to connect molecular-level behaviors with observable gas properties such as pressure and volume. Kesidou and Duit (1993) examined students' understanding of the second law of thermodynamics, finding that many students struggle with the concept of entropy and its implications for energy transfer. Similarly, Christensen et al. (2009) explored how students conceptualize entropy and the second law, revealing that these difficulties persist even in advanced physics courses.

The analysis of student understanding across different educational contexts has been a focal point of recent research. Nurhuda et al. (2017) examined students' levels of understanding using diagnostic assessments and found that misconceptions such as equating heat with molecular motion and misunderstanding gas pressure were prevalent. Robertson and Shaffer (2013) investigated university students' and K-12 teachers' reasoning about the volume of an ideal gas. Their findings indicated that even advanced learners often struggle with fundamental principles of KMT, such as the relationship between molecular collisions and gas pressure.

Treagust et al. (2010) conducted a cross-national study to evaluate students' understanding of kinetic particle theory concepts related to states of matter, changes of state, and diffusion. They observed consistent misconceptions across different cultural and educational contexts, underscoring the universality of challenges in teaching KMT. Additionally, Sanchez (2021) explored students' understanding of KMT through three modes of representation: symbolic, macroscopic, and submicroscopic. The study revealed that integrating multiple representations in teaching can significantly enhance students' ability to transition between conceptual levels, thereby improving their overall comprehension.

Impacts on Learning

Misconceptions in physics can significantly impede students' learning by creating cognitive barriers that prevent them from integrating new, scientifically accurate knowledge. Research shows that students often rely on intuitive reasoning, which may conflict with the abstract and mathematical nature of physics concepts, leading to fragmented understanding (Cai Shi & Lucietto, (2022; Clement, 1982; Vosniadou, 1994).

For example, misconceptions about the behavior of gases–such as equating pressure solely to molecular collisions–can hinder students' ability to comprehend more advanced topics like entropy and thermodynamic equilibrium (Lin & Cheng, 2000). Such misconceptions also affect students' problem-solving abilities, as their reliance on incorrect mental models can lead to systematic errors in reasoning (Admiraal et al., 2020; Chiou & Anderson, 2010). Moreover, persistent misconceptions can negatively impact students' confidence and interest in physics. Students may feel frustrated when their intuitive explanations conflict with classroom instruction, resulting in disengagement and lower achievement (Balta & Eryilmaz, 2017). This highlights the importance of addressing misconceptions not only to improve conceptual understanding but also to support students' motivation and self-efficacy in physics learning (Mazur, 1997; Pittayapiboolpong & Yasri, 2018; Zhumabay et al., 2024).

The presence of misconceptions also has broader implications for physics education. If misconceptions are not identified and corrected, students may carry these erroneous beliefs into advanced studies or real-world applications, ultimately affecting their ability to apply physics principles effectively. As such, addressing misconceptions is not merely a pedagogical challenge but a critical component of fostering deep, transferable learning.

The persistence of misconceptions has prompted researchers to propose frameworks for facilitating conceptual change (Durocher & Potvin, 2020). Posner et al.'s (1982) model of conceptual change emphasizes the need for students to experience dissatisfaction with their current understanding before they can accept a new, scientifically accurate conception. This process involves four key conditions:

1. The new concept must be intelligible–understood by the learner.
2. It must be plausible–consistent with the learner's existing knowledge.
3. It must be fruitful–offer explanatory power for real-world phenomena.
4. The learner must recognize inadequacies in their current understanding.

Relevance to Physics Education in Central Asia

In regions like Central Asia, where research on misconceptions is sparse, applying tools like KMTG concept inventory is particularly important. Limited localized studies mean that misconceptions among Kazakhstani students remain underexplored, necessitating research to adapt global findings to the regional context.

One significant area of focus has been the use of diagnostic tools to assess students' understanding of fundamental physics concepts. For instance, Aldazharova et al. (2024) evaluated artificial intelligence's (AI) problem-solving capabilities in physics using the force concept inventory (FCI). Their findings highlighted discrepancies in AI's reasoning patterns, revealing both strengths and limitations in diagnosing students' conceptual difficulties. This study indicates the potential of advanced tools to complement traditional teaching methods in the region. Similarly, Japashov et al. (2024) analyzed the structure of Kazakhstani university students' knowledge about the force concept through a three-tier FCI survey. Their work identified prevalent misconceptions and revealed the layered nature of students' conceptual understanding.

Addressing Misconceptions in Physics Education

The persistence of misconceptions is a major challenge in physics education. Research shows that traditional lecture-based teaching methods are often insufficient to address these misconceptions because they fail to actively engage students in confronting and resolving conflicts between their intuitive beliefs and scientific concepts (Hestenes et al., 1992). Even after instruction, many students retain their misconceptions, suggesting that more interactive and inquiry-based approaches are necessary to improve meaningful conceptual change.

Effective strategies for addressing misconceptions involve creating opportunities for conceptual change, as outlined by Posner et al. (1982). According to this model, students are more likely to accommodate scientifically accurate concepts if they perceive their current understanding as inadequate and the new concept as plausible, intelligible, and fruitful. Techniques such as inquiry-based learning, the use of real-world analogies, and active engagement with discrepant events have been shown to encourage conceptual change (Clement, 1982; Hestenes et al., 1992).

