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Development and Implementation of a Low-Cost, Visual Evaporative Cooling Desktop Learning Module

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Abstract

Evaporative cooling, used in many industrial and residential applications, is a complex coupled heat and mass transfer process where fluid cooling occurs due to water vaporization and the conversion of sensible to latent heat. In this paper, the development, testing, and implementation of a small, highly visual, Low-Cost Desktop Learning Module (LCDLM) for demonstration of evaporative cooling phenomena in the undergraduate classroom will be presented. The newly developed cross-flow direct evaporative cooler module is constructed from inexpensive expanded aluminum packing media, an off-the-shelf, battery-powered computer fan, a simple water distribution system with a battery-powered pump, and clear acrylic housing. The LCDLM is operated in a non-steady-state recycle mode where a small volume of water is circulated and, depending on the water temperature, either heats or cools incoming air. Preliminary data for simple experiments that can be repeated in the classroom are presented showing the effect of varying the initial water temperature, water flow rate, and air velocity on the cooling rate and temperature profiles in the module. These variables can be easily controlled in the classroom so that students can quickly observe their effect on the performance of the evaporative cooler. Finally, we outline worksheet and conceptual assessment questions to accompany classroom activities and present conceptual assessment results from a spring 2022 pilot classroom implementation of the evaporative cooler LCDLM in a Fluid Mechanics and Heat Transfer course. Significant student learning gains were observed after implementation, suggesting a positive influence of the LCDLM on understanding.

Introduction

It is now well-accepted that the use of active learning strategies, which encourage students to engage with materials rather than passively receive information, promote better academic performance and improve student attitudes compared to traditional lecture-based strategies [1, 2]. Further, interactive learning, defined by Chi as a subtype of active learning wherein students construct new knowledge through an exchange of ideas with peers [3], is postulated to promote the deepest conceptual understanding and has been shown to lead to greater learning gains than other active learning strategies [4, 5]. With this in mind, our group has developed a number of highly visual low-cost desktop learning modules (LCDLMs) for demonstration of fluid mechanics and heat transfer principles, including a module demonstrating frictional loss and continuity in a straight pipe, a venturi meter, and double pipe and shell and tube heat exchangers [6-8]. Students work in groups of 3-4 to complete simple experiments and discuss conceptual principles related to the modules, and we have shown that these modules are effective for improving conceptual understanding [6-8]. Due to the success of existing LCDLMs, we have recently developed additional modules with extended applications in fluid mechanics and heat transfer, including particle settling [9] and biomass conversion modules [10], and are now developing a simple evaporative cooling module which will allow simultaneous investigation of mass transfer, heat transfer, and fluid mechanics principles.

Evaporative cooling is a complex heat and mass transfer process with applications in cooling towers, heat rejection devices used to cool a process fluid, and air coolers, typically used in residential applications to cool warm, dry air. In a typical direct evaporative cooler, water evaporates into dry air due to a concentration driving force at the water surface and latent and sensible heat transfer occur between the water and air. Air is humidified and, depending on the water temperature, either cooled or heated as it passes through a porous media or across slats that evenly distribute water flow. Figure 1 shows a schematic of a cross-flow direct evaporative cooler used to cool water:

