Evidence-Based Strategies for Teaching Thermodynamics

Research demonstrates that a structured 3-hour thermodynamics lesson combining digital simulations, hands-on experiments, and conceptual activities in specific time blocks achieves deep understanding while aligning with NSW Stage 6 syllabus requirements.

Abstract

A synthesis of recent studies shows that a 3-hour lesson in introductory thermodynamics can achieve deep conceptual understanding by combining active, multimodal approaches with cognitive science principles. Digital simulations, microcomputer-based laboratories, and hands-on experiments improve comprehension of energy transfer, transformation, and thermal equilibrium when paired with brief conceptual change activities and cooperative tasks. For example, interventions that include thinking frames demonstrate markedly higher gains (effect size up to 2.04) compared with conventional instruction. Strategies that integrate historical contexts and real-world applications also foster precise scientific literacy and numeracy. These findings support structuring the lesson into focused segments—such as 30 minutes on conceptual change, 45 minutes on interactive simulation, 45 minutes on a hands-on experiment, and 30 minutes on guided problem solving—to engage visual, analytical, and kinesthetic learning pathways and manage cognitive load in line with the NSW Stage 6 syllabus for Year 11 Physics.

Paper search

Using your research question "Identify and justify evidence-based pedagogical strategies grounded in cognitive science and active learning methodologies for effectively teaching introductory thermodynamics within a constrained 3-hour lesson sequence to Year 11 Physics students (ages 16-17), aligned to the NSW Stage 6 syllabus.

The proposed strategies must directly address the challenge of limited instructional time while ensuring deep conceptual understanding of key syllabus concepts, including energy transfer, transformation, and thermal equilibrium. Specifically, strategies should:

1. Actively engage multiple cognitive pathways, such as visual, analytical, and conceptual reasoning, to accommodate diverse learning preferences and reinforce concept retention.
2. Effectively manage cognitive load when introducing and applying new formulas and concepts (e.g., specific heat capacity $Q=mc\Delta T$, latent heat calculations, and thermal conductivity).
3. Meaningfully integrate historical contexts (e.g., development of the steam engine) and contemporary applications or future relevance (e.g., climate science, energy efficiency, information systems) of thermodynamics concepts to enhance student motivation and contextual understanding.
4. Explicitly embed literacy (precise scientific terminology, structured argumentation) and numeracy (equation manipulation, interpretation of graphical and numerical data) skills central to mastering thermodynamics.
5. Leverage suitable ICT tools (e.g., interactive simulations, data logging sensors, computer modelling software) to enhance concept comprehension, provide immediate feedback, and actively engage students.

Include specific, actionable examples of teaching activities derived from these strategies that student science teachers can readily implement within this limited instructional timeframe.

Support your recommendations with references to relevant educational research and theoretical frameworks such as Constructivism, Cognitive Load Theory, Bloom's Taxonomy, Working Memory, Schema Theory, and Attention Management. Clearly identify how each strategy aligns with these cognitive science principles and educational frameworks.", we searched across over 126 million academic papers from the Semantic Scholar corpus. We retrieved the 500 papers most relevant to the query.

Screening

We screened in papers that met these criteria:

- **Population and Topic**: Does the study examine physics/science education interventions related to thermodynamics concepts with secondary school students aged 15-18?
- **Time Constraints**: Is the instructional intervention implemented within 5 or fewer hours per topic?
- **Pedagogical Approach**: Does the study investigate at least one of these pedagogical strategies: active learning, cognitive science-based approaches, ICT integration, or multi-modal learning approaches?
- **Outcome Measures**: Does the study measure at least one of these outcomes: conceptual understanding of thermodynamics, student engagement/motivation, or retention of scientific concepts?
- **Study Design**: Is the study an empirical investigation using one of these methods: randomized controlled trial, quasi-experimental study, mixed-methods study, or systematic review/meta-analysis?
- **Practical Application**: Does the study include practical classroom application of the intervention (not purely theoretical)?
- **Implementation Feasibility**: Is the teaching intervention described in sufficient detail to be implementable by other educators?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Research Design Type**:

  Identify the specific type of research design used in the study. Options may include:

- Experimental (e.g., randomized controlled trial, quasi-experimental)
- Quasi-experimental
- Action research
- Case study
- Mixed methods

Look in the methods section for explicit description of research design. If not clearly stated, infer from study methodology. If multiple design elements are present, list all applicable types. If uncertain, note "Design type unclear" and provide rationale.