Interactive teaching methods such as peer instruction and group problem-solving encourage students to confront and revise their misconceptions collaboratively (Mazur, 1997). Simulations and animations, such as those illustrating molecular behavior in gases, help students visualize abstract concepts and correct misconceptions (Lin & Cheng, 2000). Activities that involve experimentation and hypothesis testing enable students to experience the limitations of their misconceptions firsthand (Trumper, 2021). Studies by Japashov et al. (2024) have demonstrated that peer discussion can effectively reduce students' mistakes in conceptual physics questions, particularly when paired with strategic teacher guidance. However, research by Ospanbekov et al. (2024) identified challenges in using peer instruction to confront counterintuitive physics questions, highlighting their limitations and the need for supplemental strategies to address persistent misconceptions.

In the context of thermodynamics, strategies such as using visualizations of molecular behavior and simulations of gas laws have demonstrated effectiveness in helping students correct misconceptions and deepen their understanding (Lin & Cheng, 2000; Mulford & Robinson, 2002). Misconceptions often stem from incomplete instruction and everyday experiences that conflict with scientific explanations. Beall (1994) highlighted the effectiveness of in-class writing exercises to probe and address such misconceptions, emphasizing the need for active engagement.

Addressing misconceptions requires targeted interventions and diagnostic tools. Concept inventories, such as those for thermodynamics, have proven effective in identifying specific areas where students lack understanding (Prince et al., 2012). For example, McDermott and Shaffer (2010) developed research-based tutorials to improve understanding of heat engines and the Carnot cycle, which successfully reduced misconceptions among undergraduate students.

Dynamic and interactive learning strategies also show promise. Barbera and Wieman (2009) demonstrated the impact of dynamic tutorials on students' comprehension of heat and the first law of thermodynamics. Their research emphasizes the value of real-time feedback and visualization in correcting students' erroneous mental models.

The language used in teaching thermodynamics can significantly influence students' understanding. Kraus and Vokos (2011) argued that inconsistent terminology, such as "heat energy," often exacerbates misconceptions. They recommended a focus on precise and consistent language to help students develop clearer mental models. Additionally, Cotignola et al. (2002) noted that some difficulties in learning thermodynamic concepts may be linked to the historical development of the field itself. They suggest that instructional strategies need to carefully scaffold these ideas to align better with students' cognitive development.

Stern et al. (2008) demonstrated that computerized simulations can effectively improve middle school students' understanding of KMT. Their study revealed that simulations provide dynamic visual representations of molecular motion, enabling students to connect theoretical concepts with observable phenomena. Similarly, Yaumi et al. (2020) highlighted the benefits of modeling instruction in improving students' conceptual grasp of the kinetic theory of gases. The study emphasized that constructing and interacting with models helps learners internalize abstract concepts and overcome misconceptions.

Collaborative and interactive methods have also shown promise in improving KMT understanding. Govender et al. (2016) used CmapTools® to facilitate preservice teachers' collaborative learning of gases and KMT. Through this approach, students engaged in constructing concept maps, which helped clarify connections between different KMT principles. Waner (2010) advocated the use of particulate pictures to illustrate KMT concepts, demonstrating that visual aids and collaborative discussions can deepen conceptual understanding.

METHODS

Research Approach and Design

A quantitative descriptive approach was chosen for its ability to systematically measure and analyze patterns in students' responses, presenting an in-depth understanding of widespread misconceptions without manipulating variables (Creswell & Creswell, 2018). The cross-sectional survey design, which collects data from participants at a single point in time, was selected for its efficiency in describing phenomena and examining differences across groups, such as grade levels and university affiliations (Cohen et al., 2018). The KMTG concept inventory served as the sole instrument, as it is specifically designed to diagnose misconceptions in molecular physics, with items that include distractors based on common misconceptions (Erceg et al., 2016). Administered online via a Google Form, the inventory ensured accessibility and standardization, minimizing logistical challenges and providing a large dataset for analysis.

Participants

The sample consists of 223 university students from two institutions: the Abai Kazakh National Pedagogical University (KNPU) and South Kazakhstan Pedagogical University named after Ozbekali Zhanibekov (OKPU). Of these participants, 121 (54.3%) are female, and 102 (45.7%) are male, indicating a slight gender imbalance with females being the majority. Participants' ages range from 16 to 23 years. The largest age group is 17-18 years, comprising 178 students (79.8%), reflecting the typical entry age for university education. A smaller proportion of students, aged 21-23 years, constitutes 6.7% of the sample, with the remaining participants under or above these age ranges. The majority of students, 143 (64.1%), are in their first year, while 79 (35.4%) are second-year students, showing a clear dominance of younger students in the sample. In terms of university representation, 152 participants (68.2%) are from KNPU, while 71 (31.8%) are from OKPU, indicating a stronger involvement from KNPU in the study.

Instrument and Its Translation to Kazakh

The KMTG concept inventory was designed to measure students' conceptual understanding of gas behavior at the molecular level (Erceg et al., 2016). The development process began with a thorough review of the literature on thermodynamics and gas behavior and analysis of introductory physics curricula at the university level. This phase helped to define the construct to be measured and the behaviors associated with varying levels of understanding.

The initial version of the inventory consisted of open-ended questions designed to assess students' conceptual frameworks. These questions were piloted through think-aloud sessions with university students, which were audio-recorded and transcribed for analysis. The findings from these sessions helped identify common misconceptions and refine the questions. The revised inventory was transformed into a multiple-choice format, with distractors rooted in the misconceptions revealed during the think-aloud sessions. The final instrument contained 22 questions covering topics such as gas structure, intermolecular interactions, pressure, and kinetic energy.

