FOSTERING ENGINEERING LABORATORY COURSE TEACHING BY EMBEDDING AN INQUIRY-GUIDED LEARNING APPROACH USING COMPUTER-AIDED LEARNING PACKAGES:

EVALUATION OF LEARNING OUTCOMES IN A COOLING TOWER EXPERIMENT IN THE UNIT OPERATIONS LAB

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INTRODUCTION

The increased demand for environmental and industrial solutions and new technologies drives chemical engineering education programs to update their curricula to equip students with the required skills for present and future challenges.[1-3] Hence, laboratory courses play a vital role in training and gearing graduating engineers to operate, design, and optimize chemical plants and processes through understanding and discovering related concepts experientially by hands-on experiments with well-designed learning outcomes. Laboratory courses also provide students with a virtual sense of physical systems and help them develop the feel for engineering processes.[4-8]

According to Bloom's taxonomy, laboratory courses exhibit high-level learning outcomes that promote learning through the skills of applying, analyzing, synthesizing, and evaluating the obtained results.[9-11] Although application, analysis, and evaluation are typically well-practiced in laboratory courses through well-designed experimental schemes, the development and synthesis activities are usually less practiced. Therefore, the Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology (ABET) prescribed a Student Outcome (SO) that ensures different levels, ranging from the student's ability to develop experiments all the way to using engineering judgment to draw conclusions. This student outcome is involved in SO6, which is "*an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions*."[12] Although developing and conducting experiments influence the Course Learning Outcomes (CLOs), they do not promote the students' creative thinking towards innovative solutions for engineering problems and do not help mitigate educational fallacies.[13-16] Hence, embedding

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the inquiry-guided learning (IGL) approach can foster the learning outcomes of laboratory courses. The IGL indicates a learning process that is motivated by inquiry, including the problem-based learning approach (PBL).[17] IGL can be facilitated with Computer-Aided Learning Package (CALP) to sharpen the students' creative and critical thinking, and correct logical misconceptions by exploring and practicing a virtual environment that reflects the deep understanding of the theoretical principles.[18]

The need to revisit the lab materials and add more technology-oriented tools has been highlighted in the COVID-19 pandemic due to different challenges encountered. This also promoted learning opportunities by ensuring inclusive and equitable quality education.[19, 20]

Therefore, this paper aims to provide CALP as an IGL tool to revisit a cooling tower experiment offered for 43 students enrolled in the Unit Operations Laboratory course, a part of the undergraduate program in Chemical Engineering at Qatar University. This lab course includes hands-on and computerized experiments in mass transfer phenomena and separation processes, including humidification processes. Involved experiments for the lab include those for a cooling tower and tray dryer, gas absorption, molecular diffusion in gases, batch and fractional distillation, and fixed and fluidized bed.

Students revisited the cooling tower experiment using the CALP/IGL approach. The cooling tower is an evaporative heat exchanger that dissipates heat from hot liquid water utilizing sensible and latent heat transfer to the evaporating steam.[21,22] Cooling towers are widely used in industries such as desalination, power plants, etc. The cooling tower experiment has been assigned in chemical engineering curricula, in which students investigate the effects of various parameters (e.g., inlet water temperature, inlet air psychrometric properties, and flowrates of water and air) on the performance of the cooling tower.

THEORY

The performance of the cooling tower is evaluated using different parameters as established by Merkel and developed by Nottage,[22, 23] including the water temperature range (cooling range), water temperature approach (to the dew point), effectiveness, rate of evaporation, the ratio of water flowrate to air flowrate, number and height of the theoretical transfer units, and the overall mass transfer coefficient.[24-26] The water temperature range (R) is defined as the difference between the inlet and outlet water temperatures as shown in Eq. (1), while the water temperature approach (A) is defined as the difference between the outlet water temperature and the wet-bulb temperature of the inlet air as shown in Eq. (2).[22, 23, 26] The wet-bulb temperature of the inlet air represents the temperature at which air can theoretically reach a relative humidity of 100% with the same absolute humidity content. It also describes the lowest possible temperature to which the water can be cooled. The wet-bulb temperature of the air is used along with the dry-bulb temperature to determine psychrometric properties of air (such as humidity, enthalpy, and specific volume).[27]

$$R = T_i - T_o \tag{1}$$

$$A = T_o - T_{(WA)i} \tag{2}$$

where T_i is the temperature of the inlet water, T_o is the temperature of the outlet water, and $T_{(WA)i}$ is the wet-bulb temperature of the inlet air.