- **Pedagogical Strategies Employed**:

Systematically extract ALL pedagogical strategies used in the study, with specific attention to:

- Active learning approaches
- Cognitive science-based instructional methods
- Technology integration
- Conceptual understanding techniques

Provide verbatim quotes where possible. Categorize strategies according to their primary cognitive or pedagogical mechanism (e.g., constructivist approach, cognitive load management). Include specific examples of how each strategy was implemented in the classroom.

If multiple strategies are used, list them in order of prominence or implementation sequence.

- **Participant Demographics**:

  Extract detailed participant information:

- Age range
- Educational level/grade
- Number of participants
- Subject/course context
- Gender distribution (if reported)

Prioritize information specifically related to physics/science education context. If subgroups exist, note their specific characteristics. Use exact numbers/percentages from the study. If any demographic information is incomplete, note "Partial information available" and specify what is missing.

- **Instructional Context**:

  Describe the specific learning environment:

- Educational setting (secondary school, classroom type)
- Duration of intervention
- Technology resources available
- Syllabus or curriculum alignment

Focus on details relevant to thermodynamics instruction. Extract verbatim descriptions of classroom setup, technological infrastructure, and curriculum constraints. If multiple contexts are described, compare and contrast them.

- **Cognitive Science Frameworks Applied**:

  Identify and extract explicit references to:

- Specific cognitive science theories used
- Theoretical frameworks guiding instructional design
- Explicit connections made between cognitive science principles and teaching strategies

Look in introduction, methodology, and discussion sections. Provide direct quotes demonstrating theoretical grounding. If no explicit framework is mentioned, note "No cognitive science framework explicitly discussed."

- **Learning Outcomes and Assessment**:

  Extract:

- Primary learning outcomes measured
- Assessment methods used
- Quantitative results demonstrating conceptual understanding
- Specific metrics showing student learning gains

Prioritize outcomes related to:

- Conceptual understanding of thermodynamics
- Cognitive engagement
- Skills development

Include numerical data, statistical significance, and effect sizes where available. If multiple outcome measures exist, rank them by relevance to research question.

Results

Characteristics of Included Studies

Study	Study Design	Educational Context	Pedagogical Framework	Key Interventions	Full text retrieved
Anderson et al., 2005	Action research	Introductory thermodynamics, likely university level	Active learning	Computer-based instruction modules with interactive exercises, immediate feedback, graphical modeling, and physical world simulation	No
Assefa and Asgedom, 2017	Quasi-experimental	Grade 12 secondary school	Spiral Cognitive-Sociocultural Model of Conceptual Change (SCSMCC), Reasoned Persuasive Collaboration (RPC)	Six phases of SCSMCC and RPC method over 10 lessons	No

Study	Study Design	Educational Context	Pedagogical Framework	Key Interventions	Full text retrieved
Bulegon and Tarouco, 2013	Action research	2nd year of high school	Tres Momentos Pedagogicos (TMP)	Learning objects on thermodynamics, MOODLE, eXe Learning software, forum and chat tools	No
Clark and Jorde, 2004	Mixed methods quasi-experimental	We didn't find mention of educational level	Constructivist approach	Integrated sensory model within thermal equilibrium visualization, tactile models	No
Corrêa and Martins, 2017	Mixed methods quasi-experimental	2nd year of high school	Cognitive Flexibility Theory	Simulations and hypermedia, interdisciplinary approach	No
Faria, 2016	Action research	2nd year of high school, private school	Investigative approach, Science, Technology, and Society (CTS)	Social media integration, experimental activities, debates	No
Grasselli, 2018	Action research	High school (Ensino Medio)	Ausubel's meaningful learning theory, Piaget's cognitive development theory	Construction of thermal machines, Unidades de Ensino Potencialmente Significativas (UEPS)	No
Hasanah et al., 2023	Experimental	Class XI (11th grade)	Project-Based Learning (PjBL) with STEM integration	Simple engineering prototype products (thermos and steam engine)	No
Hernández Bravo et al., 2020	Quasi-experimental	Higher middle level (high school)	Constructivist methodology	Interactive digital board	No

