


## Article

# A New Educational Thermodynamic Software to Promote Critical Thinking in Youth Engineering Students

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**Abstract:** This article presents the application of a new educational thermodynamic software called MOLECULARDISORDER, based on graphical user interfaces created in Matlab® to promote critical thinking in youth engineering students, by means of the energy and entropy balance application in different systems. Statistics of the results obtained by the youth students are shown to determine the influence of the software in a regular course in thermodynamics to promote critical thinking. Two case studies were done by the students, where parameters such as temperature of the fluid and metal surfaces, pressure of the system, mass of the fluid and solid, volume, and velocity of the fluid are used to obtain output variables such as enthalpy, entropy, changes in entropy, entropy production, and energy transfer in the chosen system. Four cognitive skills were considered to evaluate the cognitive competencies of interpreting, arguing and proposing, and interacting with the different graphical user interfaces; these cognitive skills (CS) were argumentative claim (CS1), modeling (CS2), interpreting data/information (CS3), and organization (CS4). Student's T-test was used to compare the degree of difficulty of each criterion. The case studies were evaluated first without using the software and then with the use of the software to determine the significant effect of the software quantitatively. A population of 130 youth students was taken to perform the statistical analysis with a level of significance of 5%. With the help of the software, the students obtained an improvement when performing case study 1 since the  $p$ -value obtained was 0.03, indicating that there are significant differences between the results before and after taking the software. The overall averages of the grades for case study 1 had an increase after using the software from 3.74 to 4.04. The overall averages for case study 2 were also higher after taking the software from 3.44 to 3.75.

**Keywords:** educational software; critical thinking; graphical user interface; entropy analysis; youth engineering students

## 1. Introduction

The general industry of processes that work with equipment where there is energy transfer needs highly trained personnel in unit operations. People who possess that knowledge acquire the skills to find and solve efficiently different kind of problems in any industrial equipment or process. However, to have a complete understanding of this engineering area, it is necessary to understand its components. One of them is the heat transfer phenomenon, which is involved in many industries such as chemical and petrochemical, oil refineries, food industry, etc. This phenomenon must be profoundly understood when designing equipment that requires heat exchange due to the need to make use of maximum energy transfer. Hence the importance of studying the term entropy, since it is a particular physical quantity used to determine the part of the energy that cannot be used to produce work.

To train youth students in this area to be experts in energy systems in the future, the academy employs in their curricula particular tasks in unit operations laboratory, where the youth student can operate and understand the energy behavior of different systems. Although this methodology is highly valuable, it is complex to comprehend all phenomenological behavior entirely because it is essential to perform a significant number of experiments, which is not feasible in the time of dedication for all subjects. To mention an example, the experiments run in a shell and tube heat exchanger has to input many variables to control the exit temperature. Some variables can be handled but there are many others that cannot be manipulated, such as the number of deflectors, the number of tubes, length, diameter and material of the shell and tubes, number of tube passes, among others. Entropy and energy balances are affected by all the variables mentioned before. This situation makes it difficult for the student to understand all the internal phenomena happening inside a heat exchanger, causing a limitation in their total comprehension. This limitation affects the development of the educational skills of the students because it decreases their motivation during their learning process. The same problem happens when using other equipment. One way to help students to reach their goal of understanding all the phenomena in equipment is by using an essential complement such as computer tools, where the student using simulations can manipulate all the input variables they want and observe the behavior of all the output variables. Another way to help students is by using only books to complement their learning, but it takes lots of time to reach the goals, and it does not encourage students to obtain all the necessary knowledge as virtual media does [1].

Developing software for training youth engineering students has become a necessary action because they allow interactive learning with high effectivity compared to traditional methods [2–7]. It means that the evolution of the learning process has created the need to use additional academic tools that are linked with the state of the art of technology. The creation and use of a different kind of software in all areas of knowledge [8–14] has been a solution to this problem. The new generation of students was born in a digital era [15] where computers dominate over the books. This trend of learning addresses educators in the use of computers to teach their subjects.

Recent research on the development of educational skills has determined that schools and higher education institutions should not base their curricula on the knowledge acquisition in various areas of knowledge, but on the development of critical thinking [16–18]. Current learning in engineering has the problem of gathering information which requires students with a good memory, but not with critical thinking. Therefore, critical thinking is not an innate ability of the student, but rather a skill acquired from an educational process oriented to the excellent exercise of the educating entity, as several educators have achieved through theoretical–practical activities [19]. On the other hand, for the development of critical thinking, essential components of this good judgment of reason have been determined, such as knowledge, inference, evaluation, and metacognition [20], which are based on comparison and analysis to make deductions from the processes in an inductive or deductive way, through the regulation of the cognitive system.

Through an evaluative guide, critical thinking of students is stimulated, since connections are established between two areas of knowledge. It helps to understand the proposed case studies more assertively, and also the analysis of processes, through a critical evaluation influenced by the acquired experience of thermodynamic phenomena [21]. In this way, it is proposed the development of a thermodynamics software that encourages the cognitive and intellectual process of the student, thus generating professionals with broad metacognition [20].

The Critical Thinking Community has defined critical thinking as the disciplined intellectual process of activating [22], conceptualizing, applying, analyzing, synthesizing, and evaluating information gathered or generated by observation, experience, reflection, and reasoning with the help of a workshop related to the fundamental thermodynamic theory [23–27], as well as being a guide for constructing propositions and acting [28].

All thinking takes place within the framework of the specific area of knowledge, i.e., there are different ways of thinking: Biological, chemical, geographical, sociological, anthropological, historical,

artistic, ethical, or philosophical, according to the domain of knowledge. Good learning implies thinking with discipline within the field of knowledge studied. It involves thinking logically, to formulate vital questions and problems, to express ideas clearly and precisely, to gather and evaluate information using ideas to interpret it, to formulate conclusions and solutions, to recognize and evaluate assumptions, implications, and consequences, to communicate effectively with others, and to relate what is learned in a subject with other subjects [29].

To become a critical self-directed learner, which is the skill proposed through this educational tool to the engineering students, it is suggested seeking connections between what is known and what is sought to learn, identifying the underlying idea in the subject of study, learning the systematic way of thinking of field study, and identifying the thinking structure of the discipline [30]. However, independent of the area of knowledge, there are eight essential elements of thinking present in all domains, where students think based on a purpose or point of view, which is supported by assumptions that lead to certain consequences [31].

