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Artículos científicos

Aprendizaje de la termodinámica a través de un cambio conceptual

Learning Thermodynamics Through a Conceptual Change

Aprendizagem da termodinâmica através de uma mudança conceitual

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Resumen

Una de las principales dificultades en los procesos de enseñanza y aprendizaje es la existencia de ideas erróneas que conllevan a estructuras conceptuales deficientes llamadas frecuentemente *conceptos alternativos*. El presente trabajo propuso y puso en práctica una serie de innovaciones educativas en la enseñanza de la termodinámica, cuyo fin fue generar un conflicto cognitivo que permitiera al estudiante confrontar sus conceptos alternativos y modificarlos. Los cursos en los cuales se desarrolló este estudio se efectuaron de manera presencial durante los años del 2015 al 2019 y fue ajustada a modalidad no presencial durante los años 2020 y 2021. La metodología de investigación comprendió una extensa revisión bibliográfica, la selección de cuatro innovaciones educativas para el diseño del curso, la puesta en práctica de las innovaciones durante siete años y la evaluación de los impactos de las innovaciones a partir de encuestas escritas y entrevistas grupales. Los resultados revelan un alto grado de aceptación de las metodologías implementadas en el curso tanto para la modalidad presencial como para la modalidad no presencial. Los estudiantes expresaron que las innovaciones pedagógicas posibilitaron un cambio conceptual y el despertar de un sentido crítico sobre los contenidos de la termodinámica.

Palabras clave: conceptos alternativos, enseñanza de la termodinámica, metáforas, metodologías activas de aprendizaje.

Abstract

One of the main difficulties in the teaching and learning processes is the existence of erroneous ideas that lead to deficient conceptual structures, frequently called *alternative concepts*. The present work proposed and put into practice a series of educational innovations in the teaching of thermodynamics, whose purpose was to generate a cognitive conflict that would allow the students to confront their alternative concepts and modify them. The courses in which this study was developed were carried out face-to-face during the years 2015 to 2019 and were adjusted to non-face-to-face modality during the years 2020 and 2021. The research methodology included an extensive bibliographic review, the selection of four innovations education for the design of the course, the implementation of the innovations for seven years and the evaluation of the impacts of the innovations from written surveys and group interviews. The results reveal a high degree of acceptance of the methodologies implemented in the course, both for the face-to-face modality and for the non-face-to-face modality. The students expressed that the pedagogical innovations made possible a conceptual change and the awakening of a critical sense about the contents of thermodynamics.

Keywords: alternative concept, teaching of thermodynamics, metaphors, active learning methodology.

Resumo

Uma das principais dificuldades nos processos de ensino e aprendizagem é a existência de ideias errôneas que levam a estruturas conceituais deficientes, freqüentemente chamadas de conceitos alternativos. O presente trabalho propôs e colocou em prática uma série de inovações educacionais no ensino da termodinâmica, cujo objetivo era gerar um conflito cognitivo que permitisse ao aluno confrontar seus conceitos alternativos e modificá-los. Os cursos em que este estudo foi desenvolvido foram realizados de forma presencial durante os anos de 2015 a 2019 e foram ajustados para a modalidade não presencial durante os anos de 2020 e 2021. A metodologia de pesquisa incluiu uma extensa revisão bibliográfica, a seleção de quatro inovações educacionais para o desenho do curso, a implementação das inovações por sete anos e a avaliação dos impactos das inovações a partir de pesquisas escritas e entrevistas em grupo. Os resultados revelam um alto grau de aceitação das metodologias implementadas no curso, tanto para a modalidade presencial quanto para a modalidade não presencial. Os alunos expressaram que as inovações pedagógicas possibilitaram uma mudança conceitual e o despertar de um senso crítico sobre os conteúdos de termodinâmica.

Palavras-chave: conceitos alternativos, ensino de termodinâmica, metáforas, metodologias ativas de aprendizagem.

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Introduction

The present work proposed, put into practice and evaluated through surveys and summative evaluations the results of innovations in the teaching of the subject Thermodynamics Metallurgy. The innovations were based on generating a cognitive conflict that would allow the student to confront their "alternative concepts" and modify them. The subject is taught in the fifth semester of the Metallurgy and Materials Civil Engineering curriculum at the Federico Santa María Technical University [UTFSM] (2017, p. 4) in Chile. The number of students taking this course fluctuates between 20 and 30 people. As a prerequisite is having completed the courses of physics (four courses), chemistry (three courses) and mathematics (four courses). The course was held in person from 2015 to 2018. Due to the coronavirus disease (covid-19) pandemic, the course went online for the years 2020 and 2021.

In the literature there is a large number of publications related to the teaching and learning of thermodynamics, including Bain, Moon, Mack and Towns (2014), Cotignola, Bordogn, Punte and Cappannini (2002), Sözbilir, Pınarbaşı and Canpolat (2004) and Talanquer (2006). These studies indicate some of the difficulties that interfere with the learning process, such as the abstract nature of concepts, courses designed with information overload, and the use of teacher-centered pedagogies. There are also numerous studies related to the difficulties of modifying concepts of thermodynamics that were inaccurately constructed and wrongly integrated, such as the works of Haglund and Jeppsson (2013), Nilsson (2012), Nussbaum (1982, 1983), Talanquer (2014). The authors point out how knowledge has been acquired through formal and social learning and the interpretation of explanatory metaphors of physical phenomena that usually do not agree with those validated by the scientific community.

Although called differently, for example in Granville (1985) and Smith, diSessa, and Roschelie (1993), these misconstructed ideas will be called alternative concepts in this paper. The studies then suggest the premise that alternative concepts become mental barriers to learning thermodynamics.

The pedagogical innovations of this work sought, therefore, the generation of cognitive conflicts that would allow the student to confront their alternative concepts and modify them. For the above, the following four methodological strategies were designed:

1) A class didactic sequence that seeks to generate cognitive conflict and that allows the student to confront their alternative concepts and modify them.
2) The implementation of active teaching and learning methodologies through collaborative work and reasoned debate for the generation of cognitive conflict.
3) The search and analysis of the metaphors that the students used to build the alternative concepts.
4) The teaching of thermodynamics through postulates as opposed to the traditional method of statements.

These four points are described in detail in the following numbers, where the bibliographical references from which the ideas of the innovations were generated are included.

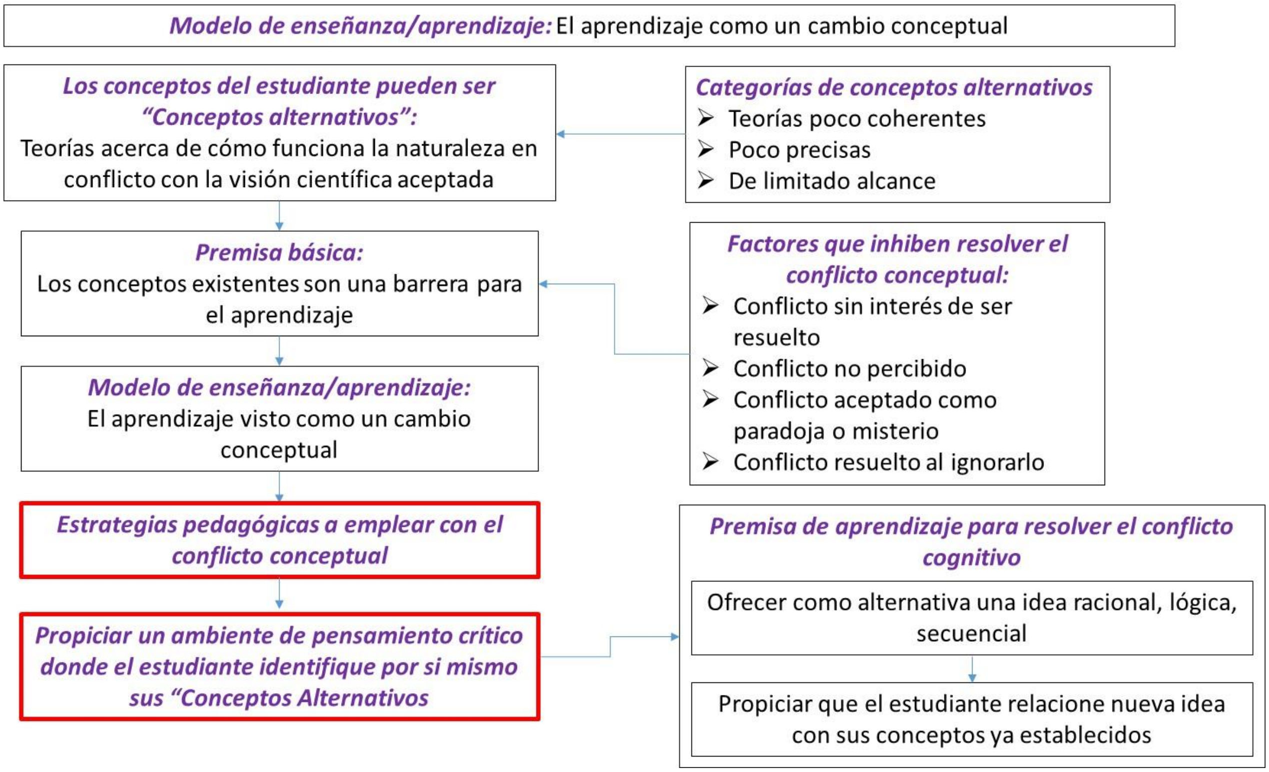
Elaborate a sequence in each class with active methodologies that allow the student to confront their metaphors