Each item in the inventory comprises one correct answer and several distractors, which are scientifically plausible but incorrect statements reflecting common misconceptions. For example:

Question: Gas molecules are in constant motion. Which of the following best describes their motion in an ideal gas?

A. Molecules move in a circular path due to intermolecular forces.
B. Molecules move in a straight-line path between collisions (correct answer).
C. Molecules remain stationary until acted upon by an external force.
D. Molecules move randomly but follow a repeating pattern.

Purpose: This item evaluates whether students understand the fundamental assumption of molecular motion in an ideal gas, addressing misconceptions such as deterministic or stationary motion.

The psychometric properties of the inventory were thoroughly evaluated to ensure its validity and reliability. It was administered to 250 students across different university curricula, providing a large and diverse dataset for analysis. Reliability was assessed using Cronbach's alpha, which yielded a moderate value

Table 1. Descriptive statistics for the KMTG concept inventory

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Key	C	C	A	B	A	B	A	B	A	A	D	E	B	A	B	D	A	D	B	D	A	C
A	80	60	46	10	184	67	34	9	188	187	11	75	56	45	10	179	65	33	8	181	180	10
B	5	14	60	27	7	85	39	129	6	4	13	4	13	56	26	7	84	36	124	6	4	12
C	86	80	62	12	7	28	68	45	3	9	85	84	78	61	12	6	25	66	43	3	9	82
D	86	80	62	12	7	28	68	45	3	9	85	84	78	61	12	6	25	66	43	3	9	82
E	29	13	6	2	2	3	15	11	0	0	8	29	13	5	2	2	3	14	11	0	0	8

of 0.6. While this value indicates room for improvement, it reflects an acceptable level of internal consistency for an instrument of this nature (Taber, 2018). Content validity was established through expert reviews, where physics educators rated the relevance of each item, achieving 92% agreement. Additionally, item discrimination and difficulty indices were analyzed to evaluate how well each question differentiated between high- and low-performing students. Questions with low discrimination or difficulty values were revised or removed.

Despite some psychometric limitations, the inventory proved effective in diagnosing common misconceptions and providing actionable insights for teaching and learning improvements. The development and validation process ensured that the KMTG concept inventory is a reliable and valuable tool for assessing students' understanding of the KMT and for identifying areas of conceptual difficulty.

The KMTG concept inventory was translated into Kazakh to ensure accessibility and comprehension for participants in the study, all of whom were native Kazakh speakers. The translation process followed a systematic approach to maintain the validity and reliability of the instrument while addressing cultural and linguistic nuances. First, the original English version of the KMTG concept inventory was translated into Kazakh by the first two authors. Particular attention was given to ensuring that technical terms and scientific concepts were accurately rendered in Kazakh to avoid introducing new ambiguities or misconceptions. Next, the translated version underwent a check by two bilingual experts. Depending on their feedback minor revisions were made. To further validate the translation, the Kazakh version of the inventory was piloted with three university students. These participants were asked to complete the inventory and provide feedback on the clarity and comprehensibility of the questions. Based on their input, minor revisions were made to improve readability and align with local linguistic conventions. Finally, the finalized Kazakh version of the inventory was reviewed by two physics instructors to ensure that it accurately reflected the original content while being culturally and contextually appropriate for Kazakhstani students.

Data Collection

After the translation process, all questions from the KMTG concept inventory were transferred to a Google Form to facilitate administration and data collection. The inventory was administered during scheduled physics class hours at both universities. Students accessed the Google Form using their laptops or smartphones, ensuring convenience and accessibility. A total of 45 minutes was allocated for students to complete the 22-item inventory, which was deemed sufficient based on preliminary trials. This standardized approach to data collection ensured consistency across both institutions, minimizing external variables that could influence the responses. The collected data was stored securely within the Google Forms platform, ensuring privacy and facilitating subsequent analysis.

Data Analyses

To examine differences between groups, non-parametric statistical tests were employed due to the ordinal nature of the data and potential violations of normality. Mann-Whitney U tests were used to compare mean ranks between gender groups, university affiliations, and grade levels. Effect sizes were calculated using rank-biserial correlation to quantify the magnitude of observed differences, where values closer to 1 or -1 indicate stronger relationships. Misconceptions were grouped into themes corresponding to the item categories. Distractors considered indicative of misconceptions (Treagust, 1988; Wilson, 2023). Distractors that drew the attention of more than 25% of the students were recognized as misconceptions.

RESULTS

Table 1 contains frequency data for each choice (A, B, C, D, and E) of 22 items. The frequencies highlighted in yellow represent the correct answers for each item, while distractors that attracted more than 25% of the students are marked in green.

Among the 22 items, the highest-performing items are 9, 10, and 5, while the lowest-performing ones are 13, 16, and 20, based on the frequency of correct responses. Specifically, item 9 (relationship between pressure and volume) had 188 correct responses, item 10 (relationship between temperature and kinetic energy) had 187, and item 5 (ideal gas law and its application) had 184, reflecting a consistent level of mastery in these areas.