The main contribution of this paper is the development of new educational software to study a specific area of thermodynamics in engineering, as a powerful tool to promote critical thinking development in undergraduate students. The software was created to let students manipulate different variables such as temperature, pressure, volume, and mass rate, among other variables, to analyze the behavior of entropy in different systems, depending if the process is reversible or irreversible, for different substances by the use of mathematical equations coded in Matlab<sup>®</sup> with the implementation of a graphical user interface. The computer program was evaluated with four cognitive skills, which are graph, document, graph-table, and analysis. The assessment of these cognitive skills was carried out under two case studies in undergraduate students of mechanical engineering in the class of thermodynamics at the Universidad del Atlántico, where 130 youth students run the software MOLECULARDISORDER. The selected case studies were heat transfer of a liquid with a metal bar in a container, and energy loss of stream in a pipe. Some student's T-tests were used to compare the degree of difficulty of each criterion. The importance of the software was confirmed in the learning process due to the significant positive effect found in the T-test.

## 2. Material and Methods

### 2.1. Critical Thinking Development

To develop critical thinking through an educational tool in engineering, the elements of critical thinking must be fulfilled. Thus, a theoretical–practical guide based on the MOLECULARDISORDER software has been proposed, as shown in Figure 1, where the student must identify the purpose of what is being thought (Element 1), and the question that the student must try to answer (Element 2). Similarly, the student is guided in the assumptions that precede this thought, which must be able to justify it considering the previous knowledge acquired (Element 3).

The other elements of critical thinking in the student are achieved through a workshop shown in Figure 2, which requires the use of the software. Figure 2 shows a workshop about the second law of thermodynamics that students must develop completely during the thermodynamics class time with the help of the software. The student must set some operating conditions, then, change some input variables, and finally determine some output variables. With the obtained results, the table shown in Figure 2 has to be filled. After that, students must proceed to make the plot shown in Figure 2 and analyze the behavior found of the dependent variables writing a discussion of the results. In other words, the student must use the concepts and present his point of view to evaluate the strengths and weaknesses of his propositions (Element 4) by identifying the input data for the development of calculations and operations with the software (Element 5). The student must present the information and evidence through plots of the process (Element 6). The student must identify the fundamental concepts of his reasoning, which allow us to study and obtain quantitative values of the phenomenon (Element 7). Finally, the students must infer on the results obtained and explain all the patterns found in

the plots (Element 8). It is required to promote a set of cognitive skills (CS) to evaluate the development of the critical thinking of the students through an educational activity [32], such as the argumentative claim (CS1), modeling (CS2), interpreting data/information (CS3), and organization (CS4).

### Critical thinking development in engineering students: case Molecular disorder

## CASE STUDY 1. SOFTWARE MOLECULARDISORDER

### INTRODUCTION.

In the mid-19th century many researcher focused on studying the heat transfer methods and the different forms of energy involved in real processes, since, as stated in the first thermodynamic law, it establishes that the cyclic integral of heat is equal to the cyclic integral of work [1], but does not impose restrictions on the direction of the forms of energy. In other words, it does not express that heat by nature is always transmitted from one focus with higher temperature to another focus with lower temperature until it remains in thermodynamic equilibrium. The second law of thermodynamics postulates this, justifying that processes go in one direction only and never in the opposite direction, unless the characteristics of the process change [1-3].

#### Element 1

The second law of thermodynamics is expressed by itself quantitatively through the entropy, which has an abstract meaning in processes. Entropy in phenomena is not preserved and represent the molecular disorder caused by the kinetic energy and untapped potential of the molecules of the substance, which are excited by heat from the environment or some internal work of the process (heat produced internally). Through a set of virtual practices based on novelty software integrated with case studies, a significant learning experience is proposed to engineering student oriented to develop the critical thinking skills as shown in Fig. 1.

Through this activity, the student is expected to develop critical thinking skills for the purpose of analyzing the information related to the second law of thermodynamics in an objective manner to make reasonable decisions.

### CASE STUDY 1.

#### Element 2

A steel 1045 bar with a mass ( $m$ ) initially has a temperature ( $T_1$ ). The bar need to be tempered using a water bath with salts, with a volume ( $v$ ) and temperature ( $T_a$ ) as shown in Fig. 2. The water temperature will remain constant until the temperature of the bar drops to ( $T_2$ ) and the pressure in the container is constant. The case is oriented to analyze the entropy production of the systems, and justify the response.

Please note the following assumptions.

- ☐ Fill in all input data.
- ☐ Enter mass greater than 0.
- ☐ Enter a temperature 2 bar greater than or equal to the water temperature.
- ☐ Enter a bar temperature higher than the water temperature.
- ☐ Assume two independent subsystems that are thermally isolated from the surrounding area.
- ☐ Assume a constant specific heat.

#### Element 3

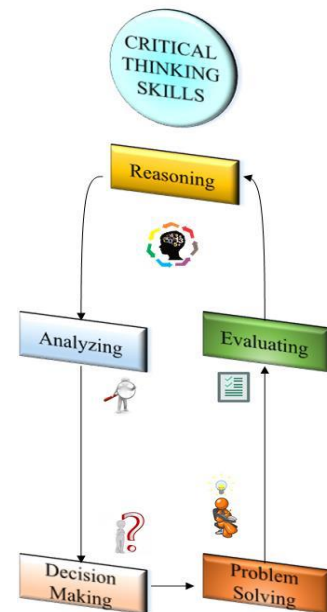


Fig. 1. Critical thinking skills in software molecular disorder.

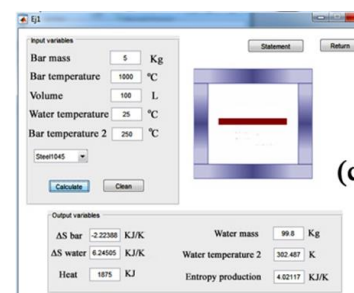


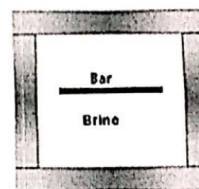
Fig. 2. Software molecular disorder case study Heat transfer of liquid with a metal bar inside a container.

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Date: 11/12/2017

1. In an isolated recipient like it is showed in Picture 1, it is wanted to analyze the change of the initial temperature of water to different final temperatures of the bar based on the formula  $(\Delta S_{\text{water}}/\Delta S_{\text{bar}})$  and entropy production, with some parameters showed in Table 1. For this, it is taken measurements when the initial temperature of water change 5 °C in the interval [25, 70] to different final temperatures of the bar [250 °C, 350 °C, 450 °C, 550 °C].