Based on the works of Kuhn (2012) and Toulmin (1975), who indicate the way in which science has historically advanced from overcoming mental paradigms, authors such as Collins (1987), Hewson (1981), Hewson and Beckett (1984), Nusbaum (1983), and Posner, Stike, Hewson, and Gertzog (1982) suggest similar processes in science learning. Some of these ideas are contained in figure 1, which was constructed, however, especially from the study by Hewson and Beckett (1984), where it is analyzed how to modify alternative concepts from conceiving the teaching and learning processes as conceptual changes.

The pedagogical innovations of this work had as its main axis the idea suggested in figure 1, namely, that it is possible to overcome a barrier in learning to the extent that a conceptual conflict is generated and the student is offered a new rational and alternative alternative. sequential, which, for the authors of this work, is not evidently clear in classical thermodynamics courses.

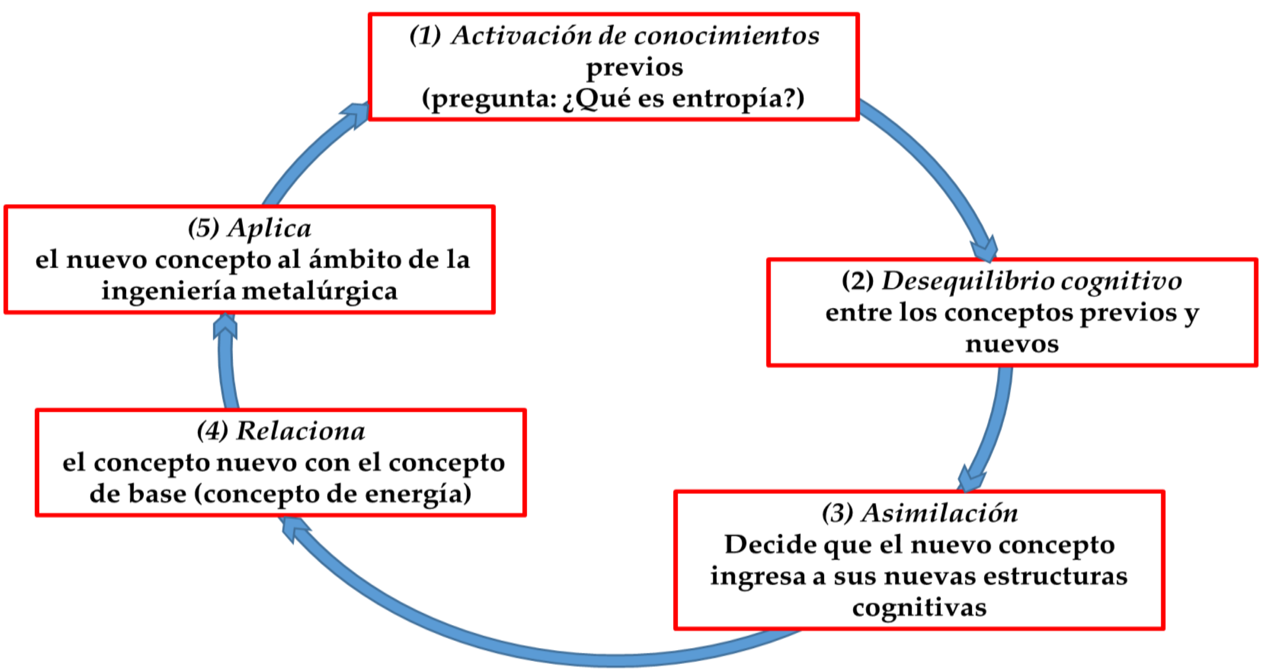
From the design of the course activities, the conceptual change proposed in figure 1 and presented in figure 2 is sought as a systemic sequence of knowledge activation, generation of a cognitive imbalance, the assimilation of a new concept as an activity rational, the relationship of knowledge to the central axis of energy and the application of knowledge to the area of metallurgy.

Figura 1. Modelo epistemológico considerando el aprendizaje como un proceso de cambio conceptual



Fuente: Elaboración propia

Figura 2. Secuencia para la generación del conflicto cognitivo



Fuente: Elaboración propia

Implementation of active teaching and learning methodologies

Taking as a reference the works of Mazur (2009) and Mills and Treagust (2003), this study considered the teacher as the person in charge of connecting the knowledge construction processes of each student with the culturally organized collective knowledge. Emphasis was placed on a class dynamic opposed to that of master classes. The main objective of the classes was to promote conceptual conflicts that allow the student a more active learning of thermodynamics, confrontation of their own ideas and receptive to the opinions of their peers and the teacher, avoiding the latter being the center of the activities.

Analysis of the alternative concepts of the students: in search of the metaphors with which these were elaborated

In the literature there are numerous works related to alternative concepts in learning thermodynamics, such as Bain et al. (2014), Cotignola et al. (2002), Sozbilir et al. (2004) and Talanker (2006). In these studies, alternative concepts are linked with metaphors, that is, we understand and perceive basic concepts in terms of something that we consider easier to grasp with our senses. This relationship is mainly based on the works of Lakoff (2003), which indicate how metaphors in our conceptual system influence our world view by highlighting certain aspects of concepts and hiding others. Therefore, our experience of the physical world is, in turn, influenced by our language, and language also influences our interpretation and understanding of our experiences when interacting with the physical world. These ideas taken from Lakoff are useful for this work as a conceptual framework for the strategy of confrontation and search for modification of alternative concepts. It is worth clarifying that, in line with Ortony (1993), there is no consensus regarding the definition of metaphor and its impact on the way of conceptualizing scientific ideas. Aware of these discrepancies, and an additional discussion in this regard being beyond the scope of this work, the didactics of topics uses the concept of metaphors in an instrumental way to analyze the metacognitive processes of students. Thus, from the students' alternative concepts, those metaphors that hindered the apprehension of thermodynamic concepts in an appropriate way were sought.

Teaching of thermodynamics through postulates as opposed to the traditional method of statements

The subject of thermodynamics is a fundamental course in the academic program of all engineering. The thematic contents of this subject in its traditional form include the statements of the laws of thermodynamics (first, second and third law), followed by deductions of calorific value, enthalpy, entropy, equilibrium criterion and Gibbs free energy. In the course of teaching, deductions are applied to hypothetical or industrially applicable problems. This type of structure is found, for example, in the textbooks by Lee (2012), Matsushita and Mukai (2018), and Mortimer (2008).