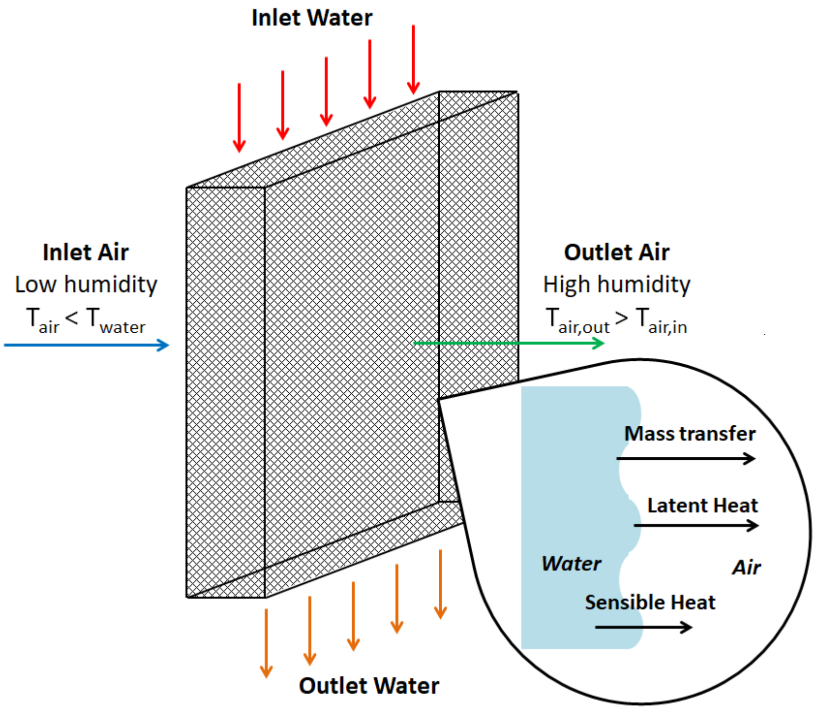


Figure 1. Diagram of crossflow direct evaporative cooler showing air properties and air and water flow. Zoomed section depicts the heat and mass transfer occurring at air-water interface.

Investigation of an evaporative cooler will encourage students to consider several important principles including energy balances, mass transport, phase changes, and sensible versus latent heat. In this paper, we outline the development of a low-cost evaporative cooler, suitable for use in a typical, non-laboratory classroom setting, provide initial performance data for the module, and detail classroom activities and assessment questions used during a pilot implementation to evaluate improvements in student understanding of principles related to the evaporative cooler.

Design of the Evaporative Cooler LCDLM

During the design phase of the evaporative cooler, several design considerations were used to select a final design. We desired that:

1. The module be low-cost (approximately the cost of a textbook)
2. The module be highly visual to allow observation of flow and the porous media
3. Simple experiments can be completed in a typical one-hour class session
4. Students can explore the impact of operating parameters such as flow rates and inlet temperature on cooler performance

With these design principles in mind, we developed the evaporative cooler module with the full set-up and components shown in Figure 2.