Pic 1. Isolated recipient.

## Element 5

Bar mass(kg)	$T_{\text{initial bar}}(^{\circ}\text{C})$	Volume (L)	$T_{\text{initial water}}(^{\circ}\text{C})$	$T_{\text{final bar}}(^{\circ}\text{C})$
5	1000	100	25	250

Table 1. Initial conditions.

### Element 7

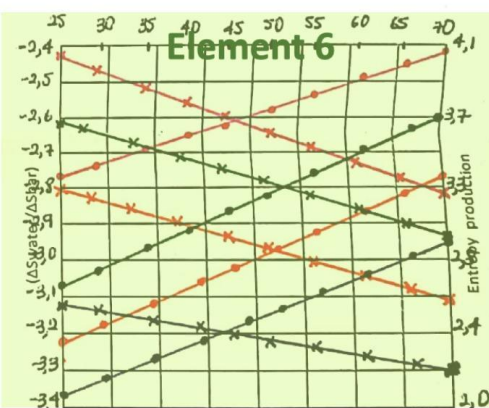
T. Initial water	T. Final bar = 250 °C		T. Final bar = 350 °C		T. Final bar = 450 °C		T. Final bar = 550 °C	
	$\Delta S_{\text{water}}/\Delta S_{\text{bar}}$	E. Production	$\Delta S_{\text{water}}/\Delta S_{\text{bar}}$	E. Production	$\Delta S_{\text{water}}/\Delta S_{\text{bar}}$	E. Production	$\Delta S_{\text{water}}/\Delta S_{\text{bar}}$	E. Production
25	-2,80818	4,02117	-3,03267	3,63123	-3,24456	3,17450	-3,44652	2,66775
30	-2,76218	3,91837	-2,92994	3,54245	-3,19130	3,09918	-3,38989	2,60603
35	-2,71766	3,81937	-2,93422	3,45648	-3,13477	3,02630	-3,33510	2,54629
40	-2,67455	3,72401	-2,8823	3,37324	-3,08977	2,95573	-3,28054	2,48844
45	-2,63294	3,63114	-2,84328	3,29261	-3,04154	2,88738	-3,23066	2,43241
50	-2,59232	3,54113	-2,79934	3,21445	-2,9947	2,82112	-3,18086	2,37810
55	-2,55307	3,45334	-2,75492	3,13867	-2,94927	2,75837	-3,13257	2,32544
60	-2,51499	3,36916	-2,71577	3,06514	-2,90520	2,69456	-3,08572	2,27436
65	-2,47803	3,28696	-2,67582	2,99378	-2,86243	2,63407	-3,04026	2,22478
70	-2,44214	3,20715	-2,63703	2,92449	-2,82094	2,57523	-2,99611	2,17664

Table 2. Results.

## Element 4

Analysis and discussion of results.

According to the obtained data, we affirm that as the initial water temperature increases, the ratio of entropy deltas increases and the production of the same decreases. On the other hand, by keeping the initial temperature of the water constant and changing the final temperature of the bar, the ratio of entropy deltas decreases and the production of the latter. Looking at the graph of results, we see a linear behavior of the variables, affirming that the initial water temperature is inversely proportional to the production of entropy, but directly to the ratio of deltas of the same and therefore it is to the delta of entropy of the water.



Water temperature

— 550 °C (Δ) — 450 °C (Δ) — 350 °C (Δ) — 250 °C (Δ)  
 — 550 °C (P) — 450 °C (P) — 350 °C (P) — 250 °C (P)

Pic 2. Graph.

## Element 8

Figure 2. Elements of the Critical Thinking theory involved in the MOLECULARDISORDER Workshop.

The main objective of the Common Core State Standards (CCSS) [33] and the Next Generation Science Standards (NGSS) [34] is to determine the topics that students should learn at different levels, for the proper development of professional practice. However, the CCSS standard focuses on the required skills in mathematics, English, and literacy, while the NGSS standard is specifically oriented to the science area. Both standards were developed independently, but their practices in mathematics (CCSS.MATH.PRACTICE) can be applied simultaneously in an effective way.

The CS1, according to the NGSS Science Practice 7 standard [33], is oriented to measure the ability of the students to support the conclusions with the result data, developing a robust point of view/argument through clear, well-sequenced statements, and understanding the objective of the case study. Therefore, the undergraduate student might propose the idea and opinion with a robust reason based on the fundamental thermodynamic concepts in the result and discussion section of the Workshop (Element 4).

The CS2 according to the standards NGSS Science Practices 2 [33] and CCSS.MATH.PRACTICE.MP2 [34], is developed by mean of the graph construction from the results obtained from the case study (Element 6). In addition, the data interpretation and information statement (CS3) defined according to the standard NGSS Science Practice 4 [33], and CCSS.MATH.PRACTICE.MP3 [34], is developed when the youth student reads the problem (Element 2 and Element 3), interprets the case study, and completes the table and plot (Element 6 and 7) of the thermodynamic workshop shown in Figure 2 properly. On the other hand, the last cognitive skill studied was the complete organization of the whole document (Element 8) based on the CCSS.ELA-LITERACY.CCRA.W.4 standard [34], which aims to encourage the ability on the youth student to elaborate an effective, clear, and coherent communication through the text structure and documentation of the results.

## 2.2. General Aim of the GUI Algorithm

The innovative program named MOLECULARDISORDER is a friendly graphical user interface (GUI) that can be used by undergraduate mechanical and chemical engineering students. The GUI has some important instructive and pedagogical components for an educational level that let students have a better comprehension of the real meaning of the relation of energy–entropy in conventional systems to reach the educational objectives of thermodynamic courses and the program outcomes expected for the new engineers.

It was designed with inputs that depend on the kind of system chosen (Container with a bar, steam stream in a pipe, evaporator, a container with a vessel, turbine, compressor, a container with resistance, and container with division).

Figure 3a–d shows the schematic diagram of some systems that can be run in the software MOLECULARDISORDER. Workshops of all these systems are implemented in the thermodynamic class. However, only the systems of Figure 3a,b are presented in this article.

The main parameters used by the software are the temperature of the fluid and metal surfaces, the pressure of the system, the mass of the fluid and solid, volume, velocity of the fluid, etc.

