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TOWARDS A THERMAL CONCEPTUAL ASSESSMENT FOR FIRST-YEAR ENGINEERING STUDENTS – TCA-1Y

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We report from an ongoing process to develop a thermal conceptual assessment that covers the essential concepts of first-year thermodynamics to be administered to engineering students. The goal is to develop a measurement instrument in order to investigate students' pre-knowledge as well as the influence of teaching and learning settings. The assessment builds on known misconceptions and concept questions described in the literature. The original items have been modified significantly in the current version 3 of the test in order to create single-choice questions with four distracters each that address frequent misconceptions from student answers in a systematic way. The working process to create these distracters is described exemplarily.

Keywords: Thermodynamics, SoTL, test development

INTRODUCTION

In order to characterize students' pre-knowledge and to determine their learning gains suitable measurement instruments are necessary. Within the scope of the scholarship of teaching and learning (SoTL) [1] such standard measurement tools are essential for the comparison of different teaching and learning settings. Often, concept inventories, which have been developed for various subjects in physics or related engineering fields, are used for this purpose [2]. Concept inventories are multiple choice questionnaires in which the correct answer is mixed up with known student misconceptions as "distracters" [3]. By analyzing students' selection of the distracters one can conclude that there is a misconception and what it could be.

One of the most commonly used concept inventory is the force concept inventory FCI [4] which is a worldwide applied and accepted tool to probe students' conceptual understanding in mechanics [5]. We have been using the FCI in a standardized manner for first-year engineering students at an University of Applied Sciences on a regular base since almost a decade. It serves us to monitor students pre-knowledge when entering our physics courses ("pre-test"), to adjust course contents towards students' needs and to determine their learning gains depending on teaching formats after the course ("post-test") [6]. In order to extend this approach to further topics in physics, we were looking for a similar instrument, first of all in thermodynamics.

From the established concept inventories presented in the literature, we could not find a test that fits all our needs. They are either intended for schools (e.g. Introductory Thermal Concept Evaluation, TCE [7]), the range of addressed concepts is too limited for our purposes (Heat and Energy Concept Inventory, HECI [3]), their level is significantly beyond the learning goals of our first-year courses (Thermal and Transport Concept Inventory TTCI [9]), or the questions are a combination of multiple-choice and open reasoning format [10].

GOAL

Our goal is to set up a feasible assessment that addresses the fundamental thermal concepts relevant to engineering students from different programs at Universities of Applied Sciences in their first year (TCA-1Y). It is to mention that the aim of these programs is to prepare students for engineering careers in industry or subsequent studies towards a master's degree. The focus is on applying science to industrial research and development, not on academical research.
Further requirements on the test are, that it is possible to use it as a pre-test (at least partly) and as post-test. Moreover, the necessary time to administer the test should be in an acceptable range and its items should be single choice with five answers each in order to ease the analysis.

FRAMEWORK

Since far more than twenty years researchers in science, technology, engineering, and mathematics education report that students often have their own ideas about the underlying mechanisms in physical or technical situations. Their ideas can be erroneous or incomplete, and are often called "misconceptions". In this work we take a perspective towards learning similar to that described by Heron [11]. We try to determine "student difficulties […] that must be addressed in instruction" for students to gain a functional understanding of the subject matter, that is (as defined by McDermott) "the ability to interpret and use knowledge in situations different from those in which it was initially acquired" [12].
Our aim here is not to conduct detailed research on student misconceptions, but we want to build on previous research and take into account known insights on the subject matter in order to adapt, combine and further develop them, towards a practical assessment that suits our needs.

TEST DEVELOPMENT PROCEDURE

According to [2] it is recommended that an ideal concept inventory should address one concept per item and should have several items per concept. An assessment that fulfills these requirements can either address only few concepts or takes a lot of time to administer, which reduces the acceptance of faculty to deploy it. As on the one hand we intended to cover the fundamental concepts of the whole thermodynamic part in the physics course and on the other hand we limited the necessary time to carry out the assessment to a maximum of 30 min, we had to make a compromise.
For that reason we decided to follow a more pragmatic strategy and reduce for each concept the number of items to two or more (except of content "principles of heat engines" with only one item). We justify our approach with the fact, that our starting point builds on previous approved test items. Additionally we worked on strategies to improve and optimize each item in a way, that we could gain maximum insight into students' thinking even with a lower number of items per concept. Being aware that this could reduce the informative value on single misconceptions, we took into account this trade-off in favor of obtaining an overview on students' overall fundamental thermodynamic concepts in the first year.
In a first step we determined the content and the underlying concepts that should be addressed by the assessment. Four longtime experienced lecturers of first-year physics courses for engineers agreed on the following content: 1. Physical perception, 2. Definition of temperature and heat, 3. Thermal equilibrium and steady state, 4. Heat capacity, 5. Phase transition, 6. Emission, reflection and absorption of thermal radiation, 7. Ideal Gas, 8. Principles of heat engines.