All the mental representations of thermodynamics agree on the phenomenological part and theoretical aspects, however, as Tarsitani and Vicentini (1996) point out, they differ in the logical structure and definition of the fundamental concepts. Some of the alternative methods of teaching thermodynamics include the extensive use of mathematics (Berker, 2012), teaching based on practical projects or the solution of chemical or thermodynamic problems (Mills, 2003; Reuf, 1983), courses based on in dynamic simulation (Schnitker, 2008), techniques for generating analogies by the student (Haglund and Jeppsson, 2013) and even the use of dramatizations (Stinner, 2003).

For the course, a method was sought that would allow the student to develop a new idea as a rational activity. The desired characteristics largely agree with the conceptualization of thermodynamics from the axiomatic formulation developed by Tisza (1978), compiled in the thermodynamics textbook by Callen (1985). The development of these two authors contrasts with the traditional way that treats thermodynamic principles as laws. Recently, a book in the same axiomatic line as Tisza has been published by Keszei (2012).

Considering the above, the following questions were raised during the development of this work:

- Can a methodological change in the teaching of thermodynamics, based on the four methodological strategies mentioned, lead students to build on previously acquired concepts until a conceptual change is achieved?
- Do the students perceive that the methodological innovations of the thermodynamics course contribute positively to their learning process?

The proposed hypothesis was that cognitive conflict can lead to a change in the student's conceptual structure and promote rational learning of thermodynamic concepts.

The objectives set were the following:

- Prepare a proposal for educational innovation to ensure concepts in a metallurgical thermodynamics course and promote critical thinking.
- Support innovations based on a literature review in the area of teaching thermodynamics.
- Implement the strategies in the classroom.
- Evaluation of the impact of innovations through written and verbal surveys to students.

We consider that this work is a contribution to the didactic innovation of thermodynamics education at the university level, since they address the teaching and learning processes through a conceptual change, with the combination of the aforementioned strategies, and with an analysis about their results.

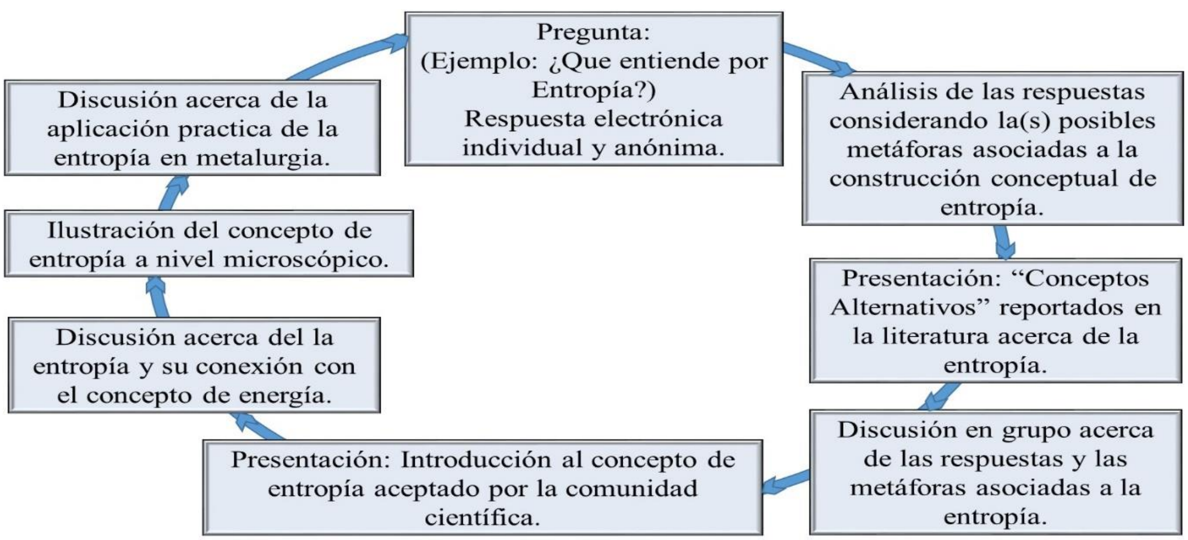
Methodology

The research methodology included an extensive literature review regarding the teaching of thermodynamics. Based on this, four educational innovations were selected for the design of the course based on generating a cognitive conflict that allows the student to confront their alternative concepts and modify them. These innovations were implemented during the years from 2015 to 2019 and were adjusted to a non-face-to-face modality during the years 2020 to 2021. The evaluation of the impacts of the innovations was carried out based on the opinions of the students collected through written surveys. and group interviews and the results of summative assessments. Some brief descriptions of the implementation in the classroom are presented in the following paragraphs.

Implementation of the didactic sequence of each class

Consistent with the stated objectives, the design of the class was designed in such a way as to generate a cognitive conflict according to the sequence presented in figure 2 and offer the logical alternative to overcome the alternative concept. The class begins with a question, for example, "What do you mean by entropy?", which, in addition to answering them, must be complemented with an example. The response is anonymous and electronic through an existing site on the course website. The student has the opportunity to reflect on their answers and compare them with those of their peers. Next, as indicated in figure 3, the teacher makes a short exposition about the alternative concepts reported in the literature. The next section corresponds to a group discussion, where students compare their answers with the alternative concepts presented. Next, the concept of entropy accepted by the scientific community and in accordance with the methodology of the course is presented by the teacher. In this stage of the course, the concepts of energy, simple thermodynamic system, compound thermodynamic system, adiabatic and diathermic walls, restrictions in a compound system and the equilibrium postulate have been discussed in previous classes. The enthalpy is, then, the postulation of a function for systems in equilibrium, for which the values of the parameters of internal energy, volume and number of moles of each one of the components of the system must be such that they minimize the value of the function. In subsequent sections, in groups, students discuss the concept and its relationship to energy. In some cases, the concept is connected with considerations of the behavior of matter at the microscopic level and the class is closed with examples of application of the concept in the area of metallurgy. As can be seen, the sequence of each class contains the chain for the generation of the cognitive conflict theorized in figure 2.

Figura 3. Diseño de las actividades de una sesión del curso



Fuente: Elaboración propia

Implementation of active methodologies

A course outline was designed with the teaching methods presented in Table 1 (the ideas referred to correspond to an adaptation of the methodologies proposed in the work of Henao, Chávez, Pizarro, García and Ibáñez [2018]). Before 2015, the course had the orientation indicated in the left column; the didactic innovations sought to orient the teaching methods to those described in the right column. The emphasis was on generating cognitive conflict, promoting critical thinking and guiding the student to find their alternative concepts.

Tabla 1. Comparación de los dos métodos de enseñanza

Método anterior	Método actual
Esfuerzo en qué enseñar y qué libro usar	Esfuerzo en ayudar a los estudiantes a generar conflictos cognitivos en el área de la termodinámica.
Presentaciones para entregar información (transmisión de información)	Promover el pensamiento crítico, permitir que el estudiante reconozca por sí mismo sus conceptos alternativos en el área de la termodinámica, ayudar al estudiante a desaprender o adaptar sus ideas al pensamiento aceptado por la comunidad científica.
Enseñanza basada en presentaciones.	Enseñanza basada en debate. Enseñanza de la termodinámica en forma de postulados, presentándola de una forma racional, lógica y secuencial.
Amplia cobertura de temas-baja comprensión	Menos cubrimiento de temas-alta comprensión. Menos énfasis en resolver problemas numéricos. Presentación breve de los tópicos de conceptos alternativos del área de la termodinámica reportados en la literatura y presentación breve de los conceptos termodinámicos de acuerdo con lo aceptado por la comunidad científica.

Fuente: Elaboración propia

In the virtual courses, a primary factor in the active methodology was to ensure attendance at the sessions through the Zoom platform. This was achieved by including an incentive in the total evaluation grade for those with attendance above 85% during the semester. In the event that most of the students had chosen to study the recorded classes, they would have forced a change in methodology not contemplated in the design of the course. For years where the course was conducted remotely, student attendance at Zoom sessions was greater than 80% on average.