The cooling tower effectiveness (η) is defined as the ratio of the actual cooling to the maximum possible cooling, which is also equal to the ratio of the water temperature range to the summation of water temperature range and water temperature approach, as shown in Eq. (3).[22, 23]

$$\eta = \frac{R}{R+A} \tag{3}$$

The evaporation rate ($\dot{m}_E$) is calculated from the difference of air moisture flow rates at the two ends of the cooling tower, as shown in Eq. (4) [22, 23]

$$\dot{m}_E = \dot{m}_a (X_o - X_i) \tag{4}$$

where $\dot{m}_a$ is the mass flow rate of the dry air through the cooling tower and X_o and X_i are the absolute humidity values of the outlet and inlet air streams (per unit mass of dry air), respectively.

An energy balance equation on the cooling tower is given by Eq. (5) [22, 23]

$$LC_P(T_o - T_i) = G\,(H_o - H_i) \tag{5}$$

where L and G are the water and dry air mass fluxes, respectively, C_P is the specific heat of water (kJ/kg °C), and H_o and H_i are the enthalpies of the outlet and inlet air, respectively (kJ/kg dry air). Accordingly, the ratio of water to air (LC_p/G) is obtained from the slope of the operating line of the cooling tower on an enthalpy-temperature diagram, also known as the driving force diagram,[28] and is equal to the ratio of the enthalpy difference between inlet and outlet air streams to the sensible heat differences between the inlet and outlet water, according to the following heat balance, Eq. (6):[22, 23]

$$\frac{LC_P}{G} = \frac{H_o - H_i}{T_o - T_i} \tag{6}$$

The cooling tower packing is essential to enhance the mass transfer at the air-water interface; the corresponding mass transfer coefficient is significantly affected by the type of packing and is correlated to air and water flow rates. To determine the required height of packing for the cooling tower (z), the computation of both the height and number of transfer units is a must. The height of transfer units (*HTU*) depends on the flowing air properties and packing type, whereas the number of transfer units (*NTU*) is the integration of the enthalpy potential as the driving force between the input and output air, as shown in the following Merkel equations.[23]

$$z = (HTU)(NTU) \tag{7}$$

$$HTU = \frac{G}{M_B K_G a P} \tag{8a}$$

$$NTU = \int_{H_{yi}}^{H_{y2}} \frac{dH_y}{H_y^* - H_y} \tag{8b}$$

where M_B is the molar mass of dry air, a is the packing density, K_G is the mass transfer coefficient, P is the ambient air pressure, H^* is the enthalpy of moist air at the bulk water temperature, and Hy_1 and Hy_2 are the enthalpies of moist air entering and leaving the cooling tower, respectively. It is noteworthy that *NTU* indicates the difficulty of the cooling process, while *HTU* indicates the system's effectiveness in the cooling process.

The higher performance of the cooling tower is indicated by higher values of the range and effectiveness, lower values of the approach to wet bulb temperature, and the number of transfer units.

METHODOLOGY

The CALP/IGL approach was applied in the cooling tower experiment in the Spring 2021 semester for 43 students enrolled in four sections of the Unit Operations Laboratory course, a part of the undergraduate program in Chemical Engineering at Qatar University. The approach was applied in two stages. In the first stage, the students experimented on a physical cooling tower experiment. This stage aims to fulfill the experiential CLOs, including elements of safely, effectively conducting experiments in a group setting, and analyzing the experimental results. The second stage includes using MATLAB® as a computer-aided learning package to compute the required height of the cooling tower using the data (such as overall mass transfer coefficient, water, and air conditions) obtained from the physical experiment conducted in the first stage. The following is an account of these two stages.

First Stage: Hands-on Experiment With a Physical Cooling Tower

A computer-controlled benchtop cooling tower (EDIBON® TTEC/TTEB, Spain) was used to offer the students the opportunity to experiment with a lab-scale modern cooling system's construction, design, and operative characteristics.[29] The packing has a height of 0.48 m in an eight-level zigzag shape, a column cross-sectional area of 0.0225 m^2, and an average packing surface area density of 112.6 m^2/m^3.

The physical unit is an open system through which water and air are allowed to flow counter-currently, as shown in Figure 1. The system consists of a water cycle, air cycle, and packing material. In the water cycle, the flow rate of hot water is controlled manually via a valve, where water is pumped from the load tank and sprayed at the top of the cooling tower. The air cycle is driven by a fan that withdraws air from the atmosphere. The airflow rate is controlled by adjusting the fan speed from the computer-control user interphase.

The unit is equipped with seven temperature sensors to measure the water temperature in the tank, water temperature before entering the tower, water temperature after exiting the tower, and the wet and dry bulb temperatures of the inlet and exit air streams. The inlet water temperature is adjusted from the computer-control user interphase, and the output results (including water temperature, wet and dry bulb temperatures of air, and air and water flow rates) are recorded and displayed on the computer.

