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DESIGN AND CONSTRUCT UNIT TO CONTROL FLUID ENTERING SOLAR COLLECTORS DURING EFFICIENCY TESTS

Jawad Kadhim Mezaal[1]*, Thamer Alameri [2]

[1] School of Engineering and Information Technology, Murdoch University, Perth, Western Australia, Australia
[2] Department of Computer Engineering, University of Technology, Baghdad, Iraq

** jawadmezaal@gmail.com*

This paper describes the development of an apparatus to control the fluids that enter a solar collector in experimental tests with respect to the Australian and New Zealand Standard AS/NZS 2535.1.2007. This standard explains the testing procedure, indicating that the inlet fluid should have specified temperature and flow rate uncertainties. The hardware components were constructed in the lab. A new sophisticated data acquisition system with an NI CompactDAQ was added to control the unit, and a new software application in LabVIEW was developed. The unit was operated in an open-loop to understand its behaviour as a multiple-inputs and multiple-outputs system (MIMO). A rule of thumb tuning method was used to design the proportional-integral PI controller for the heating system.Moreover, a custom decoupler with a PI controller was developed to reduce the interactions in the MIMO. The measured steady-state responses were analysed to determine the flow rate and temperature compared with the limited boundaries. The final results show that the system could supply water to the solar collector within the accuracy requirements. Achieving the fluid's absolute temperature and flow rate within the required constraints of the published standard has proven that the developed unit can be adapted to perform solar collector testing. However, additional steps are suggested for further work to enable the unit to provide field testing.

Keywords: Solar collectors, Control system, PID controller, Decoupler, AS/NZS2535.1.2007

1 INTRODUCTION

Solar power plays an essential role in energy production through harnessing and converting solar radiation. Therefore, the solar energy resource has a more trusted prediction than other renewable energy resources such as wind [1]. This form of energy can be from photovoltaic technologies to generate electricity or in thermal technologies to heat water in solar collectors. Solar thermal collectors absorb the radiation to heat circulating water for use in domestic consumption or other purposes. Examining the efficiency of a solar collector is stipulated in several procedures in the Australian and New Zealand Standard AS/NZS 2535.1.2007 [1]. This test is implemented to measure the amount of thermal energy that can be provided using solar collectors according to a set of performance variables.

The test procedure clarified in [2] is for collectors with one inlet and one outlet. The energy of the fluid entering and discharging the collectors is measured and compared with the energy incident on the collectors to determine the conversion efficiency. The heat transfer fluid used can be either liquid or gas. The test method has a simple mathematical model and appropriate data processing steps. However, this approach has difficult testing conditions, precise parameter requirements and lengthy test periods[3].

To facilitate the use of steady-state methods that are reached faster and more convenient, we developed a control unit and a novel nested algorithm for MIMO with a strategy that needs precise requirements. The unit's function is to control the fluid that enters the solar collector when testing its efficiency. The proposed apparatus is an alternative to the traditional one that requires an extended period to heat the water and enables only one test to be conducted during the day[4] as used in[5]. A comparison of different methods of testing can be reviewed in [6]. In the considered test case, water is also utilised as the heat transfer fluid. Our primary research concern is the uncertainty of the controlled temperature and flow rate values for the water entering the tested collectors, referred to as the outlet water, from our designed unit. These values must be set according to the Australian and New Zealand Standard AS/NZS 2535.1.2007. The apparatus is available in a Laboratory at Murdoch University in Western Australia. The steady-state is specified in the standard when the operating parameters only fluctuate from their average value throughout the testing period by ±0.1 ^oC and ±1 per cent for the temperature and the flow rate, respectively. The steady-state is achieved when these variances are met over 30 seconds. In the standard [7], the testing period should be within steady-state stability, and it should include 15-minute preconditioning followed by a testing period which is also 15 minutes, and the flow rate measurement is recommended to be set to 0.02 kg/s per square metre of the solar collector under the test. The flow rate could be measured directly, or the volumetric flow rate could be used with knowledge of the fluid temperature as the density of the fluid could change with temperature.

In this project, because there is no specific solar collector to be tested, it has been suggested [8] that the outlet flow rate of the unit could be chosen between 2 and 3 L/min.