Table 2. Mann-Whitney U test and descriptives for gender differences

Group descriptives						Mann-Whitney U test		
Sum						Score		
Group	N	Mean	Median	Standard deviation	Standard error	Statistic	p	Effect size
Female	121	11.08	10.00	3.99	0.36	5,744.00	0.371	0.07
Male	102	11.17	11.00	4.20	0.42			

Table 3. Mann-Whitney U test and descriptives for the type of university differences

Group descriptives						Mann-Whitney U test		
Score						Score		
Group	N	Mean	Median	Standard deviation	Standard error	Statistic	p	Effect size
KNPU	152	12.06	11.00	4.24	0.34	3,341.50	<.001	-0.38
OKPU	71	9.11	10.00	2.82	0.33			

Table 4. Mann-Whitney U test and descriptives for grade level differences

Group descriptives						Mann-Whitney U test		
Score						Sum		
Group	N	Mean	Median	Standard deviation	Standard error	Statistic	p	Effect size
Grade 1	144	12.20	11.00	4.31	0.36	3,360.00	<.001	-0.41
Grade 2	79	9.15	10.00	2.68	0.30			

On the other hand, item 13 (entropy changes during thermodynamic processes) had only 13 correct responses, while item 16 (adiabatic compression and temperature changes) had just 6, and item 20 (energy distribution after gas expansion) had an extremely low number of 3 correct responses.

A Mann-Whitney U test was used to reveal gender performances on KMTG concept inventory (**Table 2**).

The analysis of gender differences in the KMTG concept inventory scores reveals no statistically significant difference between male and female students. The Mann-Whitney U test yielded a U value of 5,744.00 with a p-value of 0.371, indicating that the null hypothesis (there is no statistically significant difference in the performance on the KMTG concept inventory between male and female students.) cannot be rejected. The effect size, as measured by rank biserial correlation, was 0.07, suggesting a very small practical difference between the two groups. Descriptive statistics show that the mean scores for female and male students were nearly identical, at 11.08 and 11.17, respectively. The median scores were also comparable, with females scoring 10.00 and males 11.00.

A Mann-Whitney U test was conducted to compare the performances of students from two different universities on the KMTG concept inventory (**Table 3**).

The comparison of scores between students from two universities (null hypothesis: There is no statistically significant difference in the performance on the KMTG concept inventory between students from the two universities), KNPU and OKPU, reveals a statistically significant difference in performance. The Mann-Whitney U test produced a U value of 3,341.50 with a p-value of < .001, indicating that the difference between the two groups is highly significant. The effect size, measured by rank biserial correlation, was -0.38, suggesting a moderate negative relationship between university affiliation and scores, with OKPU students scoring lower than KNPU students. Descriptive statistics further highlight this difference. The mean score for KNPU students was 12.06, compared to 9.11 for OKPU students. The median scores were 11.00 for KNPU and 10.00 for OKPU confirming the overall trend.

A Mann-Whitney U test was conducted to compare the performances of students from first and second grade levels on the KMTG concept inventory (**Table 4**).

The comparison of scores across grade levels (null hypothesis: There is no statistically significant difference in the performance on the KMTG concept inventory between grade 1 and grade 2 students) reveals a statistically significant difference between the two groups. The Mann-Whitney U test yielded a U value of 3,360.00 with a p-value of < .001, indicating a significant difference in performance between students in grade 1 and grade 2. The rank biserial correlation was -0.41, signifying a moderate negative effect size, where students in grade 2 scored lower than those in grade 1. Descriptive statistics further illustrate this disparity. The mean score for grade 1 students was 12.20, while grade 2 students had a mean score of 9.15. The median scores were 11.00 for grade 1 and 10.00 for grade 2, showing a clear difference in central tendency between the two groups.

Reliability

The Kuder-Richardson formula 20 (KR-20) for our dataset is approximately 0.81. This indicates good internal consistency reliability for the test, as KR-20 values closer to 1 signify higher reliability. Ferguson's delta (Δ) was calculated approximately as 0.91. This indicates a high level of discriminatory power, meaning