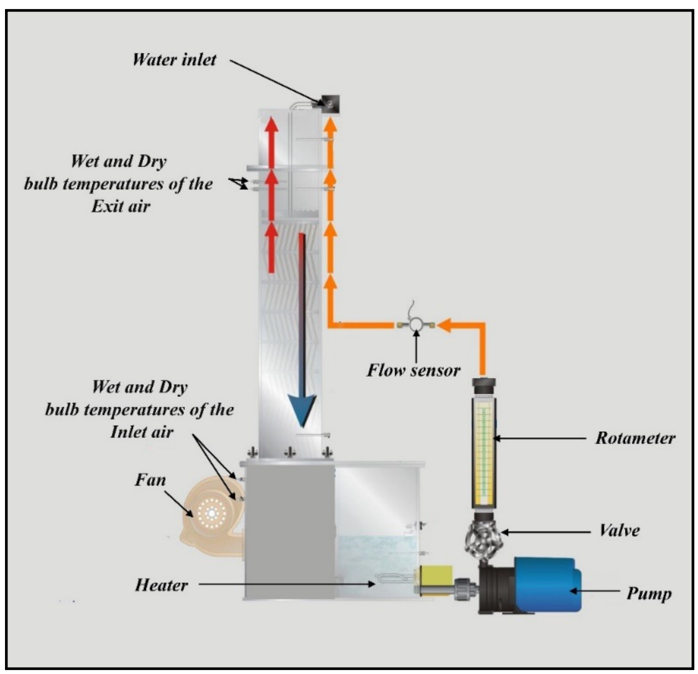

Figure 1. *Setup of cooling tower experiment.*

Second Stage: Computer-Aided Learning Package

A MATLAB application developed by John Simpson[30] was used as a computer-aided learning package to compute the required height of the cooling tower using the data obtained from the conducted experiment, such as overall mass transfer capacity coefficient and water and air stream conditions. The MATLAB application was verified by testing it with problem 10.5-2 on p. 605 of the third edition of *Transport Processes and Unit Operations*,[31] and it gave the exact answers given in the book. In addition, three experimental trials were conducted with different inlet water temperatures, and the calculated results were comparible with those calculated by MATLAB with accepted slight deviations. Before assigning the MATLAB application to students, an online tutorial was delivered to students to demonstrate the user interface and test some hypothetical experimental scenarios to foster their critical thinking and understanding while discussing the assignment results.

The MATLAB application user interface requires the following inputs: inlet air dry bulb temperature, inlet air wet bulb temperature, inlet water temperature, outlet water temperature, water flow rate, airflow rate, and the overall mass transfer capacity coefficient. The MATLAB application computes the cooling tower performance indicators, including the water temperature range (R), water temperature approach (A), the height of the cooling tower, the minimum required airflow (G_{min}), percentage of evaporated water, and the number of transfer units (enthalpy integral value) (NTU). The application also computes the characteristic enthalpy-temperature design diagram with equilibrium line, actual operating line (with the slope of LC_p/G), and the limiting operating line, also known as the critical operating line (with the slope LC_p/G_{min}). Here, the water flow rate is assumed to be constant since evaporation is slight. Also, the effect of sensible heat transfer can be ignored compared to latent heat transfer.[26] Figure 2 shows the user interface of the MATLAB application, with the specified input and calculated output of the design (Figure 2a) and the enthalpy-temperature design diagram (Figure 2b).[28, 32]