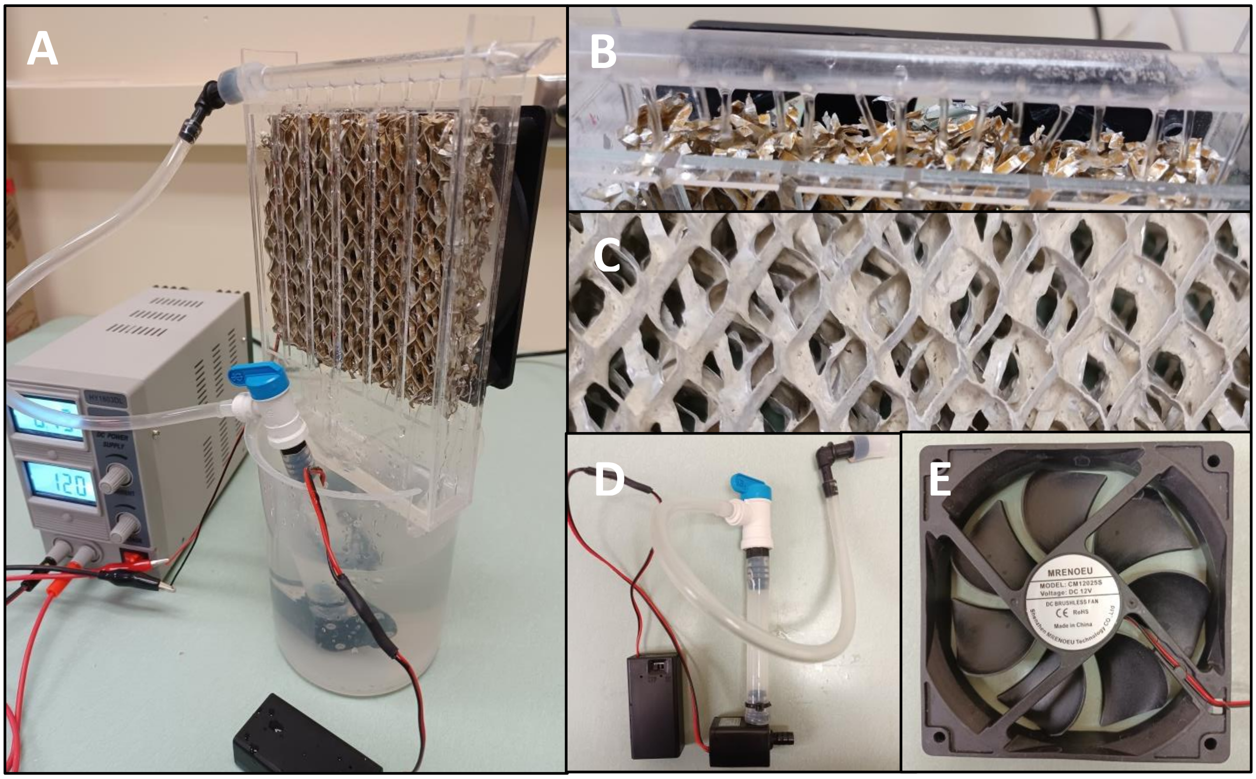


Figure 2. Full evaporative cooler LCDLM set-up (A), close-up of water distributor positioned at top of media (B), close up of porous media (C), pump assembly with quarter turn valve and battery pack (D), 12 V fan for air flow (E)

Components of the evaporative cooler include: a one liter water reservoir, a battery powered centrifugal pump with a quarter turn valve assembly to allow flow rate adjustment, a 12 V computer fan (which can be run with a DC power supply or 9 V battery), a rectangular portion of commercially-available expanded aluminum porous media, a simple water distributor created by drilling small offset holes into a 0.25” inner diameter length of polycarbonate tubing, and a clear, laser cut acrylic frame to support the distributor, media, and fan. For classroom implementations, a metal grill plate was installed to cover the fan blades and improve module safety. The porous matrix used is somewhat non-homogenous. Thus it is expected that small variations in the heat transfer rate and air and water temperature changes will occur in different module set-ups; however, these difference are expected to be minimal. The total cost of the module and all components is approximately $80 and it is small enough to fit easily on a tablet-arm chair desk, allowing use in a wide range of classroom settings. Students can measure water and air temperatures with inexpensive handheld thermometers or, alternatively, if more precise temperature measurement is desired, the module can be instrumented with thermocouples.

Several operating parameters of the cooler can be easily manipulated. Hot or cold tap water can be placed in the reservoir, allowing students to operate the module in water cooling or air cooling mode. High water cooling rates can be achieved with ~50 °C water, eliminating the need to use hotter fluid, which would introduce safety concerns. The water flow rate can be varied between approximately 10-30 mL/s by adjusting the quarter-turn valve on the pump assembly, and the air velocity can be changed by adjusting the power supplied to the fan, either by using batteries with different voltages or by changing the resistance from the battery to the fan. The evaporative cooler set-up shown in Figure 2 operates in non-steady state recycle mode, as the water is recycled continuously out of and back into the reservoir, resulting in temperature changes over time. However, if separate, large water supply and collection basins are used instead of a single one liter reservoir, the module can also be operated in steady state mode. We anticipate that this low-cost design will allow flexible experimentation and classroom use, enabling students to easily observe flow patterns, collect steady or non-steady state temperature data, and explore the impact of operating parameters such as air and water temperature changes and cooling rate.

Performance of the Evaporative Cooler LCDLM

To investigate the performance of the evaporative cooler and develop a procedure for use in the classroom, we completed a series of experiments at different operating parameters in our laboratory with the LCDLM prototype. The cooler was run in recycle mode with one liter of water. Inlet and outlet air and water temperatures were recorded in LabVIEW™ every second using calibrated Type K thermocouples. For laboratory experiments, the water flow rate and air velocity were controlled by varying the input voltage supplied with 12 V DC power supplies, allowing precise control of these parameters. A separate set of calibration experiments, not reported herein, were performed to correlate the input voltage supplied to the pump and fan to water flow rate and air velocity respectively. For the experiments reported in Figure 3 and Table 1, flow rates ranged from 21 – 28 mL/s, air velocities ranged from 0.1 – 2.25 m/s, and initial water temperatures ranged from 30 – 60 °C. Figure 3 shows temperature profiles collected during 10 min. experiments with the evaporative cooler LCDLM in recycle mode. Figure 3A shows temperature data collected at a high fan voltage of 12 V and Figure 3B shows data collected at a low fan voltage of 5 V. The difference in the temperature profiles can be clearly observed, with a steeper initial temperature change for the water, faster achievement of air cooling, and lower final air and water temperatures for the trial with higher air speed.

