AC 2012-3070: A MULTIDISCIPLINARY CAPSTONE SENIOR PROJECT: INTERACTIVE COOLING SYSTEM

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A Multidisciplinary Capstone Senior Project: Interactive Cooling System Demonstration Unit

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Abstract

The aim of this paper is to present the design, development, and construction of an Interactive Cooling System (ICS) demonstration unit. This was accomplished by a multidisciplinary capstone senior design team consisted of three mechanical engineering students and two electrical engineering students was selected to work on this project and was supported by the industry. The design team was advised by two faculty members: one mechanical engineering and one electrical engineering.

The unit demonstrates change phase as the refrigerant passes through the cold plate. The two-phase process is visible and can be observed through the glass cover of the cold plate. The ICS is capable of cooling heat loads between 100 W to 1000 W and maintain the heated surface at a temperature of less than 100^{o}C. The performance of the ICS is described by presenting some experimental test data. This paper provides details about the design and development of the ICS, as well as testing and validation of this unit.

Introduction

Precision Cooling Division of Parker Hannifin Corporation has requested the development of an educational Interactive Cooling System (ICS). The purpose of this educational Interactive Cooling System is to demonstrate the versatility and capabilities of Parker's Precision Cooling two-phase electronic-cooling technology. The two-phase cooling technology utilizes the heat of vaporization of a refrigerant in order to absorb excessive heat, commonly generated by a high powered electronic. The two-phase cooling technology is safer and more efficient method of heat transfer that reduces the weight, increases power density, and costs far less than the traditional heat sink or water cooling system.

A multidisciplinary capstone senior design team consisted of three mechanical engineering students and two electrical engineering students was selected to work on this project. The team was advised by two faculty members: one mechanical engineering and one electrical engineering. It should be noted that this is not the first senior design multidisciplinary project that we advised. We had many more in the past. The students worked and communicated effectively as a team. They chose one of them to be the team leader to coordinate the design activities. The capstone senior design project spans two semesters. In the first semester, the problem statement is formulated and basic conceptual designs are generated and then evaluated. The best conceptual design is then selected and a complete and detailed design is generated by the end of the first semester. In the second semester, a prototype of the finished design is built, tested and evaluated. A final report and oral presentation to faculty and students are required from all design teams at the end each semester.

It should be noted that there are six ABET Students Outcomes that are mapped to the course outcomes of this capstone senior design project. They are:

(a) an ability to apply knowledge of mathematics, science, and engineering
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on single-discipline and multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(g) an ability to communicate effectively
(i) a recognition of the need for, and an ability to engage in life-long learning

Based on the assessment that was conducted at the end of both semesters, all six Students Outcomes were highly achieved.

The ICS is composed of the following components: cold plate, condenser, fan, pump, accumulator, piping, pressure sensors, temperature sensors, flow meter, R-134A refrigerant, fiberglass shell, aluminum frame, power supply, personal computer (PC), touchscreen monitor, data acquisition system (DAQ), and control algorithm. These components were researched, analyzed, modeled and selected to achieve specific performance criteria.

The ICS was designed so that refrigerant would change phase as it passes through the cold plate. It was specified that this two-phase process must be visible, and the refrigerant must not enter a superheated state. The desired quality at the exit of the cold plate was set at 0.70. The ICS is capable of cooling of heat loads between 100 W to 1000 W and maintain the heated surface at a temperature of less than 100^{o}C.

Precision Cooling Division of Parker Hannifin Corporation provided support to construct two ICS units. One unit is for Parker Hannifin Corporation to be used in technology trade shows to demonstrate the versatility and capabilities of Parker's Precision Cooling two-phase electronic-cooling technology . And the other unit is for our department of engineering to demonstrate thermodynamics processes and principles for our undergraduate mechanical engineering students. Such an apparatus would enhance the teaching (and learning) of thermodynamics. Students would be able to apply thermodynamics principles, such as the first and second laws, learned in the classroom lectures, to real-life problems. This approach could make the learning of thermodynamics a more pleasant experience for undergraduate mechanical engineering students.

The Design Process and Specifications

The design process that was employed in this research project is the one outlined by Bejan et al.[1] and Jaluria[2]. The first essential and basic feature of this process is the formulation of the problem statement. The formulation of the design problem statement involves determining the requirements of the system, the given parameters, the design variables, any limitations or constraints, and any additional considerations arising from safety, financial, environmental, or other concerns. Since the ICS is required to be designed as a demonstration unit, it needs to be portable and should meet the following specifications:

- Phase Composition: The liquid-vapor composition of the refrigerant must not reach a superheated-vapor state at any point in the ICS.