Implementation of the search and analysis of metaphors

> A fundamental pillar of innovation in this work is the recognition that our conceptual system is fundamentally metaphorical in nature. These metaphors allow us to perceive some components of the concept, but necessarily hide others. For example, according to Lancor (2012), it is common to try to understand the concept of energy as something material (a substance that flows), however, this makes it difficult to grasp the aspect of energy degradation and, therefore, to understand associated concepts such as entropy.

In this pedagogical innovation, the answers of the students to questions such as what is equilibrium, energy, enthalpy, entropy and others were analyzed during the years 2015 to 2021. As explained in the previous numeral, their answers were analyzed to elucidate the possible metaphors associated with the ideas expressed by them and discussed with their classmates. A comparative analysis between the answers collected from the students with the concept accepted by the scientific community was presented in class, so that the students could compare, reflect and discuss their answers with their peers. The collected answers are presented to the students and the metaphors (or associations) are pointed out by the instructor (or students). A summarized and classified example regarding the concept of entropy is indicated in table 2; there, the answers were ordered in columns by elaboration of the concept, examples and possible metaphors or associations. The ranks according to how students associate entropy as disorder, probability, and equilibrium. In the association of entropy with energy, the students did not complement their answers with examples; in the associations related to disorder and probability, the examples are related to everyday factors. It can also be seen that the responses are vague and that the examples associated with everyday life have no relation to the scientific definition. The alternative concepts reported in the literature do not differ from those expressed by the students of the course. For example, in Brain (2014) the students define entropy as 'disorder', without stating what the term disorder means in relation to physics/statistics/thermodynamics. Information similar to that tabulated in Table 2 is developed for the different topics of thermodynamics that are studied during the course.

Tabla 2. Conceptos alternativos, ejemplos y metáforas asociadas al concepto de *entropía*

Asociación	Elaboración del concepto. Lo que mide la entropía	Ejemplos	Posible metáfora asociada
Energía	La energía (o diferencia) de energía de una reacción. Aumento de temperatura = más energía cinética = más desorden = más entropía	No reportaron ejemplos	Igual al concepto de *energía* antes discutido en clase. Entropía = energía = entalpía Entropía = temperatura
Desorden	La ruptura de enlaces en una reacción. Ruptura = desorden El desorden de un sistema. El desorden de las partículas. El universo tiende al desorden. Grado de desorden indicando si un	Probabilidad: las personas llenan aleatoriamente las bancas de un bus Desorden: si ordeno mi cuarto, la entropía del universo aumenta. Desorden a nivel molecular (un líquido tiene menos entropía que un gas).	Desorden entendido en su significado cotidiano. Desorden = probabilidad Desorden = movimiento de las partículas

	proceso puede no ser reversible.	Si la entropía del universo < 0, este colapsaría.	
Probabilidad	El sistema se encontrará donde mayor sea su probabilidad de estar Medida del posible ordenamiento de moléculas	Un gas se distribuye uniformemente en el volumen que lo contiene. Las partículas se distribuyen de tal forma que minimizan su perturbación.	Asociación espacial de probabilidad.
Equilibrio	Si un sistema no cambia y es homogéneo, su entropía es cero (si un sistema no cambia, ningún parámetro cambia).	Una caja con pelotas de colores. Si se agita, se homogeniza.	De las respuestas, no es clara la asociación entre entropía y equilibrio

Fuente: Elaboración propia

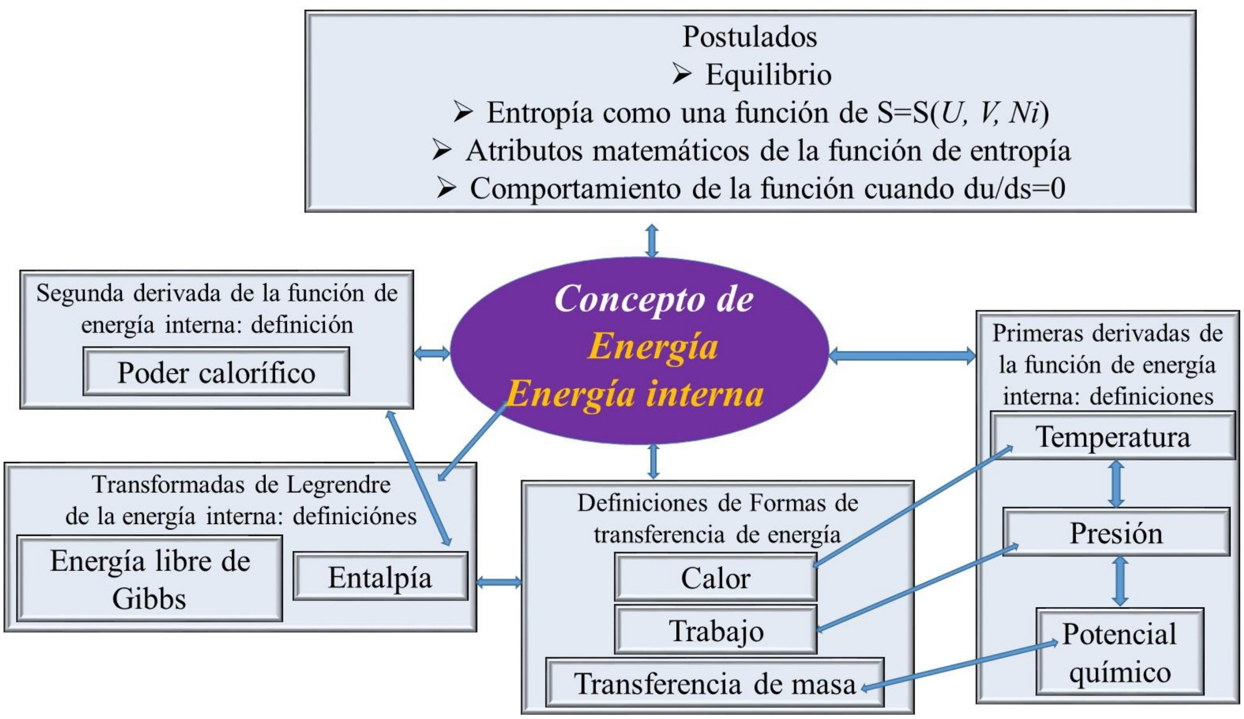
Teaching thermodynamics through postulates

In the mental representation of thermodynamics selected for the course, the student reconstructs the concepts of thermodynamics from the concept of internal energy of a system considering four basic postulates: equilibrium, entropy function, mathematical attributes of the entropy function and the behavior of the entropy function at boundary conditions. In parallel, she relates the natural phenomena of her environment and analyzes practical examples related to the area of metallurgy. The scheme indicated in figure 4 shows how the concepts of thermodynamics interrelate with those of internal energy, which constitutes a logical and sequential structure. The arrows indicate the existing correlations between the different concepts and definitions.

In all the examples and tasks, the student is asked to state the descriptive parameters of the systems in their initial states, the restrictions removed between the systems that allowed the development of a process, the descriptive parameters of the final states of the systems and to reflect about why the process is carried out and why the systems acquired these final parameters.

From these postulates, the study of thermodynamics becomes a logical-mathematical analysis operation from which temperature, pressure and chemical potential are defined. Subsequently, by means of a mathematical transform (Legendre transform), enthalpy and Gibbs free energy are defined. Next, the properties that can be measured are determined, such as the calorific value. All of the above applied to predict (model) metal recycling processes, metal production, material production processes and perform energy-environmental assessments.

Figura 4. Conceptos de la termodinámica que se relacionan con la energía



Fuente: Elaboración propia

Innovation results evaluation methodology

The impacts of the innovations were analyzed through class-to-class surveys, written and verbal surveys at mid- and end-of-semester, through quantitative evaluations of teacher performance, and through summative course evaluations.