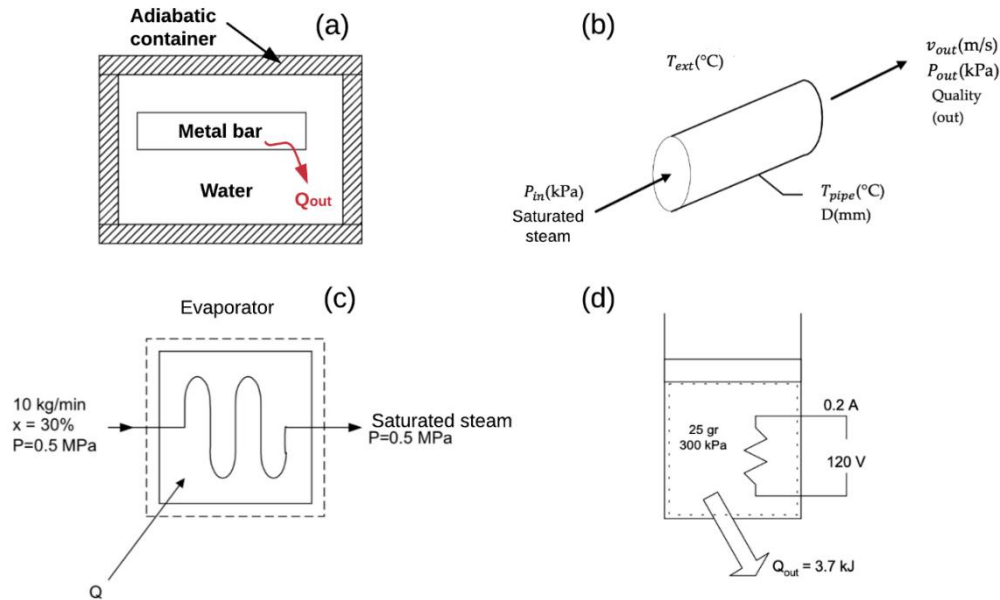
The software was coded with mathematical expressions of different fluid physical properties as a function of the temperature, such as heat capacity, dynamic viscosity, density, among others. With the help of the mentioned correlations, it is obtained the output variables such as enthalpy, entropy, changes in entropy, entropy production, heat transfer, etc., these outputs help not only students, but also engineers in the industry to understand the heat efficiency of some of their systems in a chemical plant.

The software was designed to give a continuous learning process on this part of thermodynamics. The performance of a proposed system using MOLECULARDISORDER increases with the increase of the grade of learning of the user. The learning process has important implications for plant design engineers when assessing their equipment. Also, this software was registered in the National Leadership Copyright (D.N.D.A. Dirección Nacional de Derechos de Autor, in Spanish), with registering number 13-73-132, the date 15 April 2019.

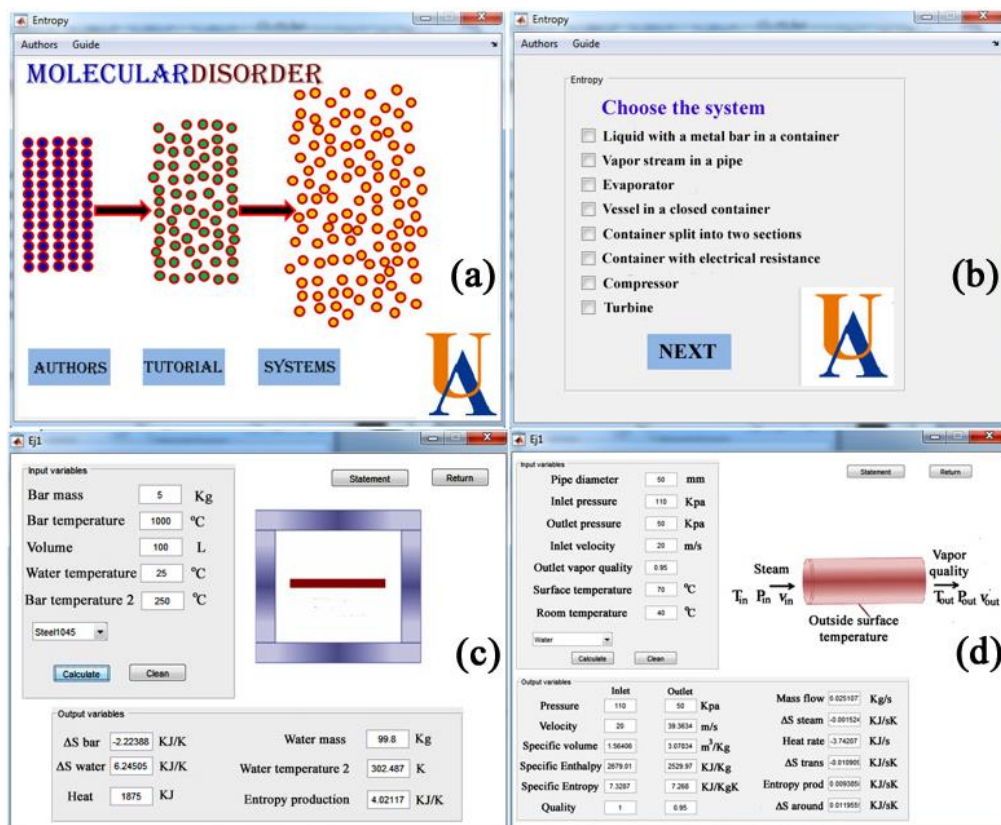
## 2.3. Flowchart of the GUI

The software MOLECULARDISORDER was coded and tested in Matlab®. The requirements of the system depend on the version of Matlab used. MOLECULARDISORDER can work on any Microsoft 32-bit or 64-bit Windows PC on which Matlab/Simulink is installed. Eight different case studies were coded, where the users can change the operating conditions depending on their needs.

Figure 4 illustrates the main view of the program with three emerging windows, one of them shows the system that can be selected by the user (eight different case studies); the other two show the first and second case studies.



**Figure 3.** Schematic of the two systems studied using the MOLECULARDISORDER software (a) Heat transfer of liquid with a metal bar inside a container, (b) steam in a pipeline, (c) evaporator, (d) container with electrical resistance.



**Figure 4.** Main view of the software MOLECULARDISORDER, (a) welcome window; (b) system selection; (c) results of case 1, P1. (d) Results of case 2, P2.