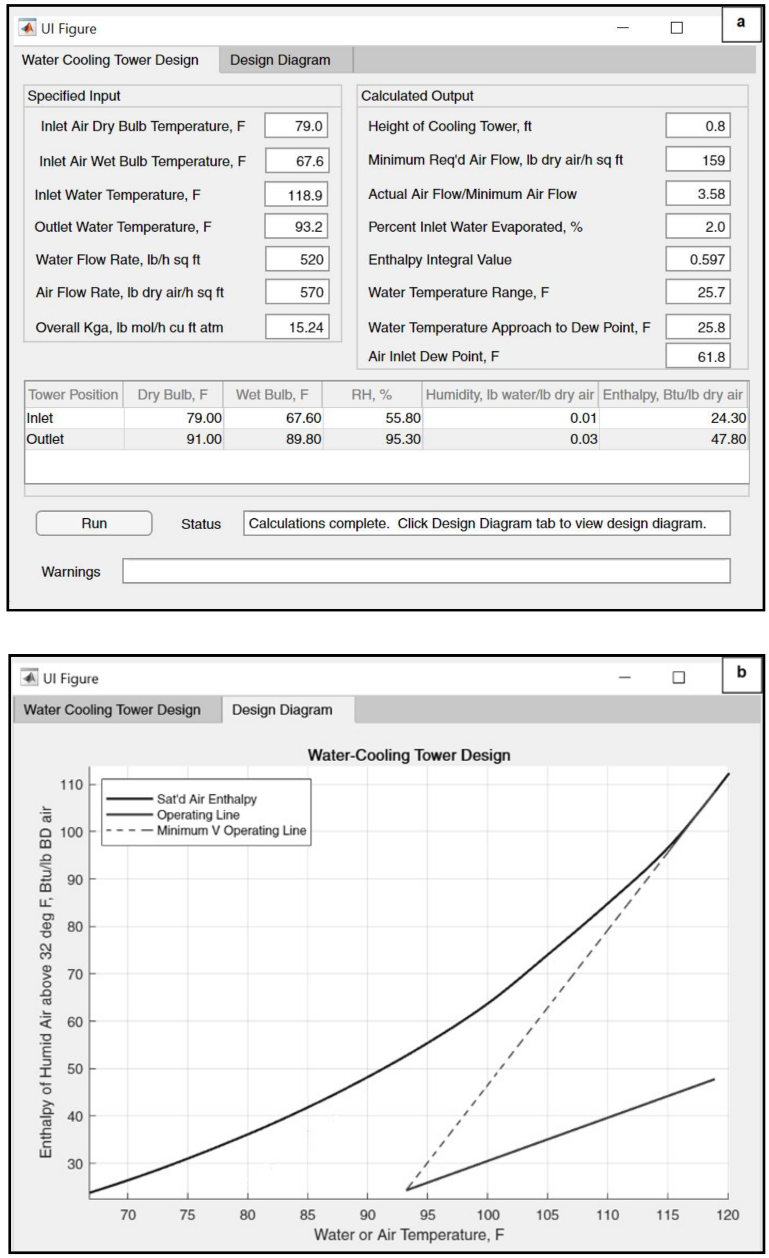

Figure 2. *The user interface of the MATLAB application showing (a) the specified input and calculated output of the design and (b) the enthalpy-temperature design diagram.*

The inputs were obtained from the experimental data of the same group experiment. However, the overall mass transfer capacity coefficient was obtained experimentally using Eqs. 7-8. First, the enthalpy driving force was integrated numerically to calculate the number of transfer units (NTU) in the cooling tower according to Eq. (8b). Since the packing height was given, it was used along with the NTU to find the height of transfer units (HTU) according to Eq. (7). Because the units in the first stage (the physical experiment) were in the SI system while the required inputs for the second stage were in English engineering (imperial) units, students were requested to convert units before inputting their values into the application.

It is noteworthy that the second phase can be run independently without any raw or calculated data from the first stage. However, the raw and calculated values obtained from Stage 1 were used as input to the MATLAB application for two reasons. The first reason is to provide students with the skill of comparing between experimental results (Stage 1) and simulated results (Stage 2), which drives them to check and explain the relative difference between the two stages, and guides them to possible miscalculations of the parameters with high relative differences between the two approaches. The second reason is to provide students with hands-on practice on unit conversion.