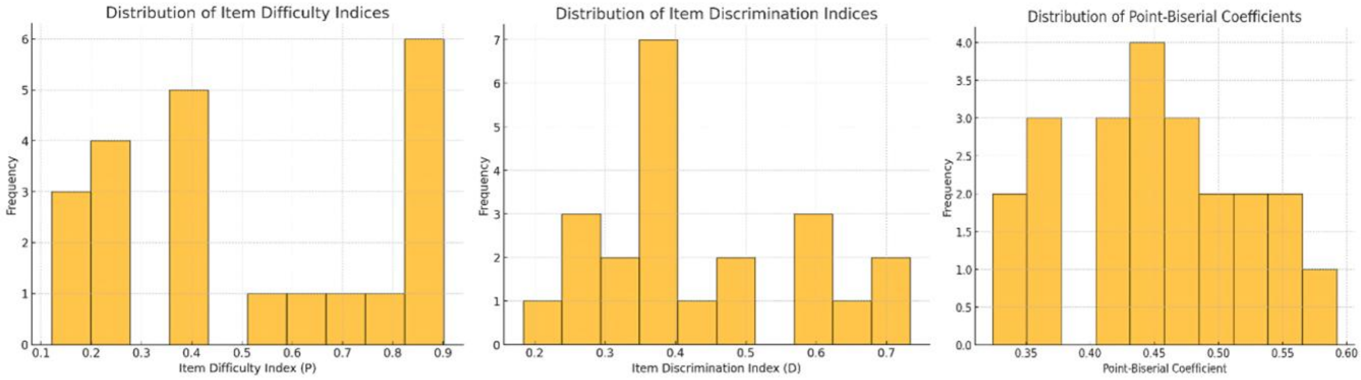
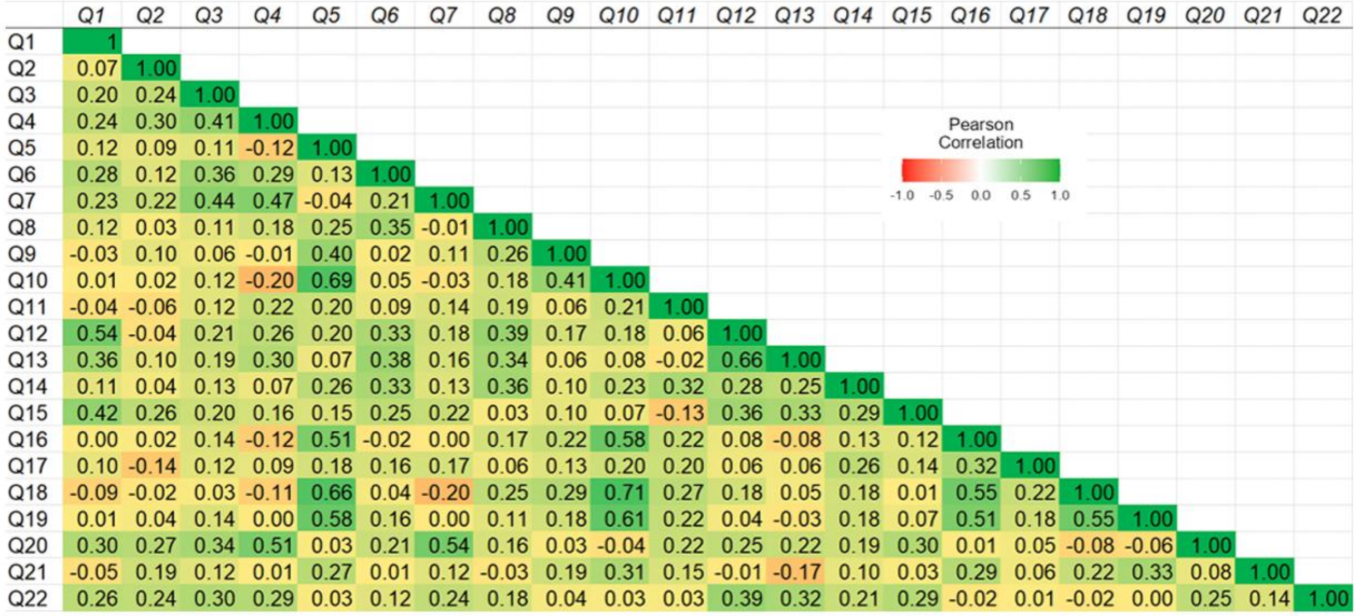


Figure 1. Distributions of item difficulty, item discrimination, and point-biserial coefficients (Source: Authors' own elaboration)



	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22
Q1	1																					
Q2	0.07	1.00																				
Q3	0.20	0.24	1.00																			
Q4	0.24	0.30	0.41	1.00																		
Q5	0.12	0.09	0.11	-0.12	1.00																	
Q6	0.28	0.12	0.36	0.29	0.13	1.00																
Q7	0.23	0.22	0.44	0.47	-0.04	0.21	1.00															
Q8	0.12	0.03	0.11	0.18	0.25	0.35	-0.01	1.00														
Q9	-0.03	0.10	0.06	-0.01	0.40	0.02	0.11	0.26	1.00													
Q10	0.01	0.02	0.12	-0.20	0.69	0.05	-0.03	0.18	0.41	1.00												
Q11	-0.04	-0.06	0.12	0.22	0.20	0.09	0.14	0.19	0.06	0.21	1.00											
Q12	0.54	-0.04	0.21	0.26	0.20	0.33	0.18	0.39	0.17	0.18	0.06	1.00										
Q13	0.36	0.10	0.19	0.30	0.07	0.38	0.16	0.34	0.06	0.08	-0.02	0.66	1.00									
Q14	0.11	0.04	0.13	0.07	0.26	0.33	0.13	0.36	0.10	0.23	0.32	0.28	0.25	1.00								
Q15	0.42	0.26	0.20	0.16	0.15	0.25	0.22	0.03	0.10	0.07	-0.13	0.36	0.33	0.29	1.00							
Q16	0.00	0.02	0.14	-0.12	0.51	-0.02	0.00	0.17	0.22	0.58	0.22	0.08	-0.08	0.13	0.12	1.00						
Q17	0.10	-0.14	0.12	0.09	0.18	0.16	0.17	0.06	0.13	0.20	0.20	0.06	0.06	0.26	0.14	0.32	1.00					
Q18	-0.09	-0.02	0.03	-0.11	0.66	0.04	-0.20	0.25	0.29	0.71	0.27	0.18	0.05	0.18	0.01	0.55	0.22	1.00				
Q19	0.01	0.04	0.14	0.00	0.58	0.16	0.00	0.11	0.18	0.61	0.22	0.04	-0.03	0.18	0.07	0.51	0.18	0.55	1.00			
Q20	0.30	0.27	0.34	0.51	0.03	0.21	0.54	0.16	0.03	-0.04	0.22	0.25	0.22	0.19	0.30	0.01	0.05	-0.08	-0.06	1.00		
Q21	-0.05	0.19	0.12	0.01	0.27	0.01	0.12	-0.03	0.19	0.31	0.15	-0.01	-0.17	0.10	0.03	0.29	0.06	0.22	0.33	0.08	1.00	
Q22	0.26	0.24	0.30	0.29	0.03	0.12	0.24	0.18	0.04	0.03	0.03	0.39	0.32	0.21	0.29	-0.02	0.01	-0.02	0.00	0.25	0.14	1.00

Figure 2. The correlation matrix for the 22-item KMTG concept inventory (Source: Authors' own elaboration)

the test effectively differentiates between examinees based on their abilities. Moreover, the average item difficulty index, the average item discrimination index, and the average point biserial coefficient were found to be 0.51, 0.43, and 0.45, respectively. The distribution of these indexes is provided in **Figure 1**.