Study	Study Design	Educational Context	Pedagogical Framework	Key Interventions	Full text retrieved
Jiménez et al., 2016	Quasi-experimental, Action research	High school, Physics I course	Cooperative learning strategies	Peer discussions, experiments in and out of academic areas, guided research	No
Komáromi, 2019	Action research case study	Secondary school (ages 14-16)	Model of Educational Reconstruction, Nersessian's methodology	Space mishap context, hands-on experiments, computer simulations	Yes
Leach and Orfanidou, 2019	Quasi-experimental	Secondary school (ages 15-16)	Feynman's abstract perspective	Research-informed teaching sequence	No
Malgieri et al., 2021	Action research	4th year of secondary school (ages 17-18)	We didn't find mention of pedagogical framework	Dice and coin toy models, computer simulations	No
McLure et al., 2020	Quasi-experimental	Year 9 (ages 14-15)	Thinking frames approach	Conceptual change strategy	No
Plata, 2019	Quasi-experimental	11th grade	Problem-based learning	Problem-based guides	No
Poggi et al., 2016	Quasi-experimental	Secondary school (ages 15-16)	Interdisciplinary approach	Integration of physics, chemistry, and biology concepts	No
Rankhumise, 2008	Quasi-experimental, Action research	Grade 10	Constructivist learning theory	Activity-based approach	No
Russell et al., 2004	Action research case study	Year 11 physics class	Constructivist theory of learning	Microcomputer-based laboratory (MBL) activities	No
Sari et al., 2023	Quasi-experimental	We didn't find mention of educational level	Problem-Based Learning (PBL)	PBL model for thermodynamics	No

Study	Study Design	Educational Context	Pedagogical Framework	Key Interventions	Full text retrieved
Serrano, "Studies in Technology and Education"	Quasi-experimental	Grade 12 STEM strand	We didn't find mention of pedagogical framework	QR code-driven strategy	No
Silva, 2019	Quasi-experimental, Action research	We didn't find mention of educational level	Ausubel's theory of meaningful learning, Bloom's taxonomy	Arduino-based experiments	No
Torres and Mejía Rodríguez, 2019	Case study	8th grade	Project-Based Learning (PBL)	Project-based activities	No
Vilanculo et al., 2021	Quasi-experimental	9th grade	Ausubel's theory of meaningful learning, constructivist approach	Active teaching approach valuing alternative conceptions	No
Vilanculo, 2020	Mixed methods quasi-experimental	9th grade (ages 13-17)	Ausubel's Theory of Significant Learning	Active methodologies, experimental activities	Yes
Zárate-Moedano et al., 2023	Design-Based Research, Mixed Methods	2nd grade of secondary education (ages 13-15)	5E model, Piaget's and Vygotsky's theories	5E instructional model for heat and temperature concepts	Yes

Our analysis of the included studies revealed a diverse range of approaches to teaching thermodynamics across various educational contexts. The majority of studies focused on secondary education, with 21 out of 25 studies conducted in this setting. We found mention of quasi-experimental designs in 12 studies, making it the most commonly reported approach in our sample. Action research was the second most frequently mentioned, appearing in 10 studies.

The pedagogical frameworks employed varied widely, with constructivist approaches being the most commonly mentioned (5 studies), followed by Ausubel's theory of meaningful learning (4 studies). Problem-based learning and Project-Based Learning were each mentioned in 2 studies. We found 17 other frameworks that were each mentioned in only one study, highlighting the diversity of approaches in thermodynamics education.

Key interventions ranged from technology-enhanced learning (e.g., computer simulations, interactive digital boards) to hands-on experiments and project-based activities. This variety suggests a trend towards multimodal and active learning strategies in thermodynamics education.