- Fan Speed: To expand upon the Parker Precision Cooling technology, the fan speed must be variable. The fan speed should be controlled based on feedback from the ICS.

- Maximum Weight: The maximum weight of the ICS is set at 500 lbs. This is a desired working specification that should be met in order to achieve a moveable interactive display. The ICS must have a robust structure and be transportable.

- Operating Temperature: The ICS must be able to function in a variety of ambient conditions. It must be fully functional in an atmosphere that has an air-temperature between 18 and 30^{o}C. The heat source surface exposed to the cold plate must be kept below 100 degrees Celsius. The ICS must be able to control the target temperature to ± 1^{o}C.

- Performance: The ICS must demonstrate cooling of heat loads between 100 W to 1000 W.

- Instrumentation**:** Every thermodynamic node in the ICS must contain property sensors (specifically to measure pressure and temperature). The ICS must contain control devices that will shut down the ICS in the event that the operating temperature is exceeded. The ICS should have the capability to export data to a PC in real time.

- Human Interaction: The ICS should allow for a significant amount of human interaction. The heat source and fan speed must be adjustable. The target temperature of the heat source, set by the user, must be within the achievable temperature range. There must be menus included in the interactive display so that the user can select different viewing options.

After the problem statement was formulated, several conceptual designs were considered and evaluated. Each design concept was evaluated by the following criteria: Effectiveness, Cost, Safety, and Size.

System Components

1. Thermodynamics Analysis

To properly control the ICS, the thermodynamic system was analyzed[3,4]. This analysis was required to properly size and select components such as the heat exchanger, the pump, the cold plate, and the fan. Figure 2 shows the thermodynamic schematic of two-phase cooling technology used in the development of the ICS. The selected refrigerant is R-134a.

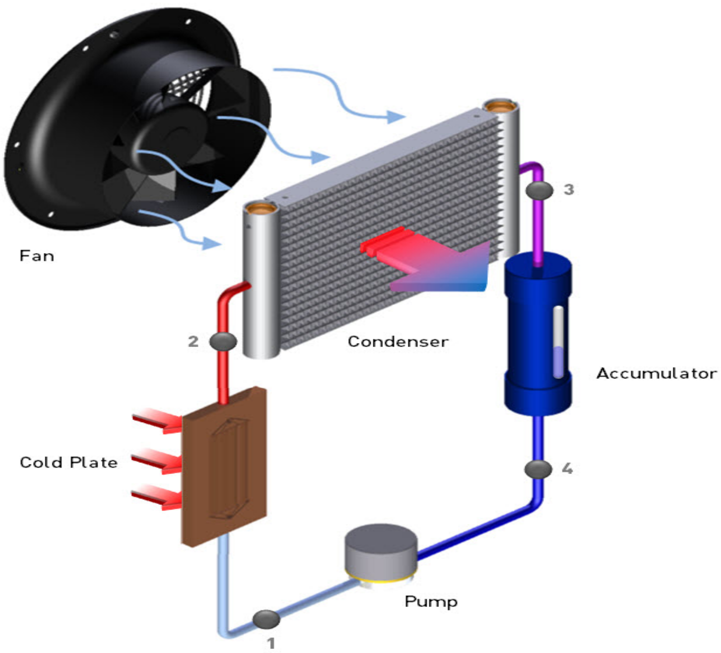

Fig. 2: Schematics of the thermodynamics two-phase cooling technology.

2. Cold Plate

The copper cold plate, shown in Fig. 3, is the device that exchanges heat from the heat source to the fluid (refrigerant). The cold plate is mounted directly to the heat source. Thermal grease is applied between the cold plate and heat source to reduce the contact thermal resistance. A custom cold plate was designed by the team for the ICS.

Fig. 3: Cold plate

The sight glass covering for the cold plate is made of tempered borosilicate glass. The thickness of glass for the ICS unit will be 1". The size will match the 3.5" by 7" dimensions of the cold plate. The manufacturing company of the glass provides a chart to assist in ordering the proper thickness of glass to withstand the pressure of the working fluid it is displaying and the unsupported length of the glass.