The following flowchart Figure 5 shows the computational steps used to make the code.

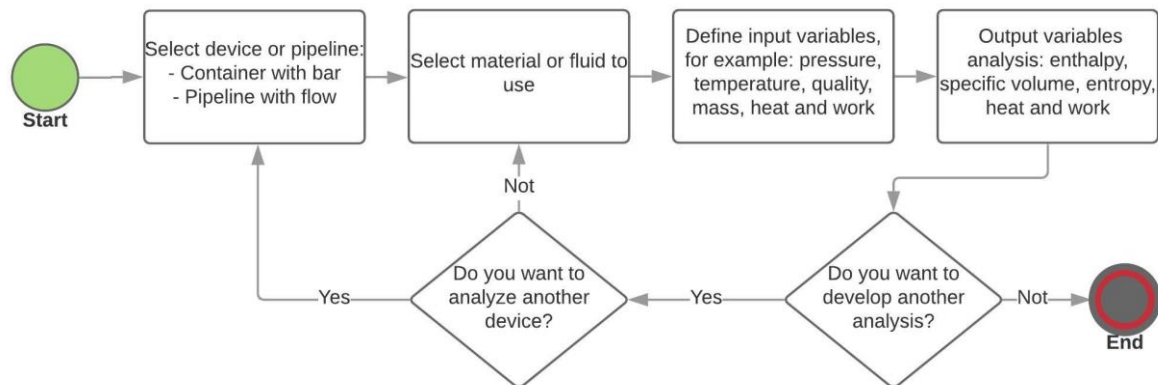


Figure 5. Flowchart of MOLECULARDISORDER.

#### 2.4. Fundamental Equations

To solve the proposed problems, MOLECULARDISORDER was focused on energy balance and the entropy change of substances equations [22,35]. The essential equations used in the problems discussed in this article are shown below and normally are used to conduct energy, exergy, and thermo-economic studies of a thermal process [36–40].

##### 2.4.1. Determination of Entropy in an Isolated Container

This section shows the equations used to determine the entropy of the selected case studies. In the first case study, the entropy change inside the container was calculated with Equation (1) as follows:

$$\Delta S = mC \ln \left( \frac{T_2}{T_1} \right) \quad (1)$$

where  $m$  is the mass,  $C$  is the specific heat of the material,  $T_1$  and  $T_2$  are the respective temperatures of states 1 and 2. After determining the entropy change of the materials, the total entropy production between the two states was calculated with Equation (2).

$$\sigma = \Delta S_{\text{bar}} + \Delta S_{\text{water}} \quad (2)$$

The entropy production  $\sigma$  only depends on the entropy change of the bar and the water, since the container is isolated and does not present heat transfer to the surroundings.

##### 2.4.2. Determination of Entropy Production in a Pipe with Saturated Steam

To determine the entropy production in a pipe with saturated steam, it is proceeded to calculate the entropy change of the fluid with Equation (3).

$$\Delta \dot{S}_{\text{mix}} = \dot{m}(s_2 - s_1) \quad (3)$$

where  $\dot{m}$  is the mass flow that goes through the pipe,  $S_1$  and  $S_2$  are the entropies in the inlet and the outlet of the pipe, respectively. Then, it is proceeded to find the entropy change from the heat that is transferred by the wall of the tube, see Equation (4). This heat transfer causes the fluid to change from state 1 to state 2.

$$\Delta \dot{S}_{\text{tr}} = \frac{\dot{Q}_i}{T_i} \quad (4)$$

where  $\dot{Q}_i$  is the heat lost by the fluid, and  $T_i$  is the temperature of the wall of the pipe. Finally, the entropy change of the surroundings is calculated considering the surrounds as a closed system, where  $\dot{Q}_i = \dot{Q}_o$  and  $T_o$  is the temperature of the surrounds, see Equation (5).

$$\Delta \dot{S}_{\text{alr}} = \frac{\dot{Q}_o}{T_o} \quad (5)$$

The entropy production is defined by the two entropy changes happening in the system, Equation (6).

$$\sigma = \Delta \dot{S}_{\text{mix}} - \Delta \dot{S}_{\text{tr}} \quad (6)$$

### 3. Results and Discussions

Two case studies, P1 and P2, were developed using the MOLECULARDISORDER software as an educational tool, where 130 youth students of Mechanical Engineering at Universidad del Atlántico solved the P1 and P2 of the workshop, understanding the phenomenon happening inside the container. The students, through the repetitive calculation of the software with changes in the input parameters, explained the fundamentals of the entropy generation of the process [22]. To make an accurate analysis of the results obtained by the students using the software, they were graded with the rubric shown in Table 1. Also, a statistical analysis of the obtained grades was carried out to classify the performance of the student for each cognitive skill into compliance levels from 1 to 5.

Table 1. Scoring rubric.

Cognitive Skills [32–34]/Element	Excellent (4.6 to 5.0)	Satisfactory (4.0 to 4.5)	Need Improvement (3.0 to 3.9)	Unsatisfactory (1.0 to 2.9)
CS1/Element 4	It describes clearly the concepts of the problem with excellent details.	It describes the concepts of the problem with some critical details.	Ambiguous description of the concepts with some details that do not clarify the analysis of the problem.	Confusing description of the problem with few details.
CS2/Element 6	Presents a very well-organized plot, highly explained.	Present a clear and organized scheme, easy to understand.	Plot with enough data, but disorganized.	It presents an unclear plot, without coherence among the parts that compose it.
CS3/Element 6-7	It presents an outstanding and organized table-chart that meets the established cognitive skill without errors.	Table-plot meet the design cognitive skill proposed, with up to two errors.	Table-plot with simple structure, but well organized, with at least three errors.	Table-plot with not enough data. It does not meet the design of cognitive skills and has more than three errors.
CS4/Element 8	Excellent presentation and documentation of the results, in the established format.	It presents complete documentation with the correct format, but some details are missing.	Complete documentation, although it does not meet the requirements of the traditional format.	Incomplete documentation and given in the wrong format.