The correlation matrix for the 22-item KMTG concept inventory was constructed to reflect patterns that can be linked to the content and structure of the questions (**Figure 2**).

Strong positive correlations (e.g., Q10 and Q18 with 0.71, or Q5 and Q18 with 0.66) suggest that these questions are likely to measure similar constructs or skills. Conversely, negative correlations, such as Q7 and Q18 (-0.20), indicate issues like misalignment with the test's objectives, conceptual opposition, or misconceptions among respondents. Weak or near-zero correlations, as seen in pairs like Q7 and Q16 (0.00), imply that these questions are likely targeting distinct topics or constructs.

KMTG Misconceptions

This study organizes the misconceptions identified from our sample into specific categories, similar to the approach taken by Erceg et al. (2016). These categories include the structure of gas, volume, pressure, intermolecular potential energy, kinetic energy, temperature, velocity, thermal internal energy, and entropy. Students' performance on items 4, 5, 8, 9, 10, 15, 19, and 21 were good (see **Table 1**) which resulted in a minor number of students having misconceptions in these items. That is why they are not included in the following results.

Structure of a gas

Misconceptions regarding the structure of gases were prevalent. In item 1, 35.9% of students incorrectly believed that, unlike a gas, the volumes of the particles for an ideal gas are negligible, which causes the particles not to collide with each other, while 38.6% believed there was no difference between the structure and interactions of an ideal gas and a real gas. In item 2, 26.9% of students incorrectly assumed that gas molecules move in a straight-line path due to thermal motion, while 35.9% believed gas molecules follow a patterned motion resembling Brownian motion. Similarly, in item 6, 36.8% of students misunderstood the random distribution of gas molecules in thermal motion, incorrectly believing that the molecules are distributed unequally or follow an ordered arrangement.

Gas volume

Misconceptions about gas volume were evident in question 7, where 30.5% of students misunderstood molecular spacing and believed gas molecules appear evenly spaced but much closer together than in the original arrangement, forming a denser structure. Another 30.5% believed that the spacing between molecules is larger and that they are not tightly packed.

Gas pressure

In item 14, 27.4% of students believed that gas pressure is higher in a container due to the smaller average intermolecular distance, while another 27.4% incorrectly attributed higher pressure to more massive molecules causing greater changes in momentum upon collision with the container walls.

Intermolecular potential energy

Students struggled with understanding intermolecular potential energy. In item 3, 26.9% of students incorrectly believed that the potential energy decreases due to increased molecular attraction, 27.8% misinterpreted the position of the average intermolecular distance as being beyond the energy minimum, and another 27.8% believed the intermolecular potential energy increases beyond the energy minimum due to repelling forces. In item 11, 38.1% of students misunderstood how smaller intermolecular distances increase potential energy due to repulsion forces.

Average kinetic energy per molecule of a gas and the total kinetic energy of gas molecules

In item 18, 29.6% of students incorrectly believed that the average kinetic energy per molecule would be higher in a smaller volume container due to more frequent collisions, ignoring the relationship between temperature and kinetic energy. Similarly, in item 22, 36.8% of students misunderstood the relationship between thermal expansion and kinetic energy, incorrectly believing that as gas expands into a vacuum, the kinetic energy increases due to changes in particle motion, overlooking the fact that average kinetic energy remains constant in a thermally insulated system.

Gas temperature

Misconceptions regarding temperature were evident in question 16, where 80.3% of students misunderstood that temperature remains constant during the compression of a thermally insulated system, neglecting the connection between work done on a gas and changes in internal energy.

Average velocity of gas molecules

In question 13, 35.0% of students failed to understand that molecules in a container with larger molecular mass would have a smaller velocity, while another 35.0% believed molecular velocity depends on the mass of molecules being lighter, leading to slower movement.

Thermal internal energy of a gas

Misconceptions about thermal internal energy were prevalent in item 12, where 37.7% of students misunderstood how molecular arrangements contribute to internal energy. Another 37.7% misinterpreted the relationship between kinetic energy and potential energy in determining internal energy. In item 17, 37.7% of students incorrectly believed the thermal internal energy of the gas is larger due to smaller potential energy differences between molecules.

Gas entropy

Entropy-related misconceptions were common. In question 20, 81.2% of students misunderstood the concept of entropy, believing it solely depends on particle arrangement rather than the disorder and number of accessible microstates in the system.

Items in which students indicated high performance

In items 4, 5, 8, 9, 10, 15, 19, and 21 students performed well. These items were about intermolecular forces, energy relationships, and thermodynamic principles. For instance, in items focusing on intermolecular potential energy (item 4 and item 8), relatively a minor proportion of students (27.8% in item 4 and 40.4% combined for distractors in item 8) misunderstood the relationship between potential energy, molecular distance, and repulsive forces. In items related to internal thermal energy and velocity distributions (items 9, 10, and 15), most students demonstrated a sound understanding (83.9% selected the correct answer in item 10, 84.3% in item 9). However, some students (11.7% in item 15) displayed minor confusion, especially regarding how molecular mass affects velocity and how internal energy is distributed in thermally insulated systems. For entropy and thermodynamic principles (item 19 and item 21), minor students struggled to grasp the concept of entropy as a measure of system disorder or microstates. Distractors in item 19 (38.6% combined) revealed misconceptions equating entropy changes solely with kinetic energy increases or collision frequencies. Similarly, in item 21, while 80.7% of students selected the correct answer, a small group (8.0%) misunderstood the conservation of energy under thermal insulation.