3. Heater

To create the varying heat loads of the user inputs, a heat sinkable planar resistor (heater) was selected for the ICS. Two 1000 W heaters with 3 inch square surfaces adhere to the underneath side of the cold plate using the recommended compound, as shown in Fig. 4. A variable voltage is connected to both leads of both heaters to create the effects of heat production from a heat source such as an IGBT, processor, or Silicon Controlled Rectifier (SCR).

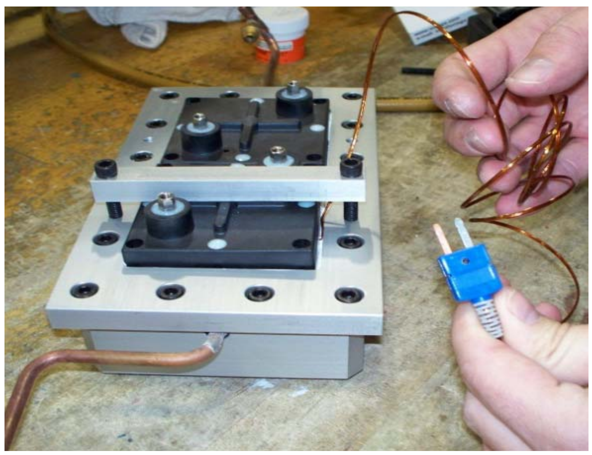

Fig. 4: Assembled cold plate housing with heaters and thermocouple

4. Touchscreen User Interface

The touchscreen selected for the ICS is the HP Compaq L2105tm monitor. The 21.5 inch optical touchscreen monitor was lower in price after more investigation using the Parker company discounts. The monitor is attached to a personal computer using a USB port and a VGA cable connection. The monitor's included stand will be removed and instead the monitor will be secured directly to the aluminum extrusion frame of the ICS using a quick-release VESA 100mm bracket

The user will be asked to choose a device to be cooled or create a custom scenario by pressing the desired option on the touchscreen. If a predefined electrical component is selected, pre-programmed input values will be used for the control system. If a custom scenario is selected, the user will be asked to enter in a heat load and desired temperature of the device being cooled (Fig. 5). To enter in the heat load and desired temperature, the user will input these values by touching the corresponding options on the touchscreen.

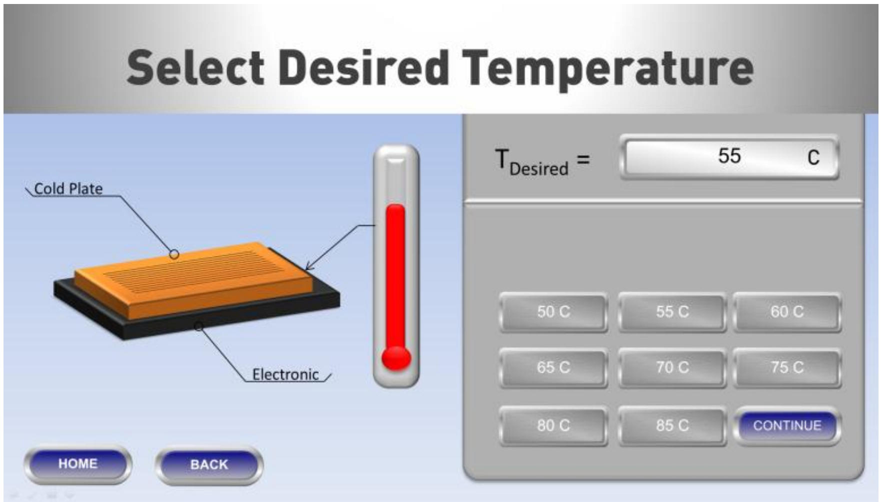

Fig. 5. Screen shot of the touchscreen

After the inputs have been entered, the system will begin working to meet the desired temperature. While the control system is in operation, the pressure and temperature at each node will be displayed. The flow rate of the refrigerant, temperature of the heat source, and ambient temperature will also be displayed.

5. Control System

In the ICS there are two controllers that were designed and developed. The first controller will set the correct voltage output for the pump in order to maintain a refrigerant quality of less than 0.7 and the second controller will control the voltage output to the fan in order to achieve a desired temperature to be maintained at the cold plate. Proportional - Derivative (PD) controller was used.