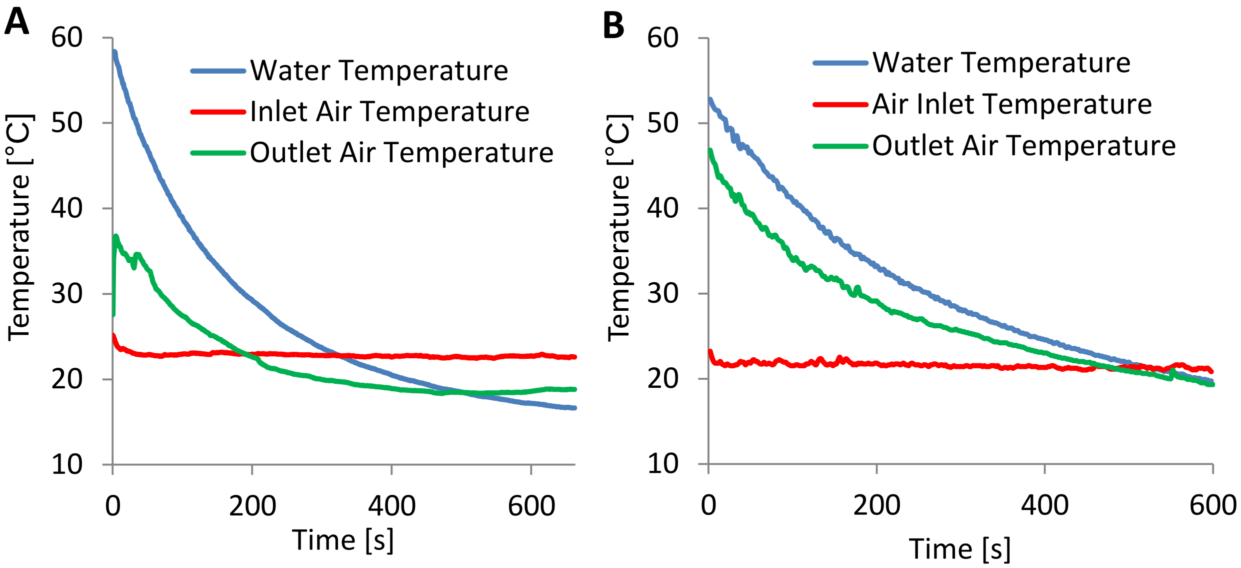


Figure 3. Temperature profiles collected during a 10 min experiment with the evaporative cooler for a) 27 mL/s water flow rate, 12 V fan voltage, 59 ^{o}C initial water temperature and b) 28 mL/s water flow rate, 5 V fan voltage, 53 ^{o}C initial water temperature.

Students can easily observe similar overall temperature profiles by collecting temperature data over time with handheld thermometers, can use temperature data to calculate simple quantities such as the initial cooling rate of the water, and can compare performance at various operating conditions. Table 1 shows examples of the impact of varying the water flowrate, fan voltage, and initial water temperature on the initial water cooling rate. The rate was measured with all parameters at a high value (Experiment 1), then one parameter at a time was changed to a lower value, with the two other parameters held at the higher value (Experiments 2-4). The cooling rate was calculated by dividing the product of the total water mass, heat capacity, and temperature change over 30 seconds by the time interval, 30 seconds.

Table 1. Initial water cooling rate at various operating conditions

Experiment	**Water flow rate [mL/s]**	**Fan voltage [V]**	**Water temperature [°C]**	**Initial cooling rate [W]**
1	27	12	60	1007
2	21	12	60	790
3	27	2.5	60	551
4	27	12	30	183

Clear differences were observed in the initial cooling rate of the water. Decreasing the water flow rate, fan voltage, or initial water temperature led to significant decreases in the initial cooling rate. Similar experiments can be performed in a classroom setting and students can be asked to postulate why rate changes occur based on their knowledge of driving forces for heat and mass transfer. In summary, the simple evaporative cooler LCDLM can be easily operated in both water cooling and air cooling modes and will allow students to explore the impact of multiple, easily alterable operating conditions such as water and air flow rate and initial water temperature on the time-dependent temperature profiles. The module operates reliably over a wide range of conditions and is simple and safe to use, allowing flexible use in the classroom.