DISCUSSION

Discussion of Achievements on KMTG Concept Inventory

The findings indicate a statistically significant difference in the performance of students from KNPU and OKPU, with students from KNPU scoring higher on average. This disparity can be attributed to differences in educational quality, access to resources, and institutional focus. KNPU emphasizes in-depth theoretical knowledge, pedagogical training, and research engagement, supported by modern laboratories and access to international research facilities (KNPU, 2023). These factors likely contribute to the superior performance and scientific achievements of its students, including success in Olympiads and scientific projects (KNPU, 2024). In contrast, OKPU prioritizes solving regional applied physics problems, which, while valuable, may limit students' exposure to theoretical foundations and advanced research opportunities. Challenges such as limited laboratory facilities and material resources further exacerbate this gap. Additionally, in Kazakhstan, universities accept students based on their performance in a national exam, and those with higher scores often select KNPU due to its reputation for academic excellence and pedagogical expertise. This selection bias further amplifies the performance disparity, as KNPU attracts students who are already academically stronger.

The results reveal a statistically significant difference in performance between grade 1 and grade 2 students, with grade 1 students outperforming their peers in grade 2. The higher scores among grade 1 students can be attributed to the recency of their exposure to molecular physics, as they have recently studied the topic and are likely to retain key concepts. In contrast, grade 2 students, who studied molecular physics earlier, may have experienced knowledge decay due to a lack of reinforcement and application of these concepts over time. This finding aligns with the well-documented phenomenon of forgetting, where students' understanding diminishes without continued practice or integration of prior knowledge (Brown et al., 2014). Differences in the academic background and preparedness of grade 1 and grade 2 students when they entered university could also serve as an alternative explanation for the observed performance gap.

Our findings indicate that there is no statistically significant difference between male and female students in their performance on the KMTG concept inventory. This result contradicts the well-documented gender gap typically observed in physics achievement. However, it aligns with previous research which has often found minimal or no consistent differences in conceptual understanding when controlling external factors such as instructional methods and prior preparation (Dubrovskiy et al., 2022; Lorenzo et al., 2006).

The Comparison of Our Findings With That of Erceg et al. (2016)

In our study, many students believed gas molecules followed a patterned motion resembling Brownian motion (35.9%) or moved in a straight-line path due to thermal motion (26.9%). In the original study, Erceg et al. (2016) identified a related but distinct misconception: students often believed that molecules in an ideal gas do not collide because their volumes are negligible. While both studies point to a misunderstanding of molecular behavior, our study highlights errors in the nature of molecular motion, while Erceg et al.'s (2016) findings focus on collisions and structural assumptions.

Our study found that 30.5% of students incorrectly believed that gas molecules are evenly spaced and closer together after cooling, forming a denser structure. Another 30.5% thought the spacing between gas molecules increased significantly. The original study similarly identified misconceptions about gas volume. Students incorrectly believed that reduced kinetic energy led to a smaller gas volume or that intermolecular forces caused significant structural changes during cooling. Both studies highlight that students fail to understand the minimal impact of temperature changes on molecular spacing in gases.

In our study, 27.4% of students believed that higher gas pressure resulted from smaller intermolecular distances, while another 27.4% attributed higher pressure to greater molecular mass causing more significant momentum changes. Similarly, the original study found that students commonly believed gas pressure depended on molecular mass, misapplying the ideal gas law. Both studies show confusion in relating molecular motion and collisions to the macroscopic concept of pressure.

Our study revealed misconceptions about potential intermolecular energy. For example, 26.9% of students thought potential energy decreases with increased attraction between molecules, while 27.8% believed it increases due to repulsive forces. In Erceg et al.'s (2016) study, students similarly misunderstood the potential energy-distance relationship. They often transferred their knowledge of solid structures to gases, believing potential energy minimized at closer molecular distances, which is valid for solids but not for gases. Both studies emphasize difficulty in applying intermolecular energy concepts to different states of matter.

Our study found that 29.6% of students believed that average kinetic energy per molecule increased in a smaller volume container due to more frequent collisions, ignoring the dependence on temperature. Additionally, 36.8% of students misunderstood the relationship between thermal expansion and kinetic energy, believing kinetic energy increases as gas expands into a vacuum. Erceg et al. (2016) also noted widespread misconceptions in this area. Many students incorrectly believed that temperature directly correlates with the frequency of molecular collisions or the confinement of molecules. Both studies highlight confusion about the proportionality between kinetic energy and temperature and the independence of these quantities from other variables in certain scenarios.

Our study found that 80.3% of students misunderstood that temperature remains constant during the compression of a thermally insulated system, neglecting the role of work done on the gas. Erceg et al. (2016) similarly observed misconceptions about adiabatic processes, with students erroneously believing thermal insulation prevents any change in temperature or internal energy. Both studies show that students struggle with connecting macroscopic thermodynamic concepts to microscopic molecular behavior.