Thematic Analysis

Cognitive Science-Based Instructional Strategies

Strategy Type	Theoretical Foundation	Implementation Method	Evidence of Effectiveness
Conceptual Change	Spiral Cognitive-Sociocultural Model of Conceptual Change (SCSMCC)	Six phases of SCSMCC and Reasoned Persuasive Collaboration (RPC) method	Significant positive differences and medium effect size in tests, attitudes, and motivations
Cognitive Flexibility	Cognitive Flexibility Theory	Interdisciplinary approach with simulations and hypermedia	We didn't find explicit mention of effectiveness in the abstract
Meaningful Learning	Ausubel's theory of meaningful learning	Construction of thermal machines, UEPS, Arduino-based experiments, Active teaching approach	Increased student interest and participation, Significant improvement in formulation of heat and temperature concepts
Constructivist Approach	Constructivist learning theory	Integrated sensory model, Interactive digital board, Activity-based approach, MBL activities	Significant outperformance of experimental groups, Improvement in understanding main topics
Thinking Frames	Conceptual change strategy	Thinking frames approach	Effect size = 2.04 for thinking frames approach vs 0.20 for traditional methods
Problem-Based Learning	Problem-based learning theory	Problem-based guides, PBL model for thermodynamics	Significant improvement in understanding heat and temperature concepts, Significant improvement in conceptual understanding and argumentation skills

Strategy Type	Theoretical Foundation	Implementation Method	Evidence of Effectiveness
Project-Based Learning	Project-Based Learning (PBL) theory	STEM-integrated PjBL, Project-based activities	Significant impact on creative thinking abilities development (N-gain = 0.353, d-effect = 2.069), Evidence of significant learning shown by conceptual progress
5E Instructional Model	Piaget's and Vygotsky's theories	5E model for heat and temperature concepts	Statistically significant improvement in posttest scores (p=0.004)

Our analysis identified mention of 8 different theoretical foundations across the studies, with each appearing in one study based on the available information. The implementation methods varied widely, with 2 studies using multiple approaches and others employing specific strategies such as SCSMCC and RPC, interdisciplinary with simulations, thinking frames, problem-based, project-based, and 5E model approaches.

Evidence of effectiveness was reported for 7 out of 8 studies, with 5 studies reporting significant improvement, 1 study reporting significant positive differences, and 1 study reporting a large effect size. We didn't find explicit effectiveness information for 1 study. All studies that reported effectiveness found positive outcomes, with varying degrees of improvement and statistical significance.

These findings suggest that a variety of cognitive science-based instructional strategies can be effective in teaching thermodynamics, with particular emphasis on active learning, conceptual change, and problem-based approaches.

Time-Optimized Learning Sequences

The challenge of teaching introductory thermodynamics within a constrained 3-hour lesson sequence necessitates careful consideration of time-optimized learning strategies. While few studies directly addressed this specific time constraint, several approaches emerged that could be adapted for efficient instruction:

1. Active Learning Approaches :
    - Predict-observe-explain sequences in microcomputer-based laboratory activities (Russell et al., 2004)
    - Cooperative learning strategies, including peer discussions and guided research (Jiménez et al., 2016)
    - STEM-integrated project-based learning, scaled down to focus on key thermodynamics principles (Hasanah et al., 2023)
2. Cognitive Load Management :
    - Thinking frames approach for addressing common misconceptions (McLure et al., 2020)
    - Visual aids and simulations for clear representations of abstract concepts (Clark and Jorde, 2004)
    - Simple dice and coin models for teaching thermal phenomena (Malgieri et al., 2021)

3. Integration of Multiple Modalities :
    - Interactive digital board combining visual, auditory, and kinesthetic learning (Hernández Bravo et al., 2020)
    - Arduino-based experiments for hands-on engagement (Silva, 2019)
    - Space physics contexts for teaching thermal conduction (Komáromi, 2019)

To optimize these strategies for a 3-hour lesson sequence:

- Prioritize key concepts : Align with New South Wales (NSW) Stage 6 syllabus
- Diversify activities : Use brief, focused tasks engaging multiple modalities
- Leverage technology : Enable rapid visualization and feedback
- Structure wisely : Alternate instruction, active learning, and reflection
- Extend learning : Utilize pre- and post-lesson materials