LCDLM Pilot Implementation Details

A pilot implementation of the evaporative cooler was completed in April 2022 in a 50 min junior level chemical engineering fluid mechanics and heat transfer course with 19 students. Students first completed a pre-test containing questions outlined in the following section, worked in groups of 4-5 to complete a worksheet with evaporative cooler experiments and conceptual discussion questions with a full version accessible on our website [11], then completed a posttest with the same questions as the pre-test after the module implementation. The multiple choice pre- and posttest were both completed during the class period in ~5-10 minutes, leaving approximately 35 minutes for the experiment and worksheet activities. All students consented to study participation via an IRB approved consent form.

Classroom Activities and Conceptual Assessment Questions

During implementation, student groups completed the following experiment. Students added hot water (~50 °C) to the beaker and monitored the outlet air and water reservoir temperatures using handheld thermometers for 10 min., recording temperatures every minute. Power to the centrifugal water pump and fan was provided with 9 V batteries. Students were also asked to note the outlet air humidity compared to the inlet humidity by holding their hand in the outlet air. At classroom operating conditions, the water temperature dropped below the inlet air temperature within 5 min., allowing observation of both water and air cooling in a short period. Due to time constraints, students only completed one experiment at a single air velocity and water flow rate; however, as previously discussed, operating parameters could be varied to allow additional experimentation as time allows. For future implementations, we suggest implementing the module in a longer laboratory session or across several lecture sessions to allow students adequate time for in-depth experimentation and discussion. In addition to the experimental portion of the activity, students completed conceptual discussion questions focused on the following concepts:

- Plotted air and water temperature profiles and discussed temperature changes of water and air
- Compared the initial cooling rate at the beginning of the experiment where water was cooled rapidly due to high temperature differences between water and air to the rate measured several minutes into the experiment when driving forces for heat/mass transfer were lower
- Discussed the impact of water temperature on heat and mass transfer driving forces and how this affects the water cooling rate in the device

- Determined direction of sensible and latent heat and mass transfer occurring at the air/water interface based on temperature and humidity observations for water cooling and air cooling regimes. Constructed interfacial temperature/humidity diagrams.
- Based on knowledge of impact of velocity on forced convection heat transfer coefficients, determined whether high or low air velocity should be used to maximize cooling rate

A full version of the experimental instructions and discussion questions is available online [11]. The LCDLM experiment and associated worksheet questions were intended to improve understanding of the heat and mass transfer occurring during water and air cooling, influences of water temperature and air velocity on the cooling rate, and the overall behavior of evaporative cooling devices. To evaluate whether students improved their understanding of these concepts, the following multiple choice pre- and post-activity questions were administered:

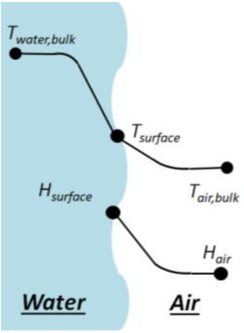
Question 1

Select all correct options. In an evaporative cooler, water vapor will:

1. transfer (condense) from low humidity air to ***slightly*** cooler water.
2. transfer (evaporate) from water that is hotter than air, to low humidity air.
3. transfer from water to low humidity air regardless of water and air temperatures.
4. not be transferred.

Question 2

Given the following temperature (T) and humidity (H) profiles for the water-air interface, select the best representation of heat and mass transfer.