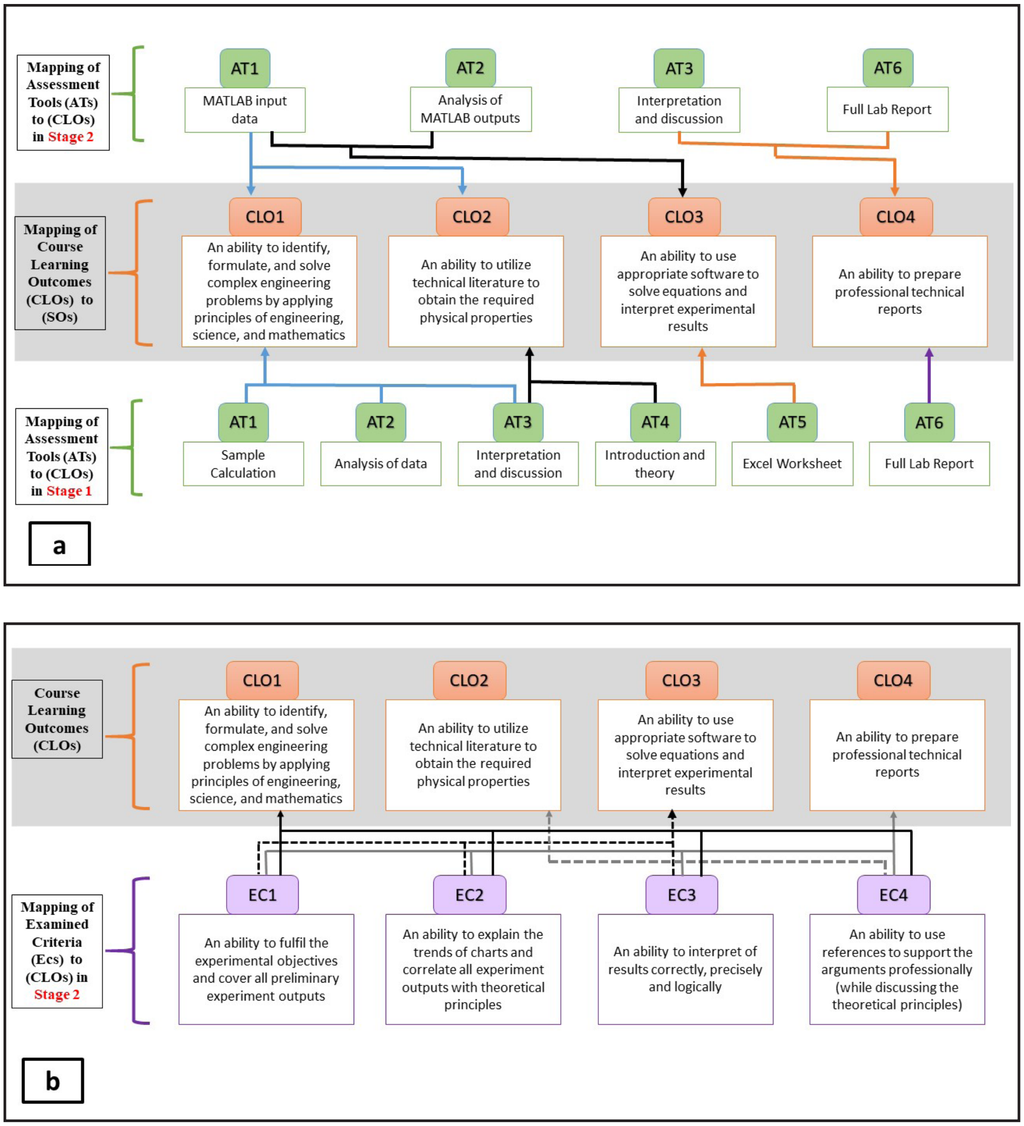

Figure 3. *The holistic mapping of (a) assessment tools (ATs) in Stage 1 and 2 to course learning outcomes (CLOs), and (b) examined criteria (ECs) in Stage 2 to course learning outcomes (CLOs).*

Method Evaluation and Assessment Tools

The attainment of learning outcomes of the first stage (hands-on experimenting with the physical cooling tower experiment) was evaluated based on the discussion of results in the submitted individual report. Several factors were considered to ensure higher learning performance, such as boosting intellectual capacity, hands-on practice, and evaluating the outputs from several perspectives.

The discussion of results was evaluated based on four criteria indicated according to a developed checklist of detailed grading rubrics that was pre-announced to students.[33] These examined criteria (ECs) were: (1) fulfilling the experimental objectives and covering all preliminary experiment outputs; (2) explaining the trends of charts and correlating all experiment outputs with theoretical principles; (3) correct, precise and logical interpretation of results; and (4) using references to support the arguments professionally (while discussing the theoretical principles). The same criteria were also used to assess the discussion section of the report to evaluate the attainment of learning outcomes in the second stage of the experiment (utilizing a computer-aided learning package). The holistic mapping of course learning outcomes (CLOs) to the assessment tools (ATs) in stages 1 and 2, and to the examined criteria (ECs) in Stage 2, are shown in Figures 3a and 3b, respectively.

It is noteworthy that the majority of the lab report is completed as a team where students contribute to the abstract, introduction, experimental setup and procedure, raw data, sample calculations, data analysis, conclusion, and references. However, the discussion section is completed as an individual assignment in order to investigate each student's weak points regarding critical thinking and writing skills.

The discussion section of each student was evaluated based on the four examined criteria (ECs), and each criterion weighed 2 points (total 8 points), and 2 points were given for students' efforts in writing the discussion. Therefore, if the student accomplishes all ECs and discusses them sufficiently, then the student gets 10 points. The student loses two points for every unaccomplished EC or for insufficient discussions.