Technology-Enhanced Learning

The integration of technology in thermodynamics instruction emerged as a significant theme across multiple studies, offering potential solutions for enhancing concept comprehension, providing immediate feedback, and actively engaging students within time constraints. Key findings include:

1. Digital Tools and Simulations :
    - Computer-based instruction modules with interactive exercises and immediate feedback (Anderson et al., 2005)
    - Integrated sensory model within thermal equilibrium visualization (Clark and Jorde, 2004)
    - Simulations and hypermedia based on Cognitive Flexibility Theory (Corrêa and Martins, 2017)
2. Real-time Assessment Strategies :
    - Microcomputer-based laboratory (MBL) activities for immediate data collection and analysis (Russell et al., 2004)
    - QR code-driven strategy for quick access to information and assessment (Serrano)
3. Interactive Demonstrations :
    - Interactive digital board for improved understanding of molecular-level phenomena (Hernández Bravo et al., 2020)
    - Arduino-based experiments for calorimetry (Silva, 2019)

The effectiveness of these technology-enhanced learning strategies is supported by several studies:

- Clark and Jorde (2004) reported significant outperformance of the experimental group using the integrated sensory model on posttests and delayed posttests.
- Hernández Bravo et al. (2020) noted improvements in students' understanding of main topics, willingness to work in the classroom, and ability to represent phenomena at the molecular level.
- Serrano's study showed significant improvement in posttest scores for the experimental group using the QR code-driven strategy.

For a 3-hour lesson sequence, technology-enhanced learning could be particularly beneficial for:

- Rapid visualization of complex thermodynamics concepts
- Immediate feedback on student understanding through interactive quizzes or simulations

- Efficient data collection and analysis in practical demonstrations
- Providing differentiated learning experiences to accommodate various learning paces and styles

Contextual Learning Integration

The integration of contextual learning, including historical perspectives and contemporary applications, emerged as a valuable strategy for enhancing student motivation and understanding of thermodynamics concepts. Key findings include:

1. Historical Perspectives :
   - Integration of historical and epistemological aspects of science in teaching thermochemistry (Faria, 2016)
   - Interdisciplinary approach incorporating historical contexts of energy concepts across physics, chemistry, and biology (Poggi et al., 2016)
2. Contemporary Applications :
   - Space physics contexts for teaching thermal conduction (Komáromi, 2019)
   - STEM-integrated project-based learning involving creation of simple engineering prototypes (Hasanah et al., 2023)
   - Project-based learning activities relating the first law of thermodynamics to everyday issues and global warming (Torres and Mejía Rodríguez, 2019)
3. Cross-disciplinary Connections :
   - Interdisciplinary approach encouraging associations between heat concepts and content from chemistry and biology (Corrêa and Martins, 2017)
   - Integrated science approach connecting energy concepts across physics, chemistry, and biology (Poggi et al., 2016)

The effectiveness of contextual learning integration is supported by several studies:

- Komáromi (2019) reported significant improvement in students' understanding of heat and heat transfer using space physics contexts.
- Torres and Mejía Rodríguez (2019) found evidence of significant learning, shown by conceptual progress in understanding the first law of thermodynamics and its real-world applications.
- Hasanah et al. (2023) demonstrated a significant impact on students' creative thinking abilities in thermodynamics through the STEM-integrated approach (N-gain = 0.353, d-effect = 2.069).

For implementingcontextual learning integration within a 3-hour lesson sequence:

- Use brief historical anecdotes or timelines to introduce key thermodynamics concepts and their development
- Incorporate quick demonstrations or thought experiments that connect thermodynamics principles to everyday experiences or current technological applications
- Present interdisciplinary problems or scenarios that require students to apply thermodynamics concepts in various contexts (e.g., biology, environmental science, engineering)
- Utilize multimedia resources (e.g., short videos, infographics) to efficiently present real-world applications of thermodynamics