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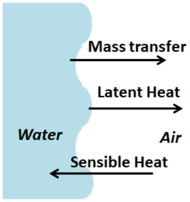

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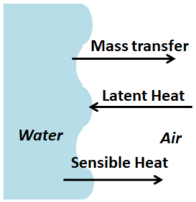

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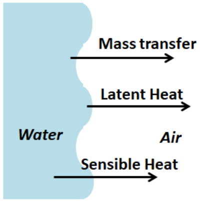

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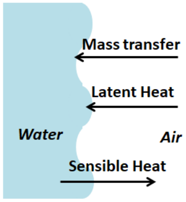

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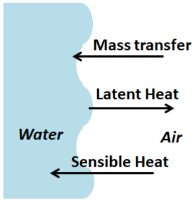
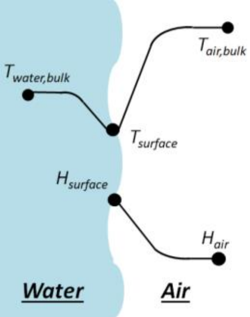


Question 3
Given the following temperature (T) and humidity (H) profiles for the water-air interface, select the best representation of heat and mass transfer.



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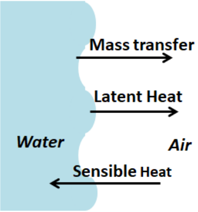

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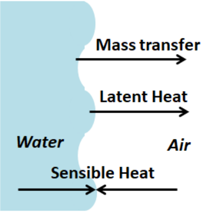

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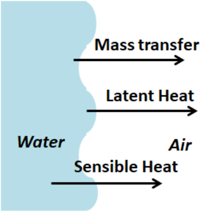

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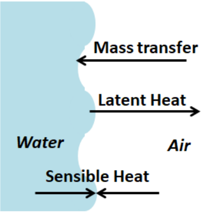

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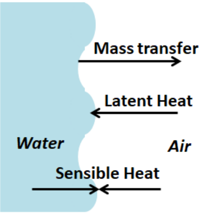

Question 4
In an evaporative cooler being used to cool hot water:

a. a lower air velocity should be used to give longer contact time between water and air.
b. a higher air velocity should be used to decrease the total resistance to convective heat and mass transfer at the air water interface.
c. the velocity of the air will not impact the cooling rate. Only the flow rate of the water and temperatures of the water and air influence the rate of water cooling.

Question 5
Are the following statements true or false for a typical evaporative cooler?

a. Evaporative coolers perform better when incoming air has low humidity. T/F
b. When cooling hot water, the water temperature can only decrease until it reaches the temperature of the inlet air. T/F
c. If the initial water temperature is slightly lower than the temperature of the incoming air, the water temperature will increase as it moves though the cooler. T/F

Question 6
Consider an evaporative cooler being used to cool hot water. If the water temperature is increased,

a. sensible heat transfer will: Increase/ Decrease
b. latent heat transfer will: Increase/ Decrease
c. mass transfer will: Increase/ Decrease

Question 1 addressed the direction of mass/water vapor transport at the air-water interface. Students who do not fully understand that mass is transferred based a concentration driving force may incorrectly assume that the direction of mass transfer depends on the temperatures of the air and water, rather than correctly select that water is transferred from the saturated air-water interface into the bulk air. Questions 2 and 3 again addressed heat and mass transfer at the interface, and required students to understand that mass transfer occurs from the air-water interface to the bulk air due to the high humidity at the interface, the majority of latent heat flows from the water to the air due to the bulk of the energy for evaporation coming from the water which has a high conductivity and heat capacity, and that the direction of sensible heat transfer depends on the temperature of the air, water, and temperature at the interface, with sensible heat flowing from the hotter to the cooler location. Question 4 required students to understand the impact of air flow rate, or velocity, on water cooling rate. Question 5a required understanding of the effect of inlet humidity (or the concentration driving force) and Questions 5b and 5C required understanding of the effect of latent heat transfer on the temperature changes of water and air. Finally, Question 6 addressed the effect of water temperature on heat and mass transfer rates.

Pilot Implementation Results

As previously described, the evaporative cooling module was implemented in a 50 minute fluid mechanics and heat transfer course. To evaluate student learning, pre- and posttest results were compared for individual questions and the overall assessment using paired t-tests for overall results and McNemar's test for individual questions due to the binary nature of question scoring. Figure 4 shows average pre- and posttest results obtained for the pilot implementation.