Class-to-class surveys

At the end of each class, students were asked to write briefly about the following:

1) Your opinion about the class.

2) Your suggestions for improvement.

Answers should not be less than 20 words. With both items, the aim was to know immediately the impressions of the students regarding the teaching methodology of the class and the level of learning that the student perceived to achieve from the study topics. Responses were found regarding whether the time for class discussions was sufficient, whether the teacher's presentations were clear and whether the sequence of the class did contribute to cognitive conflict and rational learning or whether the student perceived that his or her level of learning increased. . The survey was discussed in the next class and the suggestions were implemented in a timely manner, that is, the methodological modifications proposed by the students were made. These surveys also made it possible to detect difficulties in the teaching and learning processes. All responses were analyzed week after week and additionally compiled throughout the semester. A summary of all the answers obtained during the semester of 2018 is included in table 4 (see annexes).

Written or verbal surveys at the middle and end of the semester

A teacher evaluation survey with self-applied guidelines was carried out in the middle and at the end of each semester. The survey was prepared with the aim of obtaining information regarding the implemented methodologies. Students were asked to write their opinions about their learning experience. They could refer criticism, improvements and suggestions regarding the methodology, course content and teaching activities according to the following format in Table 3.

Tabla 3. Formato de encuesta de evaluación docente efectuada a mitad de semestre

Opine cuáles fueron los aspectos positivos y los aspectos a mejorar de la experiencia educativa en los siguientes aspectos: • El método de enseñanza: considerando el aprendizaje como un cambio conceptual. • El planteamiento de la termodinámica: en términos de postulados y como una idea racional, lógica y secuencial. • La secuencia didáctica de cada clase. • Otro aspecto o comentario que quiera incluir.

Fuente: Elaboración propia

In order to know the opinion of the students regarding non-face-to-face education, the following question was included in the years of non-face-to-face education:

- For this course in particular, do you think that the educational experience of this subject would have been more complete in person?

The responses to the surveys were studied using a discourse content analysis method, according to the methodology proposed by Bardin (2002). With this tool, categories, results and findings about these opinions were identified using commercial software for qualitative content analysis (MAXQDA 2018). The above circumscribed to a descriptive exploratory qualitative research design described by authors such as Salgado (2007), Touraine (2012) and Valdivia (2008). Summary examples of the results for the years 2018 and 2021 are indicated in table 5 and table 6 (see annexes).

In order to obtain comparative data, quantitative results of the teaching surveys carried out by the university at the end of the 2018, 2019, 2020 and 2021 semesters were included in this work. Through these, the opinion of the students about the " content management and pedagogical skills" and "the teacher-student relationship". The first included questions regarding the teacher: did he show mastery of the contents? Did he transmit the contents of the course in a clear and understandable way? Did he create a favorable environment for learning? Did he adequately answer the students' questions? Did it motivate students to acquire the content of the course? Did it stimulate the active participation of students in their classes? Did it show commitment to the students' learning process?

The second included the following questions regarding the teacher: did he promote dialogue among the students? Was he respectful with the students? Was he open to receiving criticism and suggestions from the students? students?.

In this survey the results are weighted on a rating scale from zero to four. It should be noted that the institutional survey includes the question "How much did you learn with this teacher in the course?" and that this was weighted on a scale of one to seven. The results are presented in Table 7 (see annexes).

Summative assessment of course content

To evaluate the level of conceptual knowledge of thermodynamics achieved from basic postulates and concluding in the formulation of functions for practical use in metallurgy, at the end of the course the students attended a written and individual summative evaluation. The students had to develop a conceptual map explaining the definitions of the thermodynamic variables, relate them to each other, being the concept of internal energy the central axis of the entire conceptual construction. Table 8 and Table 9 (see annexes) include the instrument used for the evaluation with the respective rating rubric.

Results

The teaching innovation of the Metallurgical Thermodynamics subject through active methodologies and the development of thermodynamics in terms of postulates, began in 2015. It was a process that started from the identification of needs for learning concepts and teachings branches of the field, taking into account the opinions of students through class-to-class surveys, mid-semester surveys and group interviews. In parallel, the possible educational innovations to be applied were investigated. The foregoing was supported by an exploratory descriptive qualitative methodological design that provided a systematic and scientific approach to what was referred by the students, in such a way that it allowed the elaboration of categories that guided the aforementioned design. With this, a didactic planning and an instructional design were achieved that guided a paradigmatic transit, not only methodological and technical. Through the surveys, the students weighed and criticized the group activities, the teacher's explanations, the plenary discussion, the individual simulation activities and material review. The years from 2015 to 2017 can be considered as implementation. The methodology described in the previous paragraphs and the adaptation of educational innovations were fully implemented as of 2018.

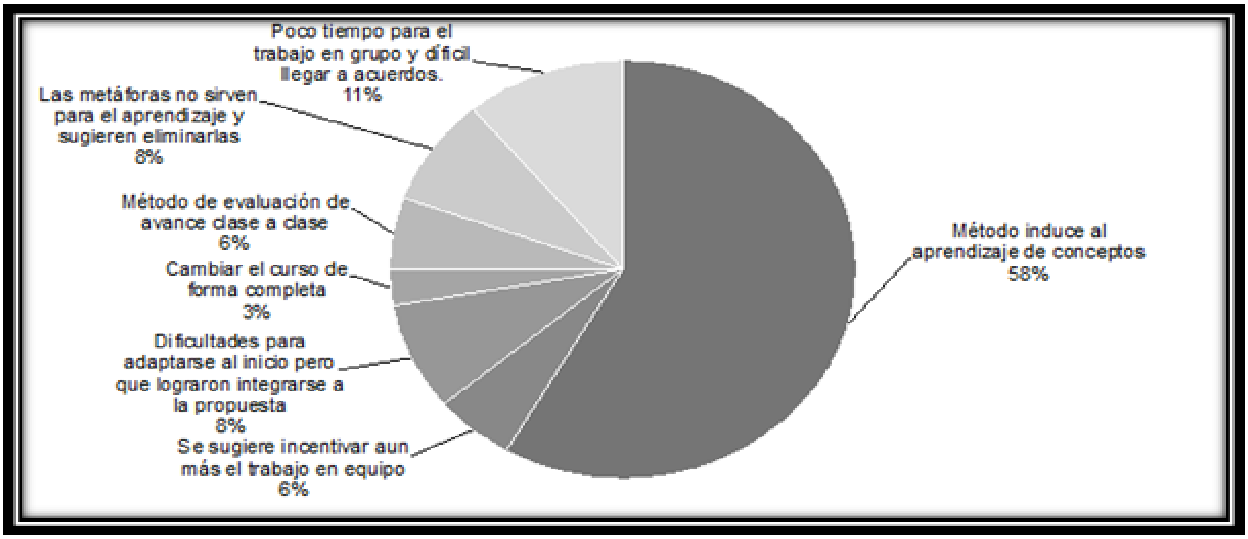
The study indicates a high degree of acceptance of the educational innovations in the course, both for the face-to-face modality and for the non-face-to-face modality. The students expressed how the course led them to a conceptual change and caused them to awaken a critical sense about the contents of thermodynamics. It follows, from the qualitative study of the responses, that there is no greater difficulty in being able to adapt to the active methodology. As indicated in figure 5, 58% of the students show a tendency to recognize the implemented method as an instrument that helps the learning of the concept and only 3% reaffirm changing the course completely. This revalidates the methodology implemented, taking the surveys carried out as an essential factor of this. It is recognized that one of the central improvements of the course is to optimize group work time and guide students in the constant search for answers.

Regarding the teacher as a mediator between knowledge and students, 57% validate it, which shows that the teacher has a clear impact on the way in which students socialize knowledge, due to the way in which the discussion develops. group. This meets the objectives of the active methodology, however, 43% of the students believe that the explanations are usually abstract, in addition to being presented very quickly.

In relation to the surveys at the end of each class, they considered that it helped to make the development of the course transparent.