2 DESCRIPTION OF THE DESIGNED UNIT

The designed unit used with solar collectors is an apparatus that supplies the inlet fluid with typical flow rates and temperatures to test the effectiveness of solar collectors based on the Australian and New Zealand Standard AS/NZS 2535.1.2007. The significant components of the unit are as follows:

2.1 Water supply tank

This tank is made of plastic PVC with a capacity of 100 L. This tank is mounted above the unit at the laboratory at a height of 10 m. The tank is supplied from the in-house water network and helps to maintain the head pressure on the unit [4].

2.2 Storage tanks

There are two storage tanks in the unit, each with a 50 L capacity. These tanks are mounted and stacked vertically. The lower one is for cold water while the upper one is for hot water. The inlet of each is supplied from the water supply tank, and the outlet provides water to the mixing system. Moreover, each tank is equipped with heating elements and a recycling system to maintain the water temperature inside the tanks.

2.3 Heating units

Each tank in the unit has three heating elements, and the power of each one is 10.4 KW. The heating elements in the hot tank were on whereas those on the cold tank remained off during operation. The power to the heating elements was manipulated by switching a solid-state relay utilising a pulse width modulation (PWM) signal. In addition, there is an internal thermostat with an interlock installed with the heating elements that switch off the heaters when the temperature inside the tank is more than 70 ^{o}C.

2.4 Recycling pumps

Each tank is equipped with a recycling system and a pump. The system takes the hot water from the tank's outlet and mixes it with the water at the inlet to ensure adequate heat distribution inside the tank.

2.5 Temperature elements

Five temperature sensors of the resistance temperature detectors RTD type with transmitters are installed to measure the water temperature and send the reading to the data acquisition unit. These sensors can measure the temperature from 0 to 150 ^{o}C and transmit the 4-20 mA signal. The temperature transmitters are in various positions in the apparatus. A sensor is installed directly at the outlet of each tank to measure the temperature inside the tanks. Two more measure the temperature on each stream before the mixing valve, and the fifth one is on the mixing stream to check the final temperature value.

2.6 Flowmeters

Two magnetic type flow meters are installed on each stream of the unit to monitor the flow rate of the water before the mixing valve. The flow meters send the measured flow rate as 4-20 mA to the control system to be scaled later to the actual values.

2.7 Mixing valve

The control valve in this unit has two inlets and one outlet. Its function is to mix the hot water stream with the water that comes from the cold tank. Two stepper motors operate this control valve on each side. This valve was modified to directly operate each side with a six-wire stepper motor by sending digital signals from the control system.

2.8 Control panel and NI CompactDAQ

The electrical and electronic equipment is mounted on a wooden panel, utilised to control, and operate the apparatus. The components that were installed on the board are as follows:

2.8.1 NI CompactDAQ 9174

This system is used to monitor and control the unit. Two modules are used with this system: the analog input module NI-9201 to read signals from the temperature transmitters and the flow meters and a digital input/output module NI-9403. The analog input has eight channels with a sampling rate of 500 KSample/s and a 12-bit resolution. Seven analog channels are utilised in the project: five for the temperature transmitters and two for the flow meters. This module measures the signal with a range ±10 V. Since the transmitters in the unit are from 4-20 mA, a 500-ohm resistor is used to convert the received signals from the transmitters to voltage signals that can be read by the analog input module [9]. The digital I/O module has 37 bidirectional channels, which are the sinking and sourcing 5 V signals. Eight channels are used to drive the two stepper motors of the mixing valve: one to operate the heater and one for the recycling pump in the hot tank.

2.8.2 Power supplies

The panel includes two power supplies at 12 and 24 V DC. These provide the instruments with DC power, as the electrical mixing valve needs 12 V while the temperature and flow meters require 24 V.

2.8.3 Magnetic relay boards

Relays were used to activate the heating elements and recycling pumps. A 5 V signal from the digital output DAQ is sent to the relays to pass the high voltage through the controlled devices.

The structure of the unit is shown in Fig 1.