The pump has a set output for a given heat input whereas the fan must vary with the temperature difference of the cold plate with relation to the desired temperature. The controllers were implemented in the same programming language used in the data acquisition process, RSLogix 500. The pump control was designed to maintain a refrigerant quality of less than 0.7. In order to do this, MATLAB was used to generate a table that specifies the correct pump speed in both volumetric and mass flow rates.

Testing and Sample Results

Several tests were carried out to verify the design:

1. Steady State and Time Constant

The objective of this test is to generate a temperature vs. time plot of the temperature at the cold plate at the nominal operating conditions (500 W) heat load, 38% pump speed, and 50% fan speed) in order to obtain the steady-state temperature and the time constant of the system. The test results are shown in Fig. 6. The figure shows that the steady state temperature is about 49°C and the x-axis crossing of the initial slope is about 14 seconds.

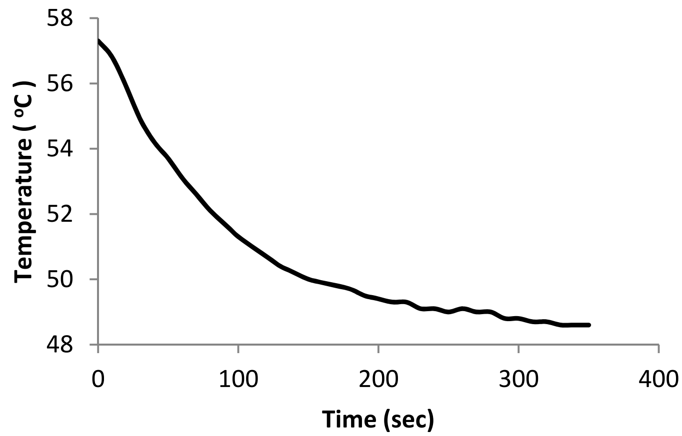

Fig. 6: Steady state test

2. Extremes Tests

The objective of these two tests is to find out how hot or cold the cold plate can get at extreme operating conditions without the fan being on and then with the fan at full speed. This gives an idea of the lowest temperature we can cool the 'electronics' to and the highest temperature the 'electronics' can get up to in our system. (Note: An electronic safety shut off was implemented in the code so that any measured temperature does not go above 90°C). The results of these tests are presented in Figs. 7 (a) and (b).