Implementation Framework

Teaching Strategy	Time Allocation	Required Resources	Learning Outcomes
Conceptual Change Activity	30 minutes	Worksheets, discussion prompts	Address common misconceptions about heat and temperature
Interactive Simulation	45 minutes	Computers/tablets, simulation software	Visualize energy transfer and transformation processes
Hands-on Experiment	45 minutes	Arduino kit or simple materials for thermal conductivity demonstration	Apply concepts of heat transfer and thermal equilibrium
Problem-Based Learning Task	30 minutes	Scenario descriptions, data sets	Develop critical thinking and application skills for thermodynamics problems
Collaborative Discussion	20 minutes	Discussion prompts, peer evaluation rubric	Enhance scientific argumentation skills and peer learning
Real-world Application Analysis	20 minutes	Case studies or news articles related to thermodynamics	Connect thermodynamics concepts to contemporary issues
Formative Assessment	20 minutes	Digital quiz platform or response system	Provide immediate feedback and identify areas for clarification
Reflection and Synthesis	10 minutes	Reflection prompts, concept map template	Consolidate learning and identify key takeaways

Based on the information in the teaching strategies table, we observed:

- Time allocation varies across strategies, with longer periods (45 minutes) allocated to interactive simulations and hands-on experiments, reflecting the importance of active engagement in learning thermodynamics concepts.
- Resources include a mix of physical materials (worksheets, experimental kits) and digital tools (computers, simulation software), aligning with the technology-enhanced learning strategies identified in the literature.
- Learning outcomes span a range of cognitive processes, from addressing misconceptions to applying concepts and developing critical thinking skills, consistent with the cognitive science-based instructional strategies found in the reviewed studies.

The proposed sequence integrates findings from various studies:

- Conceptual change activities have shown significant improvements in understanding and addressing misconceptions (McLure et al., 2020; Assefa and Asgedom, 2017).

- Interactive simulations and hands-on experiments have demonstrated effectiveness in improving concept visualization and application (Clark and Jorde, 2004; Silva, 2019).
- Problem-based and collaborative learning approaches have shown positive impacts on critical thinking and argumentation skills (Plata, 2019; Sari et al., 2023).
- Real-world application analyses have been effective in connecting abstract concepts to tangible contexts (Torres and Mejía Rodríguez, 2019).

To maximize the impact of this 3-hour sequence:

- Pre-lesson preparation : Provide materials for basic concept review
- Flip the classroom : Utilize for some theoretical content
- Post-lesson consolidation : Offer activities or projects
- Continuous improvement : Assess and refine based on feedback and performance

This framework integrates evidence-based strategies while maintaining flexibility in implementation, aiming to provide an effective approach to teaching introductory thermodynamics within the given constraints.

References

A. Komáromi. "Space Mishap as a Stimulus Context for Thermal Conduction Exploration in Secondary School." *Journal of Physics: Conference Series*, 2019.

A. L. Silva. "Uma Proposta Para Aprendizagem de Calorimetria Utilizando a Plataforma Arduino Em Uma Sequência Didática Diversificada," 2019.

Ana Marli Bulegon, and L. Tarouco. "Sequência Didática Com o Uso de Objetos de Aprendizagem Como Auxílio Ao Desenvolvimento Do Pensamento Crítico Na Aprendizagem de Termodinâmica No Ensino Médio," 2013.

Article Info, and Arman Serrano. "Studies in Technology and Education," n.d.

C. Plata. "Diseño e Implementación de Guías de Termodinámica Con Enfoque Problémico Como Estrategia Para La Enseñanza - Aprendizaje," 2019.

D. Faria. "Ensino de Termoquímica Numa Abordagem Investigativa e CTS Envolvendo Os Conceitos de Calor, Temperatura, Energia Cinética e Energia Potencial," 2016.

D. Russell, Keith B. Lucas, and C. Mcrobbie. "Role of the Microcomputer-Based Laboratory Display in Supporting the Construction of New Understandings in Thermal Physics," 2004.

Douglas B. Clark, and Doris Jorde. "Helping Students Revise Disruptive Experientially Supported Ideas about Thermodynamics: Computer Visualizations and Tactile Models," 2004.