The students admit that it is complex to understand the direction of the course in its initial stages. However, once this period is over, they begin to understand the concepts as a clearly connected sequence and consider themselves to be clearly learning. They appreciate that the course was carefully planned and class-by-class feedback is provided. They perceive deficiencies in the order of PowerPoint presentations.

Figura 5. Estadística de respuestas positivas y negativas sobre el método de enseñanza 2018



Fuente: Elaboración propia

They also consider that the method can be extended to other courses, which would help to face any area of knowledge with critical thinking. The students indicated how the methodology used has made the change from face-to-face to non-face-to-face modality bearable, although they unanimously consider that face-to-face classes would be more beneficial.

In the face-to-face classes, the participation of the students was achieved to answer the questions posed, according to the sequence of the class, by sending their answers electronically and anonymously. In the non-face-to-face classes, verbal participation, collaborative work and argumentative debate were much lower. Therefore, although the methodologies were adapted to the circumstances of non-face-to-face teaching, it is necessary to make additional adjustments to the active methodologies for this modality.

The quantitative information included in Annex 4 indicates how, for the parameters evaluated, the weighting of the students in the course in terms of content management and pedagogical skills and the student-teacher ratio in all years was above the average of the department and of the average of the university campus, without showing up for the course an appreciable difference between the face-to-face and non-face-to-face mode (information obtained from the UTFSM Management System portal).

Regarding the question of how much did you learn with the professor in Annex 4, a significant increase in the weighting of students in non-face-to-face classes is observed. These results, added to the analysis of the written surveys, indicate an adequate adaptation of the course to the non-classroom modality (information obtained from the UTFSM Management System portal).

Discussion

The hypothesis of the present work stated that cognitive conflict can lead to a change in the student's conceptual structure and promote a rational learning of thermodynamic concepts. To this end, educational innovations in the teaching of thermodynamics were proposed and put into practice for the metallurgical thermodynamics course of an engineering program. Innovations included a class sequence that allowed the student to confront their alternative concepts and modify them; implementation of active teaching and learning methodologies; search and analysis of the possible metaphors that the students used to build the alternative concepts, and teaching of thermodynamics through postulates as opposed to the traditional method of statements. The impacts of the innovations were analyzed through surveys and summative evaluations.

The result of the summative evaluation and the analysis of the surveys suggest that the course made possible in most of the students the expected conceptual change in both modalities, face-to-face and non-face-to-face.

However, part of the above conclusion was obtained from the student's perception of the course. It is difficult to assess whether the conceptual change will be sustained in the long term or whether its effect is perishable. It is important to note that various studies indicate the persistence of alternative concepts and the difficulty of eradicating them even after well-planned educational innovations.

A limitation in the implementation of the first stages of the course is the difficulty of the students to understand the dynamics and orientation of the classes. It is possible to consider that this is due to the training received in the physics courses. Like the approach of thermodynamics in terms of postulates, physics can be taught in the same way from the principle of least action (or Hamilton's principle). This could be considered equivalent to the postulate of an entropy function. Therefore, a task still to be done is to integrate physics courses with this innovation in teaching thermodynamics.

The teaching and learning investigations of thermodynamics could be classified into studies of alternative concepts with analyzes of specific topics such as energy, heat, entropy or others. They usually include methodological recommendations to achieve conceptual changes. Likewise, the literature reports the use of metaphors to examine thermodynamic concepts and their teaching and learning. Another active area of research is the use of different alternatives for teaching thermodynamics, for example, from a mathematical, historical, molecular point of view and others mentioned above. This type of research usually reports learning outcomes. Considering that the present work used a set of different methodologies for the design of the course, one of its limitations is the difficulty of evaluating the weight of each one in the learning process. Therefore, it is difficult to make a comparison of the present work with those found in the literature. It could be considered that teaching through postulates and the generation of the cognitive conflict that this contributes to generating are the factors with the greatest impact on students.

Conclusions

The results of the summative evaluations showed that 84% of the students passed the evaluation with an average of 75/100 in their grades, which can be considered as an additional indication of the effectiveness of the implemented methodologies. In 2018, tests of a knowledge test model were started in order to evaluate the possible comparative conceptual change at the beginning and end of the course. The results will be the subject of a future work.

It is beyond the scope of the study to assess which (or which) of the four strategies is more effective in the teaching and learning process. From the results of the face-to-face and non-face-to-face years, it can be concluded that the active methodology is probably not the most important. Despite the difficulties in its implementation in the non-attendance modality, the perception of the course by the students improved in some aspects. Nor do we have answers about how to implement a non-face-to-face modality that includes active methodologies to a greater extent. The students suggest dividing the group into small sessions, where interactive small group discussions take place. These ideas will be implemented in the following courses, in case they continue in a non-face-to-face way.

This paper does not present comparisons between a traditional course and this one using the four methodologies. The only possible comparison at the moment is the traditional course taught by another teacher. As Exhibit 4 indicates, for that particular course the students quantitatively weighted it below the department and campus average.

Future lines of research

The implementation of the course in a non-face-to-face way was due to situations beyond our control, therefore, the methodological adaptations were made on the fly. Future research could study bibliographical references that allow having a conceptual support to incorporate non-face-to-face methodologies in a planned way. On this basis, research could include objective comparisons between face-to-face and non-face-to-face courses.

On the other hand, in most of the groups of students with whom this research was carried out, it is clear that a percentage of them have difficulties in adapting to the teaching methodologies implemented. These students, if previously identified, could be part of a control group. In this way, the traditional teaching method would be compared with greater certainty with the one proposed in this study. The identification of students as possible members of the control group could be selected through psychological tests and with the acceptance of the student.

Another aspect to include in future research is the impact of the methodologies of this study in the solution of practical problems in metallurgy, compared to the traditional method of teaching thermodynamics. This study could be carried out in parallel with the one suggested in the previous paragraph.

This study will be complemented in the future with an evaluation of conceptual knowledge of thermodynamics at the beginning and end of the course, different from the summative evaluation. At the moment, the necessary instrument for said evaluation is being developed. Although this type of instrument exists in the literature, its objective is to evaluate very specific concepts such as energy, without taking into account a general integration of thermodynamics.

Another interesting line of study is related to determining the long-term impact of the methodologies implemented in the course. For example, its influence on other courses, on the solution of engineering problems where thermodynamics is not the predominant factor (for example, the kinetic aspects of processes) and on performance in working life as engineers. This would require a long-term follow-up of the student in their university and work performance.

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Anexos

Tabla 4. Resumen de resultados de encuestas clase a clase para el año 2018

Pregunta	Núm. de respuestas	Categoría	Respuestas
Opiniones acerca de la clase	15	Metodología y comprensión de los conceptos	El método de enseñanza induce al aprendizaje de los conceptos de termodinámica
	8	Capacidad del profesor	Estudiantes declaran que “es capaz de enseñar”, “tiene buena disposición”, “el profesor se preocupa”, “es un excelente guía en la clase”.
	6	Aprendizaje activo	La metodología estimula la búsqueda y aprendizaje de conceptos. Distintas técnicas del curso son mencionadas como facilitadoras: el debate, el diálogo grupal, ejemplos y método basado en metáforas.
	2	Método de evaluación por clase	Se refiere tanto al interés del profesor en medir e implementar mejoras como a la valoración del estudiante en torno a su aprendizaje.
	2	Promoción del trabajo en grupo	Manifiestan que fue generado un ambiente propicio para: “escuchar otras ideas”. Aunque, se sugiere incentivar aún más el trabajo grupal y plenario.
Sugerencias de mejora	8	Las PPT y tutoriales	Son señalados como recursos insuficientes. La mayoría sugiere un

			cambio en el diseño y ejecución de tutoriales.
	7	Ejemplos, Talleres y Ejercicios	Fueron considerados como insuficientes
	6	Explicación del profesor	Se califican como "muy abstractas", "repetitivas", "no bien preparadas" y "muy rápidas". Se pide ser más concreto en la explicación.
	4	Metodología grupal	Hay dificultades en acoplar un buen grupo de trabajo con sus pares. Además, se critica el diseño de las actividades; no es suficiente el tiempo asignado para ejecutarlas y hay dificultad en acordar/consensuar el trabajo asignado.
	5	Adaptación a la nueva metodología	Los estudiantes expresan qué dificultades iniciales para ajustarse a una metodología activa de aprendizaje. Sin embargo, enuncian que lograron integrarse a la propuesta. Un estudiante prefiere la clase magistral.
	3	Método basado en metáforas	Indican que no aportó a su aprendizaje. Es preferible no seguir usando metáforas.