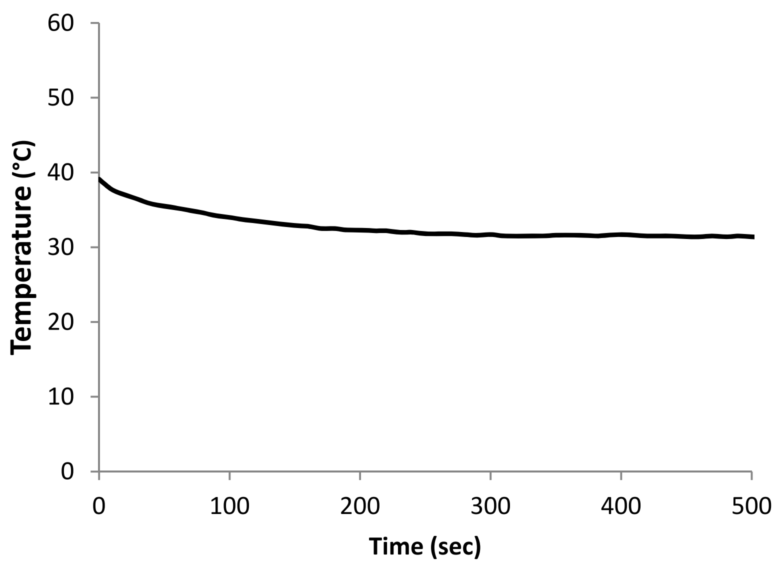

Fig. 7a: Extreme test – 100W

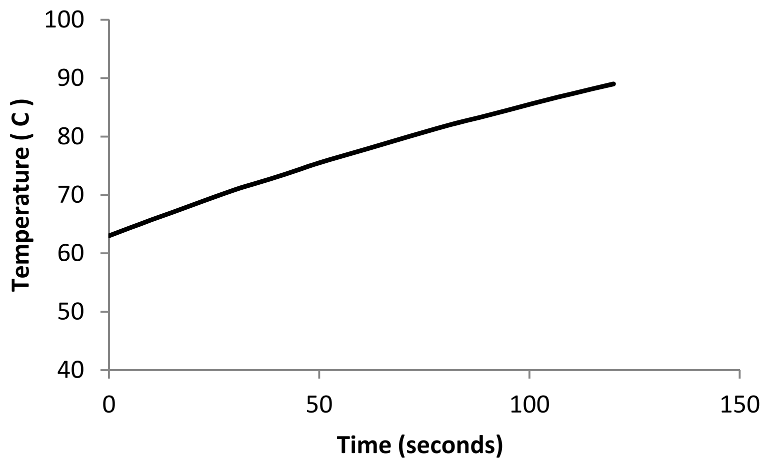

Fig. 7b: Extreme test – 1000W

The results show that the lowest temperature that 'electronics' can be cooled to in our system is approximately 31°C (Fig. 7a). This is with the lowest heat load (100 W) and the highest fan speed. And the highest temperature that 'electronics' can get up to in our system is approximately 90°C at which the load is 1000 W. At this point, the safety feature kicks in and turns off the heat and then the temperature starts to drop.

Control System Modification:

A problem was discovered during testing of the control system that required an innovative solution to fix. It was noticed that when the user was going from one trial at a higher heat input and higher desired temperature to another trial with a lower heat input and lower desired temperature that the system would become temporarily unstable. This instability was a result of the refrigerant leaving the two-phase region and vaporizing. Figure 8 shows the transient response of the ICS going from 900 W at 80°C to 600 W at 55°C before the control system modification. Note the instability that occurred when the two-phase refrigerant composition was lost.

The refrigerant is able to enter a superheated state during the transient operation when going from a higher heat-load and high temperature to a lower heat load with a low temperature. The pump immediately slows its speed per the lower heat-load pump control. However, since the system is still running at a high temperature, the pump is not running fast enough to get the refrigerant over the cold plate before it completely vaporizes.

To solve this problem the pump control system was redesigned to account for this transient operation. This is accomplished by increasing the pump speed when the system changes from a high temperature to a low temperature while the fan is operating at 100%. This higher pump speed forces the refrigerant through the cold plate fast enough to prevent it from vaporizing before the exit. Figure 9 shows the transient response of the ICS going from 900 W at 80°C to 600 W at 55°C after the control system modification.