Edward E. Anderson, R. Taraban, and M. P. Sharma. "Implementing and Assessing Computer- Based Active Learning Materials in Introductory Thermodynamics*," 2005.

Erasmo Carlos Grasselli. "Uma Abordagem Das Máquinas Térmicas No Ensino Da Termodinâmica Sob a Ótica Da Aprendizagem Significativa," 2018.

Felicity I. McLure, Mihye Won, and D. Treagust. "Teaching Thermal Physics to Year 9 Students: The Thinking Frames Approach." *The Physical Educator*, 2020.

H. D. Jiménez, Marco Negrete, and A. López-Ortega. "El Uso Del Aprendizaje Cooperativo Para La Enseñanza de Los Conceptos de Calor y Temperatura a Nivel Medio Superior," 2016.

J. Leach, and D. Orfanidou. "Design, Implementation and Evaluation of a Research-Informed Teaching Sequence about Energy," 2019.

Jossias Arnaldo Vilanculo. "Active Methodologies for Teaching and Learning Physics: Case Study of the Formulation of Heat and Temperature Concepts." *Revista Científica Multidisciplinar Núcleo Do Conhec-*

imento, 2020.

Jossias Arnaldo Vilanculo, Inocente Vasco Mutumucuio, and C. Silva. “Use of Active Teaching-Learning Methodologies in Approaching the Basic Concepts of Engineering Education: Influence of the Experimental Approach to Students' Alternative Conceptions in Learning the Concepts of Heat and Temperature.” *2021 4th International Conference of the Portuguese Society for Engineering Education (CISPEE)*, 2021.

Lasmita Sari, R. Adimayuda, S. Gumilar, Arip Nurahman, and Hazrati Ashel. “Applying Problem-Based Learning in Thermodynamics to Enhance Comprehension of Physics Concepts and Argumentation Skills.” *Tadris: Jurnal Keguruan Dan Ilmu Tarbiyah*, 2023.

M. Malgieri, A. De Ambrosis, Monica Di Savino, and P. Onorato. “Teaching Thermal Phenomena and Irreversibility Through Playable Dice and Coin Toy Models.” *Teaching-Learning Contemporary Physics*, 2021.

M. Rankhumise. “Effective Teaching of Energy in Mechanics,” 2008.

M. T. Torres, and Katherine Lucía Mejía Rodríguez. “Aprendizaje Basado En Proyectos : Estrategia Pedagógica Que Posibilita El Aprendizaje de La Primera Ley de La Termodinámica,” 2019.

Martha Patricia Hernández Bravo, A. O. Valdivia, Carlos Montaño Osornio, and Y. M. Vargas-Rodríguez. “Didactic Strategy: Interactive Digital Board in Teaching Learning Heat Capacity for High School,” 2020.

Ramón Zárate-Moedano, J. Suárez-Medellín, and Rosaura Pérez-Hernández. “Modelo 5E Para La Enseñanza de La Termodinámica. Diseño y Evaluación de Secuencias de Enseñanza-Aprendizaje.” *Uniciencia*, 2023.

S. Corrêa, and M. Martins. “DESENVOLVIMENTO DE UMA SEQUÊNCIA DIDÁTICA PARA O ENSINO DA TEMÁTICA CALOR COM HIPERMÍDIAS,” 2017.

Shimeles Assefa, and A. Asgedom. “Effectiveness of the Integrated Model of Conceptual Change in Teaching Science: The Case of Grade 12 Thermodynamics Learning at a Secondary School in Addis Ababa,” 2017.

Syifa’ul Hasanah, P. Parno, A. Hidayat, E. Supriana, L. Yuliati, Eny Latifah, and Marlina Ali. “Building Students' Creative Thinking Ability Through STEM Integrated Project-Based Learning with Formative Assessment on Thermodynamics Topics.” *THE 5TH INTERNATIONAL CONFERENCE ON MATHEMATICS AND SCIENCE EDUCATION (ICoMSE) 2021: Science and Mathematics Education Research: Current Challenges and Opportunities*, 2023.

Valeria Poggi, C. Miceli, and I. Testa. “Teaching Energy Using an Integrated Science Approach,” 2016.