In a second step we searched for known misconceptions and approved questions to this content in literature. After a detailed inspection we selected 19 possibly suitable items from literature, translated them into German, but left the structure and content mostly unchanged. It is to mention that already the translation can have an impact on the meaning of the respective item and it has to be examined carefully. We started a first run of version 1 with a pilot group of 47 and 39 engineering students as pre- and post-test respectively in the winter term 2018/19.

In the subsequent analysis it turned out, that the first version of the assessment had several drawbacks: questions were partly too easy, some questions were not precise or unambiguous, or one would need pre-knowledge to understand them. Others were multi-step questions with either a second multiple-choice answer or asking for reasoning. Those questions are difficult to analyze. In fact we had to modify all except two of the initially selected items in order to meet our requirements in form and content.

In version 2 of the assessment 6 questions were completely replaced. The new questions either stem from literature or by experiences from lecturers with student difficulties in informal context and exam answers. Moreover we aimed to obtain a systematic base for the development of single choice questions with 5 items each, that contain distracters with the most common misconceptions.

In order to do so, we additionally asked in 10 out of the 19 items the students to give reasoning for their answers in free-response format. In 4 other questions of the 19 we pose two-step questions with the second step containing the reasoning for the preceding answer. Other multiple choice questions had more or less than 5 answers. There we tested, which items are chosen most frequently by the students.

Version 2 was administered to another pilot group of 130 engineering students as pre-test and 110 engineering students as post-test in the summer term 2019.

From an in-depth analysis of student answers and reasoning of version 2, we could newly build most of the 19 items (details see below). They now comprise the new version 3, that is the current working version of the assessment - the thermal concept assessment, first year: – TCA-1Y. It contains only single-choice questions with five answers each. The items often have sketches of the underlying physical situation in order offer different representations (words and pictures) of the same situation. Moreover the test starts with more simple questions and address slightly advanced questions in the rear part. The order was chosen in that way, because we consider to use item 1 to 10 as pre-test, and item 1 to 19 as post-test for future investigations. This is a difference to the administration of the FCI, which can be used as pre- and post-test as a whole. The reason for this is, that the students' pre-knowledge in thermodynamics is often less pronounced than in mechanics.

Version 3 of the test was administered as pre-test with 33 students in the winter semester 2019/ 20 and as post-test from winter semester 2019/20 to 2021/22 to 52 students.

ITEM DEVELOPMENT IN DETAIL

The modifications of the items in version 3 of the assessment with respect to formulation, level, context, or answers are often quite substantial. The distracters of 10 questions have been constructed from student reasoning, by carefully identifying, analyzing and counting the prevailing misconception in the free-responses. The distracters of 4 two-step questions have been developed by determining the most dominating combinations of wrong answers and reasoning.

When choosing and adapting the formulation of the distracters directly from students' free-responses we were careful that they contain correct physical expressions and technical terms. For example we don't write: "in wool more heat can be conserved" but: "in wool more thermal energy can be conserved". Even though a wrong answer, we don't want to mess students up with wrong usage of state or process variables. We wanted to avoid that students, who take part in the assessment get used to wrong concepts due to the assessment itself. Moreover we intended to elicit intuitive misconceptions in contrast to other misunderstandings.

EXAMPLE FOR ITEM DEVELOPMENT

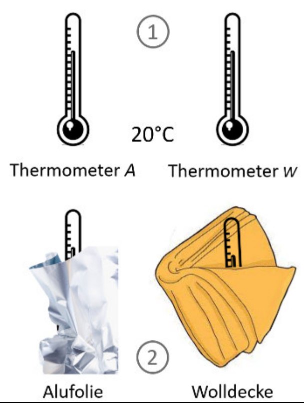
The steps of the development of an item is shown exemplarily with item 5 of the TCA-1Y addressing thermal equilibrium. In different studies it has been shown that students have difficulties in applying the concept that all bodies and materials have the same temperature in thermal equilibrium. Several misconceptions that go along with it are reported in [8]: the temperature of different objects is different even though they have been placed in the same environment, wool warms things up, or metal attracts, hold or store heat and cold. Items addressing this concept can be found in several concept tests like TCE, TTCI and HECI.