#### 3.1. Statistical Analysis

A statistical analysis of the data obtained was done to establish the cognitive skill where the youth students are strong and weak. Table 2 highlights the standard deviation, the minimum grade, the maximum grade, the average of all the cognitive skills, and the total averaging of the grades. The values show that the dispersion among the data obtained with the standard deviation is small in the CS4 and CS3, and high the CS1 and CS2. It helps explain the maximum and minimum scores obtained

in the CS where the difference between the maximum and the minimum is high for high standard deviations, and the difference is low for low standard deviations. The higher the standard deviation, the higher the complexity of the CS evaluated, which, in our case, can be observed in the CS1 and CS2. It makes sense because the analysis of the results of a problem evidences the skills and the knowledge of the students about the topics evaluated. When a student has excellent knowledge about a theme, it is easy for him to do the analysis. In a regular class, all students have different learning styles, and the professors usually teach using only one learning style. It benefits only a single group of students, causing the dispersion in grades shown.

**Table 2.** Statistical analysis of the CS.

Cognitive Skill	N total	Mean	SD	Minimum	Maximum
CS1	130	3.45	0.94	1.0	5
CS4	130	3.99	0.53	3.0	5
CS3	130	4.57	0.53	3.3	5
CS2	130	3.58	1.01	1.0	5
Total	130	3.90	0.55	2.6	5

On the other hand, considering the critical thinking of the students, the grades obtained in this process determine the good student judgment using cognitive components, at the moment of inferring about the procedure that takes place in the software. It is shown that the higher the magnitude of the deviation, the larger the differences between the student's inference ability since erroneous deductive or inductive inferences, are presented in some cases due to lack of knowledge.

Table 3 shows the total number of workshops reviewed, the standard deviation, the minimum value, the maximum value, and the average of the data of each case study solved with the software. It can be seen that the highest standard deviation was obtained in the case of study P2, as well as the highest difference between the maximum value and minimum value, which allows us to deduce that this problem (P2) presents a slightly higher complexity than case study 1 (P1). Also, the average of the data presented in this case does represent the complexity of the problem, since this statistical study was based on the average scores of the four CS.

**Table 3.** Statistic of case study 1 and 2.

Case Study	N Total	Mean	SD	Minimum	Maximum
P1	130	4.04	0.47	3.1	5.0
P2	130	3.75	0.66	2.0	5.0

Figure 6 shows the average scores of the 130 youth students for each criterion for the two problems, case studies 1 and 2 (P1 and P2). It can be seen that CS1 is the one that obtained the lowest score. Therefore, we can say that the weak performance in this criterion is due to the lack of theoretical knowledge by the students. Also, it can be appreciated that the highest grades are in the cognitive skill CS3 and CS4, which means that the students spend more time in the presentation of the workshop than in making an in-depth analysis of the topic studied. It happens because the software allows the students to obtain the results more accessibly, faster, and organized than getting them with a calculator, letting the student be more organized when presenting a written work. The Analysis criterion always tends to improve with the use of software; however, due to the complexity of the criterion, a grade lower than the other CS evaluated is to be expected.

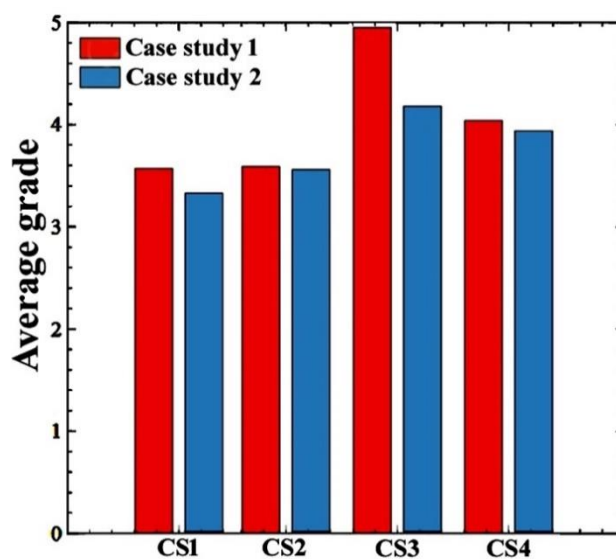


Figure 6. The average grade for all the cognitive skill in case studies 1 and 2.

To find significant differences between the two problems and among all the cognitive skills, T-tests and Tukey tests were made. Table 4 shows the results of the Tukey test, within which can be seen the *p*-value, the difference between the means of the student grades (MeanDiff) obtained in each cognitive skills (CS), the upper control limit (UCL), and the lower control limit (LCL) of the difference between the student grades in each cognitive skill.

Table 4. Tukey test for a confidence level of 95%, to compare the results of the cognitive skills.

Cognitive Skills	MeanDiff	P	LCL	UCL
CS4/CS1	0.538	0.0307	0.036	1.040
CS3/CS1	1.114	$3.2 \times 10^{-7}$	0.612	1.616
CS3/CS4	0.576	0.0177	0.074	1.078
CS2/CS1	0.121	0.9228	−0.381	0.623
CS4/CS2	−0.417	0.1401	−0.919	0.085
CS3/CS2	−0.992	$5.8 \times 10^{-6}$	−1.495	−0.490

It can be seen that the different combinations of cognitive skill were studied to know the complexity of each of them compared with the rest. The results show that the combinations CS2/CS1 and CS4/CS2 had a *p*-value higher than 0.05, indicating that the grades between them are the same. For the other four combinations, the *p*-values were less than 0.05. It suggests that the degree of complexity of one of the cognitive skills is high, given that the difference in inference between the CS is also high. It can be observed when analyzing the averages of the grades obtained in the CS in Table 2.

Table 5 show the comparison between problems P1 and P2 using T-tests for each criterion, helping to understand which of the two problems has a higher degree of difficulty. The responses of the students show that there are no significant differences among the cognitive skills argumentative claim (CS1), modeling (CS2), and organization (CS4). However, there is a considerable difference for the cognitive skill in the interpreting data/information (CS3), indicating that there is a higher degree of difficulty in problem 2, and the average scores for all the cognitive skill of P1 are higher than P2, suggesting that P2 is more complicated than P1.

**Table 5.** T-Test to compare all the cognitive skills in the case study 1 and 2 (a) CS1, argumentative claim; (b) CS2, modeling; (c) CS3, interpreting data/information; and (d) CS4, organization.