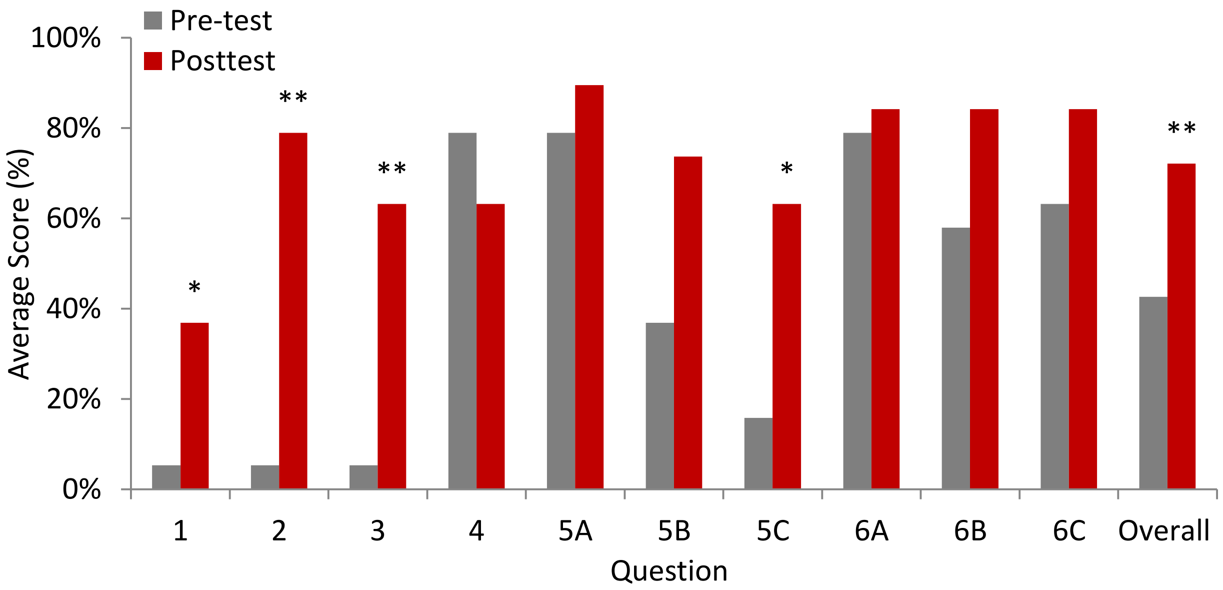

Figure 4. Pre- and posttest conceptual assessment results for pilot LCDLM implementation (N=19). *,** indicate significant improvement from pre- to posttest at $p<0.05$ and $p<0.01$ significance levels, respectively.

As can be seen, the LCDLM experiment and associated worksheet questions promoted a significant overall increase in understanding evidenced by the 30% average score improvement ($p < 0.01$) on the posttest compared to the pre-test. Score increases for individual questions were observed for 9/10 questions, with 4/10 questions showing significant improvement ($p < 0.05$). Questions with significant improvement included Question 1 (32% increase), focused on the direction of mass transfer, Questions 2 and 3 (74 and 58% increases), focused on identification of the directions of sensible and latent heat and mass transfer for water cooling and air cooling regimes, and Question 5C (47% increase), focused on the further temperature decrease of water slightly below the incoming air temperature due to energy required for evaporation. Less than 20% of students answered these questions correctly prior to the activity, suggesting poor understanding of these concepts. After the activity, greater than 60% of students answered Questions 2, 3, and 5C correctly, and 37% of students answered Question 1 correctly. Based on these results, we conclude that the LCDLM activity was successful for improving the understanding of several key evaporative cooling concepts, justifying further use in engineering classrooms.

Conclusions and Future Work

A visual, flexible cross-flow evaporative cooler low-cost desktop learning module has been developed for use in undergraduate engineering classrooms. Preliminary performance data collected in our laboratory shows that the cooler functions effectively in water cooling or air-cooling modes and that operating parameters such as initial water temperature, air velocity, and water flow rate affect the performance significantly, allowing a wide range of classroom experimentation possibilities. Worksheet and assessment materials for the evaporative cooling module were developed to promote improved understanding of heat and mass transfer phenomena and overall device behavior. A pilot implementation was completed in a junior level chemical engineering course, and conceptual assessment results indicate that the module promoted significant improvements in understanding. In summary, we believe the low-cost, visual module will be a valuable tool for introducing and improving the understanding of the complex heat and mass transfer phenomena occurring in evaporative cooling devices used extensively in industry.

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