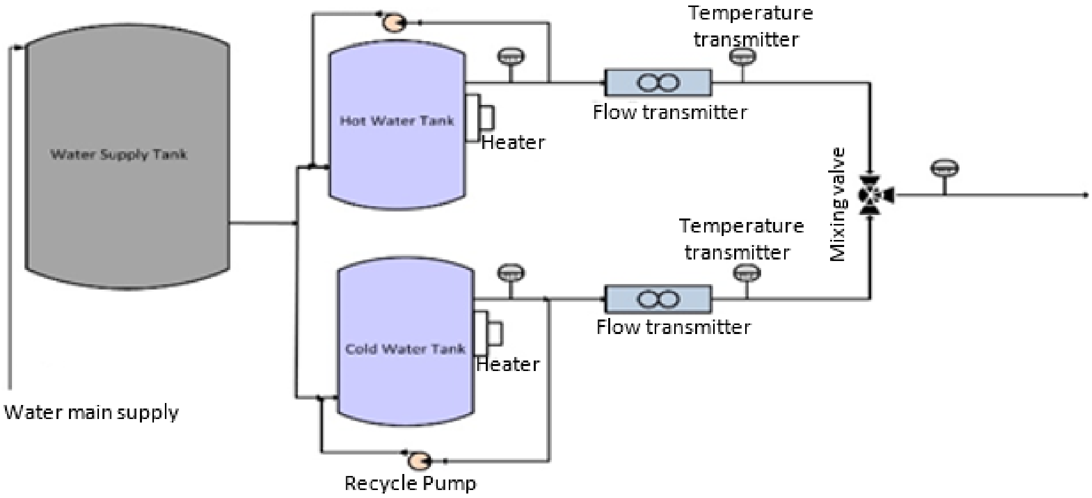

Fig. 1. Schematic diagram of the unit.

2.8.4 Operating software

The 32-bit LabVIEW from National Instruments was used to integrate with the CompactDAC. In addition, the program was utilised to develop a custom application software to monitor, control and record the data in real-time.

LabVIEW consists of the function block and the front panel[10]. The function block is a graphical programming environment. In the created application software for this unit, the code in the function block was divided into three separate parts. First, the analog reading signal loop is to read from seven physical analog signals: the five temperature transmitters and the two flow meters.

The MAX software associated with LabVIEW was used to perform a custom scaling of the input analog signals. The sample rate to read the analog signal was 1000 samples per channel per second, whereas there were 100 samples to be read. The second part of the code regards the operation of the stepper motors. The method used to run the stepper motors is unique, where four output digital signals are sent to each motor to manipulate the mixing control valve.

The third part of the code is to record the data on an excel datasheet. A front panel was used to develop the interface as a human-machine interface HMI with the system to operate, enter the controller parameters and monitor the system behaviour. Fig 2 shows the designed front panel for the system.

Fig. 2. The main front panel of the LabVIEW application for the system

3 DESIGN CONTROL

The unit's primary purpose is to produce a controlled water flow with precise accuracies for the flow rate and temperature. Therefore, it is necessary to design a control system for these final parameters. The control unit should maintain the temperature of the hot tank to a stipulated value, while the cold water would be at ambient temperature.

3.1 Hot water temperature controller for hot storage tank

Changing the water temperature in the hot tank results in an unstable temperature in the outlet stream of the unit. Therefore, an accurate control system should be implemented to manipulate the amount of heat provided by the heater in the hot tank. To this end, a PWM signal was generated in LabVIEW [11] to change the amount of heat by switching the heater on and off.

The PWM duty cycle was manipulated by utilising a conventional PI controller. The temperature measured in the hot tank using the sensor is sent to the PI controller and compared with the desired value. The controller stipulates the required amount of the heat by manipulating the square wave's duty cycle to be sent to the heater.

The rule of thumb method was used to determine the appropriate parameters for the PID controller. The strategy was to set the integral and the derivative terms of the controller to zero and then use trial and error methods to change the values of the proportional terms until an oscillatory response output result for the temperature were achieved. After obtaining the oscillating response, the oscillation period t_{osc} and the oscillation width X_{cos} were recorded to count the tuning parameters, as shown in Fig 3.