(a)					(b)				
	N	Mean	SD	SE Mean		N	Mean	SD	SE Mean
CS1-P1	130	3.58	0.88	0.15	CS2-P1	130	3.59	0.99	0.17
CS1-P2	130	3.33	1.09	0.19	CS2-P2	130	3.56	1.07	0.19
Difference = $\mu$ (CS1-P1) – $\mu$ (CS1-P2)					Difference = $\mu$ (CS2-P1) – $\mu$ (CS2-P2)				
Estimate for difference: 0.24					Estimate for difference: 0.030				
T-Value = 0.99 <i>p</i> -Value = 0.324					T-Value = 0.12 <i>p</i> -Value = 0.905				
(c)					(d)				
	N	Mean	SD	SE Mean		N	Mean	SD	SE Mean
CS3-P1	130	4.96	0.26	0.05	CS4-P1	130	4.05	0.51	0.09
CS3-P2	130	4.18	0.97	0.17	CS4-P2	130	3.94	0.57	0.10
Difference = $\mu$ (CS3-P1) – $\mu$ (CS3-P2)					Difference = $\mu$ (CS4 P1) – $\mu$ (CS4 P2)				
Estimate for difference: 0.78					Estimate for difference: 0.11				
T-Value = 4.43 <i>p</i> -Value = 0.000					T-Value = 0.80 <i>p</i> -Value = 0.427				

Table 6 shows a T-test between the grades obtained from the same problems before using the software and after using it. The results statistically indicate that there are significant differences between the results obtained before and after taking the software since the *p*-value obtained was lower than 0.05. The overall averages of the grades were higher for P1 after using the software. It indicates that the software helps the students to get better performance when solving P1.

**Table 6.** Student's t-test to evaluate the effect of the software, (a) two-sample T for P1 vs. P1-before, and (b) two-sample T for P2 vs. P2-before.

(a)					(b)				
	N	Mean	SD	SE Mean		N	Mean	SD	SE Mean
P1	130	4.04	0.61	0.11	P2	130	3.75	0.89	0.16
P1-before	130	3.74	0.68	0.12	P2-before	130	3.44	0.99	0.17
Difference = $\mu$ (P1) – $\mu$ (P1 before)					Difference = $\mu$ (P2) – $\mu$ (P2 before)				
Estimate for difference: 0.30					Estimate for difference: 0.31				
T-Test of difference = 0(vs>):					T-Test of difference = 0(vs>):				
T-Value=1.92 <i>p</i> -Value = 0.03					T-Value=1.92 <i>p</i> -Value = 0.094				

For problem 2, the *p*-value was higher than 0.05, indicating that there was no significant difference after and before using the software. However, the average grade for P1 when taking the software was higher than before using the software. It means that with a higher confidence interval, it can be shown that the software helps the youth students.

### 3.2. Case Studies

#### 3.2.1. Heat Transfer of Liquid with a Metal Bar inside a Container

Figure 4c showed an isolated container that has a metallic bar in contact with water to study the influence of the initial temperature of the water in the ABS value of ( $\Delta S_{\text{water}}/\Delta S_{\text{bar}}$ ), and the entropy production at different bar final temperatures, with the input parameters shown in Table 7.

**Table 7.** Input parameters of the system.

Mass bar (kg)	$T_{i \text{ bar}}$ (°C)	Vol (L)	$T_{i \text{ water}}$ (°C)	$T_{f \text{ bar}}$ (°C)
5	1000	100	25	250

The initial water temperature is changed in the range from 25 °C to 70 °C for different final temperatures of the bar [250 °C, 350 °C, 450 °C, 550 °C]. Figure 7 shows that the relation of the parameters ABS ( $\Delta S_{\text{water}}/\Delta S_{\text{bar}}$ ) and (Production of entropy) have the same behavior because the container is not molecularly influenced by thermal changes of the surrounding area, therefore, the entropy production is only affected by the molecular disorder provided by the entropy changes in the water and the steel bar. Also, Figure 7 shows that the higher the initial temperature of the water, the lower the entropy production, which is something essential, and that can only be analyzed if the software is used with several input conditions like the one shown. It helps the engineer to choose the initial conditions of a process to work at maximum efficiency with minimal effect of the entropic conditions. A critical annotation is that in the case of using the relation ( $\Delta S_{\text{water}}/\Delta S_{\text{bar}}$ ) instead of ABS ( $\Delta S_{\text{water}}/\Delta S_{\text{bar}}$ ), the plot behavior would change direction and would be inversely proportional to the functions of the entropy production, since the metallic bar goes from a state of higher entropy to a lower one. On the other hand, we can see that the creation of entropy at the same initial temperature of water decreases in a non-linear way as the final temperature of the bar decreases.

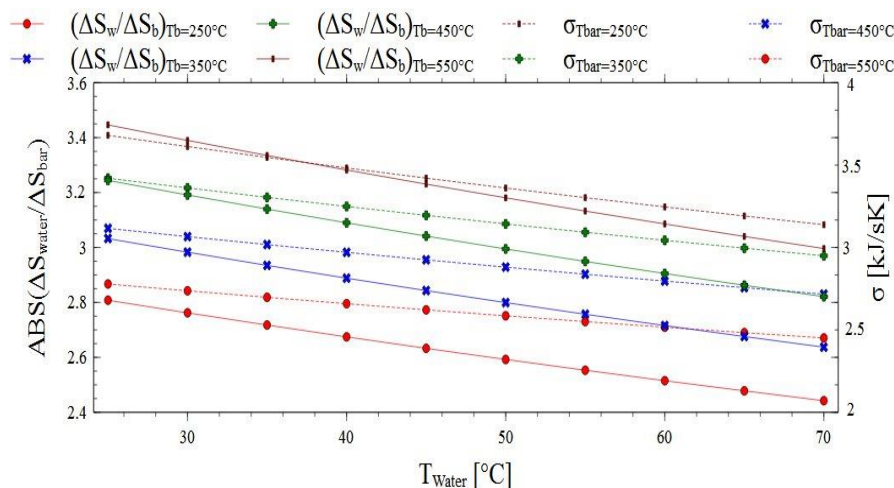


Figure 7. Entropy behavior for liquid with a metal bar inside a container.

### 3.2.2. Steam in a Pipeline

Figure 4d showed the system of a steam pipeline to study the influence of the change of ( $\Delta P$ ) in the ( $\Delta S_{\text{trans}}$ ) and the ( $\Delta S_{\text{steam}}$ ) for different steam qualities in the outlet of the pipe with the parameters established in Table 8.

Table 8. Initial Condition.