Fuente: Elaboración propia

Tabla 5. Resumen de resultados de encuestas escritas o verbales a mitad y final de semestre para el año 2018.

Metodología	Núm.	Respuestas
Planteamiento en términos de postulados	25	Se describe como novedoso
		Es una metodología distinta a otras, no se basa en entregar información para asumirla como verdad absoluta.
		En el discurso de los estudiantes el ejercicio de metaforizar, reflexionar críticamente y favorecer el entendimiento es desempeñado/facilitado por el profesor
		Es posible describir que los resultados descritos y las actitudes positivas hacia la metodología ocurrieron de manera sucesiva y acumulativa a lo largo de las clases.
		Una de las frases señala que al profesor “le gusta enseñar”. Se aprecia compromiso, preocupación e intentos permanentes para favorecer el correcto entendimiento por parte de los estudiantes.
		El profesor influyó para desarrollar pensamiento crítico ante la literatura/bibliografía. Las teorías se entienden como postulados o convenciones que no constituyen una verdad absoluta.
		El profesor se preocupa por aprender y mejorar continuamente.
		El profesor y su modalidad es excelente, el curso requiere de dedicación si deseas aprender. Todos los cursos debiesen tener esta modalidad, ya que el estudiante aprende por sí mismo y no se limita a repetir lo que dice el profesor, como suele pasar en todos los demás ramos.
Planteamiento en términos de postulados	10	Es reconocida la metodología para introducir la clase, enunciar los contenidos que serían abordados en la jornada. Además, favoreció el diálogo.
		Este método facilitó el entendimiento, promovió el pensamiento crítico y científico, se logró dar materialidad y objetivar el concepto.
		Se aprecia interés por parte del profesor para que el estudiante entienda los conceptos tratados. El profesor otorga tiempo tanto en

		la sesión o clase como en otros espacios de la universidad y su oficina.
Secuencia de cada clase Iniciar la clase con una pregunta	11	Otorga confianza a los estudiantes.
		El trabajo grupal aumenta la velocidad del aprendizaje por la interacción y el efecto sinérgico que implica focalizarse en un concepto u objetivo.
		Es valorado en comparación con el método tradicional donde es expuesto/entregado unidireccionalmente el conocimiento.
		El rol del profesor es descrito en la intencionalidad de generar diálogo y discusión durante el trabajo grupal.
		La participación dentro del grupo y en los plenarios aumentó con el paso de las clases
		El profesor promovió reflexionar críticamente sobre la propia práctica como ingenieros.
Otros aspectos	7	El uso de pizarra facilitó la comprensión sin la necesidad de anotar en cuaderno u otro medio de registro.
		El uso de pizarras en el trabajo grupal promovía la participación

Fuente: Elaboración propia

Tabla 6. Resumen de resultados de encuestas escritas o verbales a mitad y final de semestre para el año 2021.

Metodología	Núm.	Respuestas
Planteamiento en términos de postulados	22	Me ayudó a eliminar ideas que vienen de antes.
		Me aclaró los conceptos que tenía, permitiéndome completar y entender de mejor manera el curso.
		Jamás me había preguntado si se podía aprender o no, o qué ideas tenían previamente de los conceptos.
		Considero que es una metodología aplicable a otros cursos.
		El curso lo encuentro un desafío personal. Estoy acostumbrada a que simplemente me presenten cómo enfrentar un problema con fórmulas sin plantearme ni cuestionarme todo desde cero.
		Este método me cuestionó todo lo que ha aprendido y se comienza a entender de otra manera los conceptos.
		El método me hace sentir que el profesor confía en nuestra capacidad intelectual.
Planteamiento en términos de postulados	15	Es positivo tener una misma línea de trabajo a lo largo del curso y que los conceptos se vayan relacionando entre sí. Asimismo, la metodología de trabajo clase a clase ayuda a ir asimilando los conceptos de forma colectiva.
		El trabajo con postulados nos permite tener una idea general sin perder demasiada información relevante.
		El plantear la termodinámica desde distintos puntos de vista (tanto matemático como conceptual) ayuda a pulir los conceptos de forma adecuada.
		Las clases han sido llevaderas ya que se ha ido secuenciando cada uno de los aspectos importantes, generando un pensamiento un poco más profundo y crítico de la termodinámica.
		En un comienzo me causó un poco de queja mental, no entendía cuál era el planteamiento de la termodinámica, o el enfoque del profesor. Sin embargo, con el tiempo logré tomar el sentido del planteamiento, tomándolo como algo más reflexivo y teórico, en contraste con algo

		numérico. Con esto, logré entender que la mayoría de estas ideas están basados en postulados, con una sintaxis lógica, que van unidos racionalmente con un tema en común, y esto atribuye a un término más general sobre los temas tratados de energía. Ahora considero primordial partir de lo básico o el origen hacia una manera de captar algo más allá.
		El plantear la termodinámica y sus postulados como una idea racional, lógica y secuencial ayuda a ver todo como un conjunto, es decir, nos muestra el cómo se relacionan los conceptos.
		La manera en la cual se planifico la asignatura está bien, nos ha enseñado todo de la manera más secuencial posible. Logra que unamos contenidos simples con algunos más complejos. A veces es más difícil de entender cuando se va directamente al punto.
		Al no estar familiarizados, la metodología se hace densa y difícil de comprender. Con el paso del tiempo y acostumbrándose un poco más, el método se hace más fácil.
Secuencia de cada clase	17	La estructura de las clases propicia el entendimiento de los conceptos planteados en clase.
		El profesor planteó el curso de una forma meticulosa y planeada con antelación. Gracias a esto, el curso se hace más ameno y amigable para el estudiante.
		Me gusta que se analicen las respuestas de las encuestas previas, ya que así se facilita percibir el pensamiento errado.
		Se genera una constante complementación de la materia, lo cual hace que muchos conceptos no logren perderse con el paso de la materia y las clases.
		La retroalimentación en términos de la clase y su contenido, para luego partir con preguntas respecto a la materia que se empezará a conocer, para finalmente lograr una discusión del tema a tratar es acertado. Se toma cada parte de lo necesario para seguir aprendiendo, y lograr naturalizar los conocimientos o al menos tomar un juicio (o duda) de la ciencia como tal.

		Es un buen ejercicio de razonamiento el hacernos pensar sobre los conceptos, concientizándonos respecto a lo que creíamos significaban. El problema de los conceptos se atacó desde la base, más que incorporando nuevos conocimientos.
		Al estar todo relacionado y cada concepto unido con otro, se puede hacer un seguimiento sin perder el hilo.
		Se podría mejorar con actividades colaborativas entre los estudiantes.
Otros aspectos	7	Es motivador el efectuar una consultas al inicio de la clase con la finalidad de reconstruir los contenidos presentados en el curso y analizando las opiniones de los estudiantes constantemente para transparentar el desarrollo del curso.
		Considero que revisar los comentarios de los estudiantes antes de comenzar una clase es una muy buena dinámica para transparentar el desarrollo del curso.
		La secuencia de clase está muy bien diseñada, pero los PowerPoint deben mejorarse. Hacerlos en manera secuencial, de paso a paso, puede que permita que sea más divertido de leerlos o tomarles atención durante o después de la clase.
		No colocar tanto texto en las diapositivas para que no se genere un estrés visual.
Experiencia educativa no presencial	18	La actitud y predisposición en cada clase hace que esta sea más amena, y que pese a todo este sistema de clases no presencial, se haga más llevable el asistir a clases, ya que interactúa con nosotros, a diferencia de otros ramos.
		El profesor de por sí fomenta bastante la participación en clase, lástima que el contexto no dé para realizar este curso de forma presencial, pues ahí se notaría mucho más potenciada la metodología que plantea el profesor.
		Me hubiese gustado que este curso fuera presencial, considero que se hubiese aprovechado al máximo.