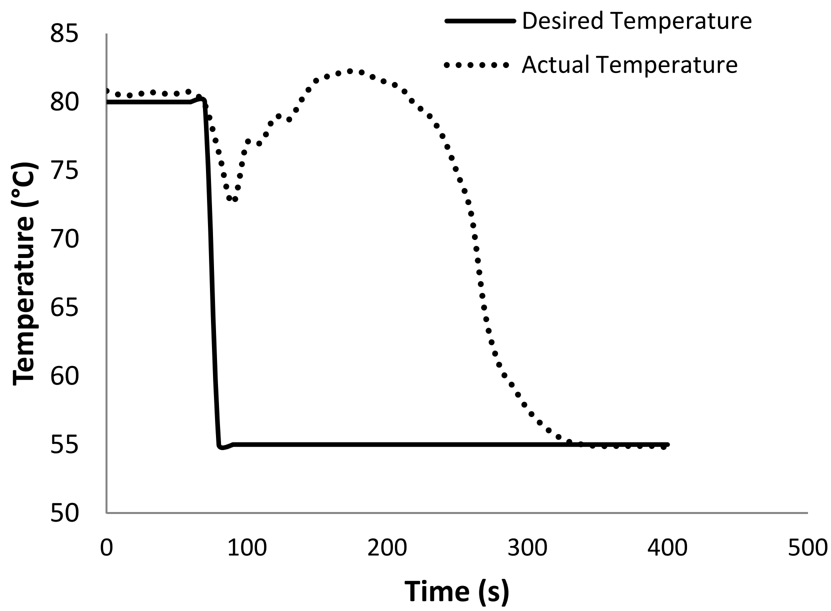

Fig. 8: Transient response before control modification

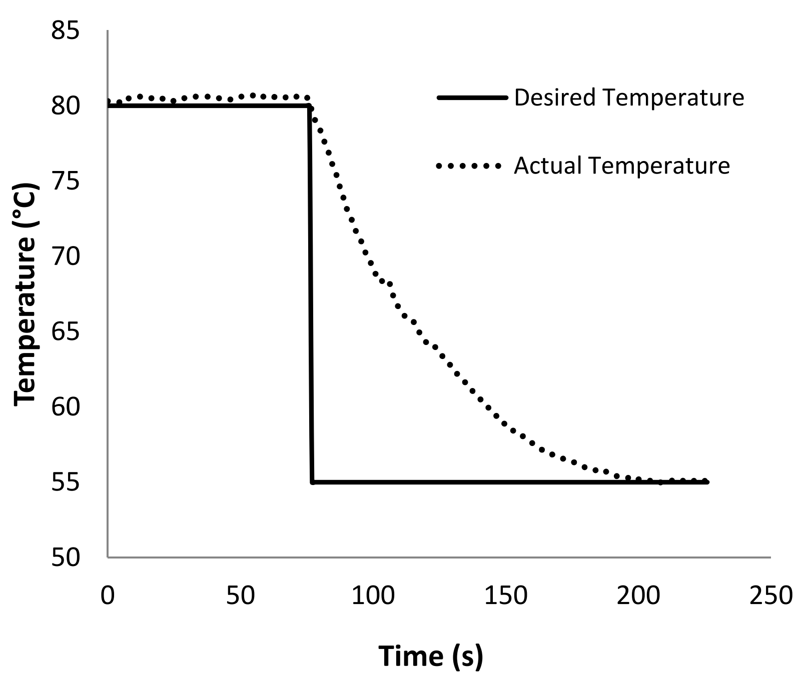

Fig. 9: Transient response after control modification

It can be seen from these two figures that the time it takes to achieve the desired temperature is much less after the modification. The control system was tested rigorously after the modifications were made in order to ensure performance across the heat and temperature inputs, as shown in Fig. 10. Note the absence of unstable peaks that were developed in Fig. 8; indicating that the two-phase refrigerant composition was not lost.

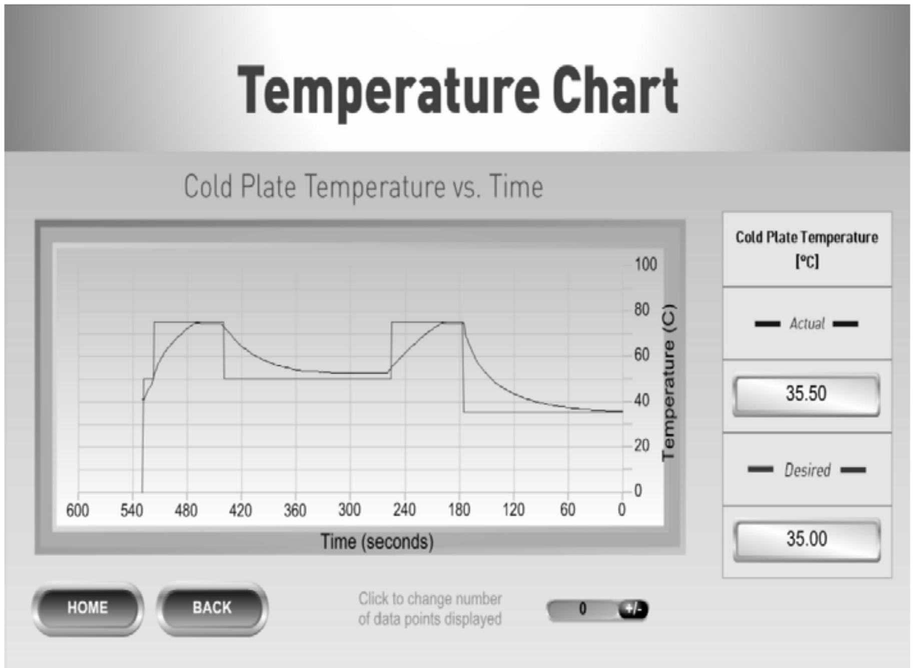

Fig. 10: Screen-shot of modified control system test

Conclusion

An educational Interactive Cooling System (ICS) was developed. The ICS system is visually striking and attracts the interest of prospective customers at trade shows, employees at the Parker Hannifin - New Haven facility, and students at IPFW. Once people are interested in the display unit, the ICS allows the user to adjust the heat load and desired temperature of the heat source. The automatic control system then accurately brings the electronic device that needs to be cooled to the desired temperature in a minimal amount of time. They are able to easily navigate through the GUI on the touch screen to see different properties of the system and information on the two-phase cooling technology.

Acknowledgments

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