Table 1: Item 5: original item from [7], version 2, and version 3

<table>
<tr>
<td>Original:
Four students were discussing things they did as kids. The following conversation was heard: Ami: "I used to wrap my dolls in blankets but could never understand why they didn't warm up."
a. Nick replied: "It's because the blankets you used were probably poor insulators."
b. Lyn replied: "It's because the blankets you used were probably poor conductors."
c. Jay replied: "It's because the dolls were made of materials which did not hold heat well.
d. Kev replied: "It's because the dolls were made of material which took a long time to warm up."
e. Joy replied: "You're all wrong."

Who do you agree with?</td>
<td>Version 2, Item 5 (Translation from German):
Two identical thermometer in the same room show 20°C at room temperature. One thermometer is wrapped in a shining aluminum foil, the other in a woolen blanket. How does the temperature reading changes on both thermometers?
A. The thermometer in the aluminum foil shows a lower reading than the thermometer that is insulated with a blanket.
B. The thermometer insulated with the blanket shows a lower reading than the thermometer that is in the aluminum foil.
C. Both thermometer continue to show the same reading.

The answer to the preceding question is correct….
a. Because the woolen blanket is a significantly better thermal insulator than the aluminum foil.
b. Because the shining aluminum foil reflects incoming radiation more effectively than the woolen blanket.
c. Because the shining aluminum foil emits radiation more effectively than the woolen blanket.
d. Because the system is in thermal equilibrium.</td>
</tr>
<tr>
<td colspan="2">Version 3, Item 5 (Translation from German): Two identical thermometers in the same room show the same temperature reading at 20°C. Now, thermometer A is wrapped in a shining aluminum foil, thermometer W in a woolen blanket. How do the temperature readings change relatively to each other of the thermometer A that is insulated with aluminum foil compared to thermometer W that is insulated with wool?

a. A shows a lower temperature than W, because the shining aluminum foil reflects the radiation more effectively than the woolen blanket.
b. A shows a higher temperature than W, because the shining aluminum foil A reflects the radiation more effectively than the woolen blanket.
c. A shows a lower temperature than W, because in the material wool more thermal energy can be stored than in the aluminum foil.
d. A shows a higher temperature than W, because the woolen blanket is a much better thermal insulator than the aluminum foil
e. A and W continue to show the same temperature, because the system is in thermal equilibrium.

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We chose item 26 from TCE [7] to address this concept (original see Table 1). After translating the text into German, we changed it into a more scientific setting by replacing the doll with a thermometer. We did so because the test is to be used with engineering students. In order to have a clear reference frame we shifted the problem towards a setting that compares two situations – wool and aluminum foil. As being a good thermal insulator involves being a poor thermal conductor, we only chose "insulator" and we additionally offered reasoning that addresses thermal radiation.

Table 2: Students' result of item 5, version 2 + 3

Version 2: Combination of answers and reasoning for post-test, item 5, summer 2019 of 100 first-year engineering students. Answers A, B, C are given in rows, combined with the reasoning in columns. Percentage of students choosing the corresponding combination. The correct combination C+d is highlighted green. Highlighted in red is the physically illogical combination of answer and reason. The three most frequent wrong combinations (highlighted blue) have been selected for distracter construction.

100 students				
	a	b	c	d
A	4%	21%	2%	0%
B	10%	4%	6%	0%
C	0%	0%	0%	53%

Version 3: Single choice post-test results from winter terms 2019/20 to 2021/22 from a total of 52 engineering students. Percentage of students choosing the corresponding answer. The same blue tone in the results of version 2 and 3 address the same answer and reasoning combination. Answer e is correct.

52 students				
a	b	c	d	e
23%	4%	4%	8%	52%

Additionally we formulated it as a two-step question in order to separate answer and reasoning. The students' combined answers with reasoning for version 2 are presented in Table 2. Approximately half of the students selected the correct answer with correct reasoning. After determining the three most prevailing wrong answer patterns we constructed three distracters for a new version 3 of item 5. The known misconception that wool stores thermal energy was added as a further distracter. The physically wrong reasoning (highlighted red in Table 2) was skipped. The new version 3 of item 5 can be found in Table 1, the percentage of students choosing the corresponding answer Table 2. The results in Table 2 show that the prevailing misconceptions in version 2 are also selected in version 3.
In order to refine the results and to analyze the new version 3 of the assessment in more detail with respect to validity, difficulty and discrimination more student data have to be gathered, which can hopefully be done as soon as the pandemic allows face-to-face lecture again.

SUMMARY AND CONCLUSIONS

We report our procedure to set up a conceptual thermal assessment for first year engineering students. Known misconceptions and existing concept inventories were taken as a starting point. Special tests were designed in order to obtain the prevailing reasoning students give in the context of wrong answers. The present version 3 of the TCA-1Y covers eight concepts with 19 items. We plan to use version 3 as pre – test and post – test in order to understand students pre-knowledge and study the influence of teaching methods on learning gains.

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