		Siento que la forma presencial hace más propicio el estudio de la asignatura, destacando que el profesor se adaptó bien de forma virtual.
		Según mi experiencia con las clases no presencial, siento que se ha perdido la costumbre de interactuar a la hora de responder las preguntas planteadas, y también el hecho de realizar preguntas al profesor, por el hecho de que se siente lejanía, al no conocerse en persona.
		De forma virtual no suele ser tan motivante, quizás la esencia de vivir no es sólo mirar una pantalla, o hablar tras un micrófono, pues es difícil naturalizar aquello de un día para otro, pues el humano como tal, tarda años y mucho más en adecuar costumbres o formas de percepciones distintas a la tomadas desde la niñez, pero es totalmente entendible que se quiera mejorar siempre la educación y la forma de enseñar bajo este contexto que ha traído muchas repercusiones en términos de salud y psicológicos.
Otros aspectos	7	Lo más probable es que sí, debido a que por medio de las clases no presencial hay muchos problemas que se pueden generar en los estudiantes, ya sea distracciones u otros caminos como ayudar en casa y no tener el tiempo necesario para estar pendiente 100 % a la clase, ya que cuando a veces hay que ayudar en la casa, la mamá a veces se enoja si uno no lo hace.

Fuente: Elaboración propia

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Tabla 7. Resultados de encuesta docente comparativos, profesor, departamento, campus. Años 2018, 2019, 2020, 2021

Aspecto evaluado	Modalidad	Año	Profesor	Departamento	Campus
Manejo de contenidos y habilidades pedagógicas (escala del 1 al 4)	Presencial	2018	3.6	3.4	3.7
		2019	3.8	3.5	3.7
	No presencial	2020	3.8	3.7	3.7
		2021	3.9	3.6	3.7
	Curso metodología tradicional		3.3	3.5	3.7
Relación profesor estudiante (escala del 1 al 4)	Presencial	2018	3.7	3.5	3.7
		2019	3.9	3.5	3.7
	No presencial	2020	3.9	3.7	3.7
		2021	3.9	3.6	3.7
	Curso metodología tradicional		3.4	3.5	3.7
¿Cuánto aprendiste con este profesor en el curso? (escala del 1 al 7)	Presencial	2018	5.6	5.6	5.9
		2019	5,5	5,5	5,9
	No presencial	2020	6.4	5.9	5.9
		2021	6.5	5.8	6.0
	Curso metodología tradicional		4.8	5.6	5.9

Fuente: Información obtenida del portal del Sistema de Gestión de la UTFST

Objetivo del certamen:

Evaluar el nivel de conocimiento del estudiante acerca del desarrollo conceptual de la termodinámica, partiendo de postulados básicos y concluyendo en la formulación de funciones de uso práctico. Se espera que el estudiante demuestre que el desarrollo conceptual desemboca en la formulación de ecuaciones que describen los procesos termodinámicos por medio de parámetros susceptibles de medir experimentalmente.

Preguntas:

1) (10 puntos) Describa el concepto de energía, con las características dadas a esta y el modelo (o metáfora) que ha servido de base para el curso. Indique cómo el modelo (o metáfora) incluye las características asignadas al dicho concepto.

2) (50 puntos) Describa la secuencia del desarrollo conceptual de la termodinámica partiendo del principio de "La Conservación de la Energía" hasta la obtención de una ecuación de uso práctico de la "Energía Libre de Gibbs".

El desarrollo conceptual deberá incluir mínimamente los siguientes aspectos:

- Estar alineado con el desarrollado del curso de Termodinámica Metalúrgica (MET 137), segundo semestre del 2016.
- Incluir ejemplos prácticos relacionados con la metalurgia, tales como reacciones químicas en procesos metalúrgicos, diagramas de fases de sistemas metálicos u óxidos, procesos de producción de cobre usando un horno *flash*, etc. Los ejemplos prácticos deberán incluir claramente el *objetivo de la termodinámica* y la forma de resolverlos.
- El desarrollo conceptual deberá indicar de forma precisa cuáles son los parámetros susceptibles de medir experimentalmente el equilibrio y dar ejemplos de cuáles se pueden calcular a partir de las mediciones.
- Emplear en su respuesta los siguientes conceptos o definiciones. El significado termodinámico de las definiciones o conceptos empleados deberán estar claramente explicados durante el desarrollo de la secuencia conceptual.
    - Calor
    - Calor específico a presión constante
    - Conservación de energía
    - Definición cuantitativa de calor
    - Definición de la energía libre de Gibbs

- Definición de la ecuación de entalpía
- Equilibrio termodinámico
- Equilibrio térmico
- Equilibrio mecánico
- Equilibrio químico
- Energía interna
- Medición de cambio de energía interna
- Ecuación de entropía
- Parámetros termodinámicos extensivos
- Parámetros termodinámicos intensivos
- Potencial químico
- Postulado de maximización de la entropía
- Postulado de la minimización de la energía interna
- Presión
- Propiedades matemáticas de la función de entropía
- Sistema termodinámico simple
- Sistema termodinámico compuesto
- Sistema termodinámico cerrado
- Sistema diatermal
- Sistema adiabático
- Transferencia de calor
- Temperatura

1) (10 puntos) Teniendo en cuenta el desarrollo anterior, describir claramente el "Objetivo de la Termodinámica" y su aplicación en la metalurgia.

2) (10 puntos) Describa la función de energía libre de Gibbs para una mezcla de gases ideales. Explique el significado de la función y cómo se asocia al potencial químico de cada uno de los componentes del gas.

3) (10 puntos) Usando la derivada total de la función de entropía (o de energía interna), desarrolle cómo en el equilibrio la definición de *temperatura*, *presión* y *potencial químico* concuerdan con las características a nivel sensoriales que percibimos de estos parámetros. Efectúe el análisis solo para una de estas definiciones.

4) (10 puntos) Explique de forma breve cómo obtener experimentalmente el calor específico de una sustancia.

Tabla 8. Rúbrica de evaluación para el numeral 2. La naturaleza conceptual de este certamen requirió elaborar una rúbrica especial

Aspectos	> 85	55-85	> 54
1) Mapa conceptual (30 puntos)	Mapa conceptual completo partiendo del principio de "la conservación de la energía" hasta una ecuación de energía libre de Gibbs. La secuencia es lógica y claramente explicada.	La secuencia es clara pero le faltan elementos.	La secuencia no es clara y contiene muy pocos elementos.
2) Descripción del objetivo de la termodinámica (10 puntos)	Descripción clara del objetivo de la termodinámica de acuerdo con lo discutido en clase y con el libro de Callen.	La descripción es incompleta.	No fue incluida.
3) Ejemplos prácticos relacionados a la metalurgia (20 puntos)	Ejemplos claros de procesos metalúrgicos, diagramas de fases, procesos de producción de cobre.	Ejemplos imprecisos. Solo uno o dos ejemplos.	No incluye ejemplos.

		Ejemplos no conectados con la discusión en curso.	
4) Descripción matemática de “energía libre de Gibbs” (10 puntos)	Formulación completa de una ecuación de energía libre de Gibbs.	Formulación incompleta de una ecuación de energía libre de Gibbs.	No incluye una ecuación de energía libre de Gibbs.
5) Definición de los conceptos (30 puntos)	Incluye la mayoría de los conceptos incluidos en la lista. Conceptos precisos y claramente definidos.	Incluye algunos conceptos o los conceptos no están claramente definidos.	Incluye solo algunos conceptos o no fueron claramente definidos.

Fuente: Elaboración propia