In our study, 35.0% of students failed to recognize that the velocity of heavier molecules is smaller, while another 35.0% believed molecular velocity depends on mass, assuming lighter molecules always move slower. The original study identified similar difficulties, noting that students often conflated molecular size with mass and velocity, assuming smaller molecules inherently move faster. Both studies highlight challenges in interpreting molecular velocity distributions.

In our study, 37.7% of students misunderstood how molecular arrangements contribute to internal energy. Many believed internal energy changes were solely due to kinetic energy or incorrectly linked internal energy to molecular mass. Similarly, Erceg et al. (2016) found that students failed to distinguish between heat and internal energy, often attributing changes in thermal energy to factors irrelevant to the context. Both studies emphasize the confusion surrounding internal energy as a combination of kinetic and potential energy.

In our study, 81.2% of students misunderstood entropy, believing it solely depends on particle arrangement, neglecting the concept of accessible microstates and disorder. Erceg et al. (2016) also identified this misconception, noting that students often equated entropy with order and disorder, failing to grasp its statistical nature. Both studies highlight the challenge of teaching abstract thermodynamic concepts like entropy.

Discussion Based on Literature

In our study, students frequently believed that gas molecules follow a patterned motion resembling Brownian motion (35.9%) or move in a straight-line path due to thermal motion (26.9%). This misconception aligns with observations by Meltzer (2005), who reported that students struggle to conceptualize random molecular motion, often conflating it with deterministic patterns. Similarly, Kautz et al. (2005) found that students often ignored the probabilistic nature of molecular motion and collisions, leading to erroneous interpretations. This aligns also with findings by Lin and Cheng (2000), who documented that students often misunderstand the random and continuous nature of molecular motion. Similarly, Mulford and Robinson (2002) noted that students frequently attribute deterministic behavior to molecular motion, which conflicts with the probabilistic principles of the KMT.

Our findings revealed that 30.5% of students believed molecules are evenly spaced and closer together after cooling, while another 30.5% thought the spacing between gas molecules increased significantly. This aligns with Robertson and Shaffer's (2013) findings that students struggle with understanding the relationship between temperature and molecular spacing. Students often view gas particles as resembling a liquid or solid in certain conditions, a misconception also noted by Treagust et al. (2010). Robertson and Shaffer (2014) observed a similar misconception, where students erroneously believed that the molecular arrangement of gases resembles liquids or solids upon cooling.

Our study showed that 27.4% of students attributed higher gas pressure to smaller intermolecular distances, while others incorrectly linked pressure to molecular mass. Kautz et al. (2005) similarly reported that students frequently misapplied the ideal gas law, focusing on incorrect variables like molecular mass rather than the number of collisions or temperature. Nurhuda et al. (2017) also documented similar misconceptions, particularly in associating gas pressure with the number and force of molecular collisions without considering molecular speed.

Our study found that students struggled with understanding intermolecular potential energy, with 26.9% incorrectly believing it decreases with increased attraction and 27.8% misinterpreting the relationship between potential energy and molecular distance. Similar findings were reported by Thomas and Schwenz (1998), who noted that students often conflated potential energy in gases with concepts more appropriate for solids or liquids, such as gravitational potential energy or bond energy.

In our study, 29.6% of students believed that average kinetic energy per molecule increased in smaller containers due to more frequent collisions, and 36.8% misunderstood how thermal expansion affects kinetic energy. Meltzer (2005) highlighted a similar issue, where students conflated the frequency of molecular collisions with temperature changes.

Our study found that 81.2% of students misunderstood entropy, believing it solely depends on particle arrangement rather than accessible microstates. This mirrors results from Christensen et al. (2009), who found that entropy is often reduced to a concept of order and disorder, neglecting its statistical underpinnings. Swendsen (2014) similarly noted that students have difficulty connecting entropy to the number of microstates and thermodynamic probability.

CONCLUSIONS

This study examined university students' understanding of the KMTG concept inventory in Kazakhstan, identifying critical aspects of their misconceptions. The findings demonstrate a persistent prevalence of misconceptions in areas such as molecular motion, gas pressure, intermolecular potential energy, and entropy. For example, a significant proportion of students held incorrect beliefs about entropy, thermodynamic processes, and the behavior of gas molecules, indicating challenges in reconciling everyday experiences with scientific concepts.

Performance differences between students from the two participating universities revealed the impact of institutional factors, such as educational quality and resource availability, on conceptual understanding. Students from KNPU achieved higher scores than their peers from OKPU, likely due to better access to pedagogical and research resources. Similarly, first-year students performed better than second-year students, indicating the effect of recently learned concepts.

Notably, no significant gender-based differences were found, contradicting the commonly reported gender gap in physics achievement. This finding is consistent with research that emphasizes the role of instructional quality and context over inherent gender disparities in conceptual understanding.

The study does not deeply explore contextual factors such as differences in teaching methods, resources, or curriculum design between the two universities, which could have influenced the results. Although the KMTG concept inventory was translated into Kazakh and validated for comprehension, potential nuances in translation might have influenced the students' interpretation of questions.

Future research could focus on implementing and evaluating specific instructional strategies, such as inquiry-based learning or peer instruction, to address identified misconceptions. Incorporating qualitative methods, such as interviews or focus groups, could provide a deeper understanding of the reasons behind students' misconceptions and their thought processes.

The study's findings have practical implications for physics education in Kazakhstan. Addressing misconceptions requires targeted interventions, including interactive teaching methods, diagnostic assessments, and contextually relevant instructional materials.

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