The results are presented at a confidence interval estimate (CI) of 95% ($\alpha = 0.05$, $z = 1.97$). The details of the statistical calculations are presented elsewhere.[5]

DIVERSITY, EQUITY, AND INCLUSION (DEI) LEARNING ENVIRONMENT

A diverse, equitable, and inclusive (DEI) learning environment for students was ensured by creating a supportive spirit to encourage mutual respect, equal treatment, and fair assessment of students from various backgrounds and individual differences. This enabled everyone to feel valued and productive. DEI fosters successful learning experiences by encouraging students from various religious, ethnic, and cultural backgrounds to work together in a teamwork setting. People from diverse backgrounds working together during the lab or the different stages of report progressing encouraged mutual respect and, in a way, fostered successful learning experiences. Furthermore, using individual differences, equity was ensured as every student received equal treatment and fair assessment using various tools, including office hours, one-to-one support, and other different tools to assess the learning outcomes, such as detailed rubrics and constructive feedback on students' work.

RESULTS AND DISCUSSION

Evaluation of the MATLAB Application Outputs

The MATLAB application[30] computed the required height of the cooling tower using input data that were obtained from the conducted physical experiment. Such data include the overall mass transfer coefficient, and water and air stream conditions. Table 1 lists the experimental and MATLAB input and output parameters. It is noteworthy that there are slight deviations between the input parameters of the experiment and MATLAB due to the limitation of some fields regarding the allowed significant figures in MATLAB. As indicated in Table 1, the data computed by the MATLAB application are close to those produced during the physical experiment, including the range, approach, evaporation loss, and height of the transfer unit. However, the number of transfer units, column height, and the minimum required air flowrate (G_{min}) estimated by the application are less than those obtained in the physical experiment. The MATLAB application computed the minimum required airflow as 159 lb dry air/h ft^2, which is less than one-third of the actual value in the physical experiment where G_{min} is determined experimentally as 259 lb dry air/h ft^2 (less than half of the actual value of 570 lb dry air/h ft^2).

The value of G_{min} was determined experimentally by extending a line from the point representing the temperature and enthalpy at the bottom of the column (inlet air and exit water) on the enthalpy-temperature design diagram to make a tangent with the saturation (equilibrium) curve. The slope of that line (known as the critical operating line) is LC_p/G_{min}, which represents the minimum possible driving force at the top end of the cooling tower at which the packing has an infinite height to achieve the desired cooling. However, the actual packing height can be determined by increasing the airflow rate above G_{min}. In the MATLAB application, G_{min} is computed using a built-in iterative numerical technique to decrease the airflow rate (G) while the water flow rate (L) is fixed. This increases the slope of the operating line until it becomes tangential to the saturation curve, as shown by the dashed line in Figure 2b. The tangent or intersection point of the critical operating line with the saturation curve determines G_{min}. The value of G_{min} estimated in the MATLAB application is less than the experimental value due to a lower value of NTU, which can be attributed to differences in the regression parameters of the operation line and saturation curve between MATLAB and experimental calculation. The HTU is almost identical in both the MATLAB application and physical experiment, representing the system's effectiveness in the cooling process. However, having a lower NTU value in the MATLAB application indicates less difficulty in the cooling process, resulting in estimating less required packing height.

Evaluation of the Learning Outcomes of Implementing CALP/IGL

The attainment of learning outcomes of implementing the Computer-Aided Learning Package (CALP) as Inquiry-guided Learning (IGL) tool in the cooling tower experiment was evaluated according to a developed checklist of detailed rubrics that was pre-announced to students[33] in the four lab sections enrolled in the unit operations laboratory course in Spring 2021 as shown in Figure 4(a). The overall students' performance in the first stage was 7.12±0.59 (out of 10), which escalated significantly in the second stage by 32.58% to reach 9.44±0.18. There are variations between the different sections in the first stage, where section 2 showed the worst performance of 5.89±0.35, while section 1 showed the best performance, 7.83±0.94. Four weaknesses were recorded in the students' discussions in Stage 1: (1) some correlations and trends were not interpreted correctly, (2) some

TABLE 1
Comparison Between Experimental and MATLAB Parameters.

(a) Input Parameters (from experimental data)	
Inlet Water Temperature (°F)	= 118.9
Outlet Water Temperature (°F)	= 93.2
Water Flow Rate ($lb/ft^2 \cdot hr$)	= 520
Air Flow Rate ($lb/ft^2 \cdot hr$)	= 570
Inlet Air Wet Bulb Temperature (°F)	= 67.6
Inlet Air Dry Bulb Temperature (°F)	= 79.0
Overall Kha, (lb-mol/h ft^3 atm)	= 15.25