D (mm)	$P_{in}$ (kPa)	$v_{out}$ (m/s)	$P_{out}$ (kPa)	$T_{pipe}$ (°C)	$T_{ext}$ (°C)	Steam Quality (out)
50	110	20	50	70	40	0.95

The outlet pressure is changed in the range from 50 kPa to 95 kPa for the following steam qualities [0.95, 0.75, 0.55, 0.35]. Figure 8 shows that the higher the pressure changes ( $\Delta P$ ) in the pipe, the lower the magnitude of entropy changes ( $\Delta S_{\text{trans}}$ ), caused by the heat given to the surrounds, obtained from the difference in the state of the fluid.

On the other hand, the variation of the entropy change of the fluid ( $\Delta S_{\text{mix}}$ ) depends on the pressure and quality, since the molecular disorder begins to increase if the working fluid presents more steam than liquid at the outlet, and for the opposing case, the molecular disorder tends to decrease with the decrease of steam quality. As can be seen in Figure 9, the entropy production decreases as the difference in pressure decreases as well. It happens because the molecular disorder suffers small changes when the pressure in the studied system has a slight decrease.

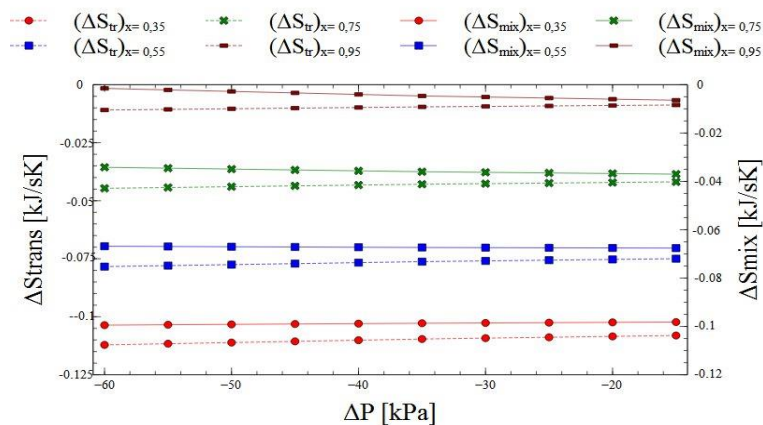


Figure 8. Entropy behavior for the system of steam in a pipeline.

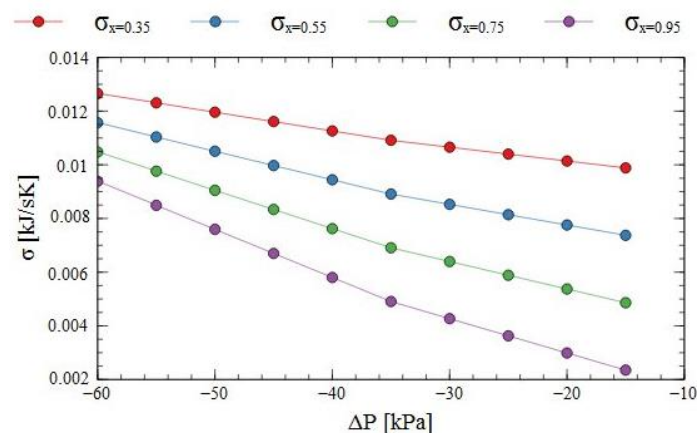


Figure 9. Entropy production behavior for the system of steam in a pipeline.

This effect is affected when increasing the quality of the steam. The lower the quality of the steam, the higher the entropy production. The analysis of the mentioned case studies is highly essential for students because it helps them to have a better understanding of the phenomena, which is complex to see with simple equations.

#### 4. Conclusions

A new friendly graphical user interface to promote critical thinking in youth engineering students called “MOLECULARDISORDER” was presented and evaluated with two case studies where the student can measure its learning capacity in the thermodynamic subject by making a simple analysis of different heating systems.

An analysis of the quantitative data was done to verify the positive effect of the software MOLECULARDISORDER on the youth student learning process in the two case studies. It was done using the T-Student tests with a level of significance of 0.05. An increase in the means of the grades was obtained for all the CS evaluated in the answers given by the students. The result obtained statistically shows that with the help of the software, the youth student got an improvement when performing problem 1 since the  $p$ -value was 0.03, indicating that there are significant differences between the results before and after taking the software. The overall averages of the youth student grades were higher for P1 after using the software ( $4.04 > 3.74$ ). The total averages for P2 were also higher after taking the software ( $3.75 > 3.44$ ); however, the  $p$ -value was 0.094, indicating that there was no significant effect on the use of the software.

It was determined that youth students present difficulty in interpreting data/information (CS3) cognitive skill, which measure the skill to read the problem, interpret the phenomena, and use the

ability of the inference and the knowledge to solve the case study. So, the absence of a clear knowledge in the youth student of the fundamental thermodynamic processes imply a learning process based on inductive inference, since youth student proposed conclusions from inferred information, and not by means of a deductive inference from the case study result.

Comparing all the results between P1 and P2 with a confidence level of 95%, there is only a significant difference for the Element 6 and 7 of the critical thinking theories, which was evaluated in this research with the cognitive skill 3. It is evidenced by the average scores and educational performance in all the cognitive skills with the P1 were higher than P2, demonstrating that P2 has a higher degree of complexity.

Some technical phenomena presented in the case studies of the workshop benefit the development of critical thinking, due to facilitating the adoption of the cognitive skill that normally, under a traditional class, is difficult to obtain. One of these technical phenomena is presented in the case study of the container isolated with water, where the youth student needs to explain the entropy production behavior, at the same initial temperature of water decreases in a non-linear approach as the final temperature of the bar decreases.

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## Abbreviations

The following abbreviations were used in this manuscript:

ICT	Information and communication technologies
TEL	Technology-enhanced learning
ABET	Accreditation board of engineering and technology
DNDA	Dirección nacional de derechos de autor
HSD	Honestly significant difference
LSD	Least significant difference
COP	Coefficient of performance
CS	Cognitive skill
UCL	Upper Control Limit
LCL	Lower Control Limit
SD	Standard Deviation

## Nomenclature:

$C_p$	Specific heat at constant pressure
$S$	Entropy
$V$	Velocity
$h$	Specific enthalpy
$m$	Mass
$Q$	Heat
$P$	Pressure
$T$	Temperature
$\dot{W}$	Rate of heat transfer
$A$	Area

## Greek Letters

$\Delta$	Delta
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## Subscripts

$Rev$	Reversible
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