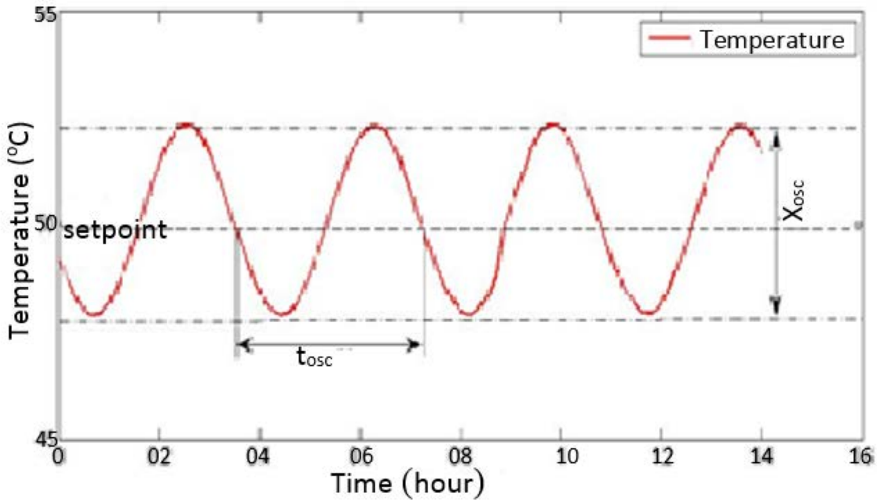

Fig. 3. Hot water tank temperature oscillation using only the proportional controller.

By using the proposed method, the PID controller parameters can be calculated as in [12]:

Proportional= 2.0 x Xosc

Integral= 1.5 x tosc

The derivative term can be calculated as

Derivative= Integral/5

Therefore, the PID parameters of the heating system for the unit are as shown in Table 1.

Table 1. PID controller parameters for the heating system.

Proportional gain	Integral time (minutes)	Derivative time (minutes)
8.88	33	6.6

Only the PI controller was used to control the heating system in the hot tank, which gave a controlled and slightly sluggish system, as illustrated in Fig 4.

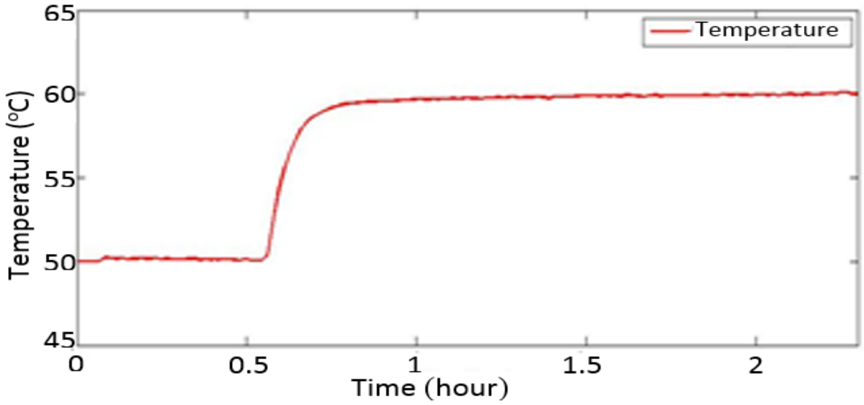

Fig. 4. Temperature setpoint change in the hot water tank

3.2 Final flow and temperature controller design

The outlet's final flow rate and temperature need to be controlled in the developed system. Therefore, a robust control system should be implemented to fulfil the standard's requirements. The flow rate and temperature as process variables can be controlled by individually manipulating the control valve of both flow streams. Therefore, the two process variables with manipulation variables would specify this design as a MIMO control system. In this case, manipulating one input could impact both outputs. Changing the flow rate of one stream would affect the final flow rate and the final temperature. This phenomenon is known as process interaction, which is not a concern in single-input single-output systems[13]. The developed control strategy works as an alternative method of pairing loops and should be identified by performing relative gain array RGA analysis. Cascade controller to eliminate the offset was experienced in the original model. The offset controller monitors the instantaneous final temperature, and the output of this controller is a temperature setpoint to the decoupler block, which in turn calculates the flow rate setpoints of both streams. Fig 5 illustrates the new model of the control system structure.