(b) Output parameters			
Parameter	**MATLAB Data**	**Experimental Data**	**Relative Difference**
Min Air Flow Rate ($lb/ft^2 \cdot hr$)	159	260	38.82%
Range (°F)	25.70	25.74	0.16%
Approach to Dew Point (°F)	25.60	25.56	0.16%
Outlet Air Wet Bulb Temperature (°F)	89.80	99.32	9.59%
Outlet Air Dry Bulb Temperature (°F)	91.00	106.70	14.71%
Outlet humidity ratio(lb water/lb day)	0.03	0.03	0.00%
Outlet air enthalpy (Btu/lb)	47.80	55.50	13.87%
% of evaporation	2.00	2.19	8.68%
NTU	0.60	1.07	44.35%
HTU (ft)	1.34	1.29	3.93%
Height of Cooling tower (ft)	0.80	1.47	45.51%
L· Cp/G (Btu/lb ·°F)	0.91	0.92	0.61%

results and correlations were not explained according to the theoretical principles, (3) the discussion sometimes had misconception mistakes, and (4) references were sometimes not used or misused to support the discussion.

It is worth mentioning that revisiting the experiment using the CALP/IGL approach in the second stage was conducted six weeks after the first stage. During this period, students were engaged in other experiments, which also helped improve their attainment of some learning outcomes in the examined criteria EC1 (that measures the student ability to fulfill the experimental objectives and cover all preliminary experiment outputs) and EC4 (that measures the students' ability to use references to support the arguments professionally).[5] Nonetheless, the CALP/IGL impacted the other two criteria, EC2 (that measures the students' ability to explain the trends of charts and relate experimental observations with theoretical principles) and EC4 (that measures the students' ability to interpret results correctly, precisely, and logically). Hence, using CALP as an IGL tool to revisit a cooling tower experiment helped relieve weaknesses in the students' discussion and comprehension of results, including explaining the chart trends according to the theoretical principles and honing the students' knowledge and understanding, which resulted in avoiding conceptual mistakes.

By using the IGL approach to revisit a lab experiment, the attainment of learning outcomes of the teaching labs has improved significantly in all lab sections, with an average student score of at least 9 (out of 10) for all sections in the second stage of the experiment, as shown in Figure 4(a). The students' performance improved from Stage 1 to Stage 2 of every lab in this experiment, ranging from a 26.44% improvement for the best-performing lab section to a 51.10% improvement for the worst-performing lab section. This improvement reflects that the CALP/IGL approach is a constructive activity in boosting the attainment of learning outcomes, especially for less achieving students. The CALP/IGL approach triggers students' creative and critical thinking to use this problem-based learning approach to compare the results obtained from the MATLAB application to those obtained from the physical experiment, which in turn hones their more profound understanding of the theoretical principles.[18] The improvement is significant for lower achieving students because they usually have difficulties in calculations and performing logical correlations to interpret chart trends and discuss outputs according to theoretical principles. Making mistakes in calculations results in higher relative errors, guiding students to think thoroughly and critically to find potential mistakes in their calculations. On the contrary, this type of mistake is rare among more achieving students. This improvement is shown in Figure 4(b), where the examined criteria EC3 (that measures the students' ability to interpret results correctly, precisely, and logically) improved significantly from 61±0.88% to 92±4%.

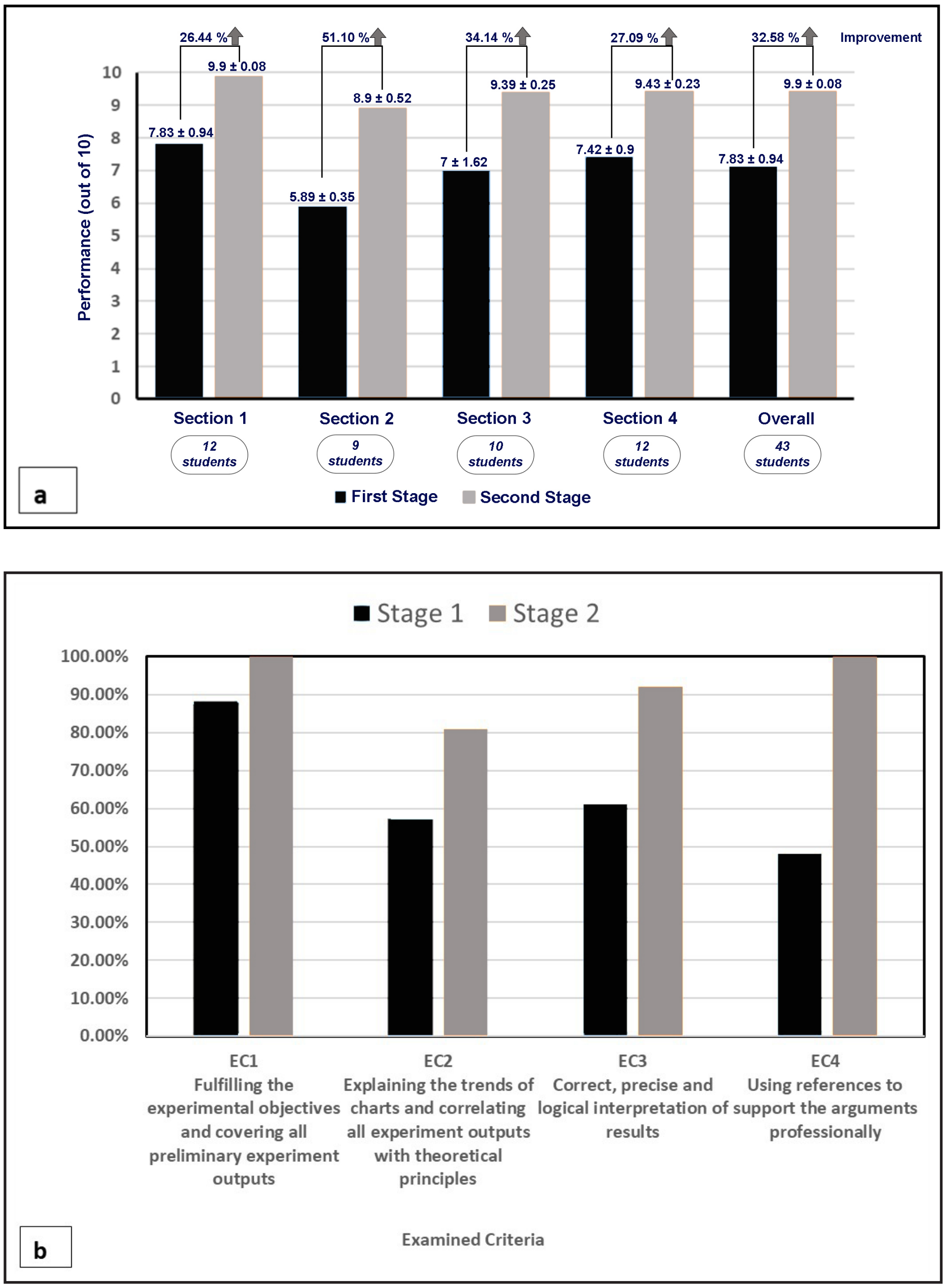

Figure 4. *Evaluation of students' performances in the first and second stages: (a) data separated according to sections, (b) data separated according to the examined criteria (ECs).*

Furthermore, revisiting the experiment using the CALP/IGL approach helped improve the aforementioned weaknesses in the discussion, including explaining the chart trends according to the theoretical principles and honing students' knowledge and understanding, which results in avoiding conceptual mistakes. This is because applying wrong correlations and interpreting them might result in a wrong/misconceptual interpretation that could seem logical to a student, who ends up retaining these misconceptions, a phenomenon is known as "Logical Fallacies."[16,34] Hence, revisiting the experiment by embedding the CALP/IGL approach alerts students to mistakes in their calculations or interpretations, leading to correcting any conceptual mistakes. This structure of return to a problem also helps foster a more consistent high-level performance among most students, which is indicated by the drop of the estimated deviation in the overall score from ±0.38 in the first stage to ±0.12 in the second stage. It is noteworthy that feedback on students' work in Stage 1 helped some improve, especially with criterion (4) of using references to support the arguments professionally (while discussing the theoretical principles). However, other criteria (1, 2, and 3) of fulfilling the experimental objectives, explaining the trends of charts, correlating all experiment outputs with theoretical principles, and precise and logical interpretation of results were boosted by this approach in Stage 2. Notably, in Stage 1, the student listed the raw and calculated results without any explanation, discussion, or using references. Nevertheless, the student skills have improved in Stage 2 regarding explaining trends, discussing results, and using references to support the arguments. This improvement is clearly shown in Figure 4(b), where the examined criteria EC2 (that measures the students' ability to explain the trends of charts and correlate all experiment outputs with theoretical principles) improved considerably from 57±0.85% to 81±6%.

CONCLUSION

Revisiting the experiment using the CALP/IGL approach boosted the attainment of learning outcomes of the cooling tower experiment. It helped relieve weaknesses in the students' discussion and comprehension of results, including explaining the chart trends according to the theoretical principles and honing the students' knowledge and understanding, which resulted in avoiding conceptual mistakes. It also helped students with weak performance to have a better achievement of the corresponding learning outcomes. As a result, it helped reduce the academic gap among students with different learning styles and capabilities. Therefore, revisiting the experiment using the CALP/IGL approach is highly recommended in teaching laboratory courses to promote the students' creative thinking towards comprehensive and innovative solutions for engineering problems.

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