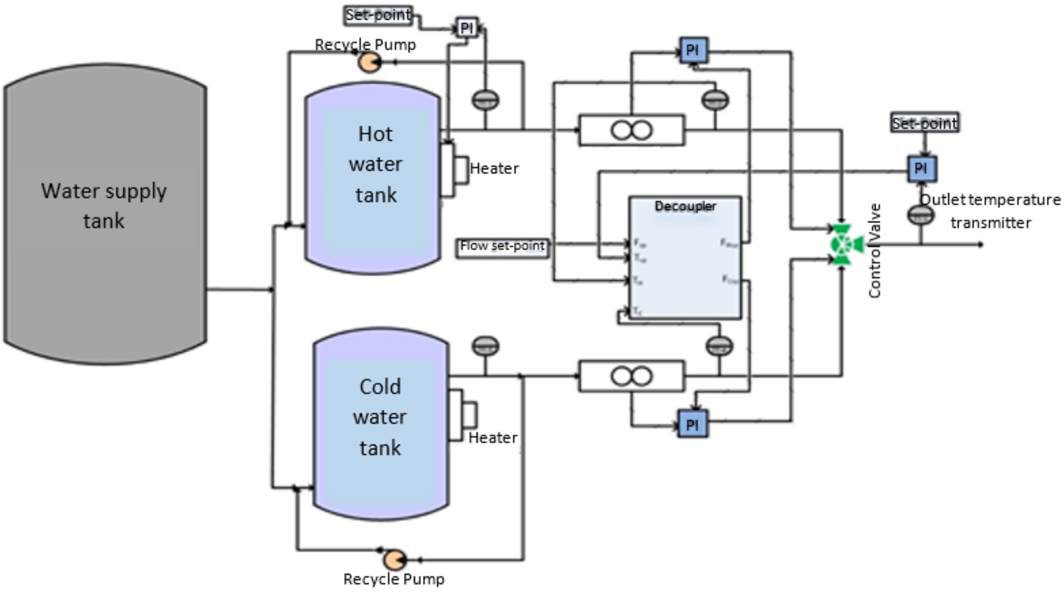

Fig. 5. The modified control system structure.

The process model is calculated as follows [8]:

$$F_M = F_H + F_C \qquad (1)$$

The final flow rate from the unit FM is the summation of the cold flow rate FC and the hot flow rate FH. Therefore, the heat balance for the system is given as in Eq. (2)[8].

$$T_M F_M = T_H F_H + T_C F_C \qquad (2)$$

The setpoint for the cold stream can be calculated as

$$F_{CSP} = F_{SP} \frac{T_H - T_{SP}}{T_H - T_C} \qquad (3)$$

Similarly, for the hot stream, this would be

$$F_{HSP} = F_{SP} \frac{T_{SP} - T_C}{T_H - T_C} \qquad (4)$$

Where

F_C is the flow of the cold stream

F_H is the flow of the hot stream

F_M is the mixed flow

T_C is the temperature of the cold stream

T_H is the temperature of the hot stream

T_M is the temperature of the mixed stream

F_{SP} is the final desired flow setpoint

Tsp is the desired temperature setpoint

F_{CSP} is the calculated set point of the cold stream

F_{HSP} is the computed set point of the hot stream

The flow rates of the hot and cold streams setpoints were calculated from Eq. (3) and Eq. (4), which represent the decoupler block. However, the T_{SP} is the adjusted set point of the desired temperature, which is the output of the cascade controller.

3.3 Final Process Variable Controllers Tunings

The control strategy utilised in this system differs from the usual approaches of a MIMO control loop. There are no specific manipulated variables that can control a particular process variable. Nevertheless, both manipulated variables cooperate to control both process variables, the final temperature, and the final flow rate. Therefore, a trial and error tuning method was conducted to find the parameters that lead to the optimal system stability [14]. The calculated PID parameters used are shown in Table 2.

Table 2. PID controller parameter values for the flow rate streams.

PID Controller Parameters	Cold Stream Controller	Hot Stream Controller
Proportional gain	15	15
Integral time (minute)	0.02	0.02
Derivative time (minute)	0	0

The same parameters were employed for the two PI controllers on the hot and cold streams. Similarly, the offset controller was also tuned using a trial and error method.

The final proportional parameter gain was set to 1, while the integral time was set to 0.5 minutes. However, the derivative term was not employed for this controller. These values provided a stable response to the final flow and temperature. Moreover, this modified control strategy assisted in eliminating the offset that was previously experienced in the final temperature value.

3.4 Test the response of the control system

Several experiments were performed to test the system and the new control strategy. Changing the desired process variable setpoints reveals the interactions between the temperature and the flow rate of the water outlets.

3.4.1 setpoint change in the final temperature

In one test, the set point of the final temperature was increased after it was stable from 35 °C to 45 °C, and the final flow rate remained the same at 2 L/min. As shown in Fig 6, the new desired temperature value was reached in approximately three minutes.

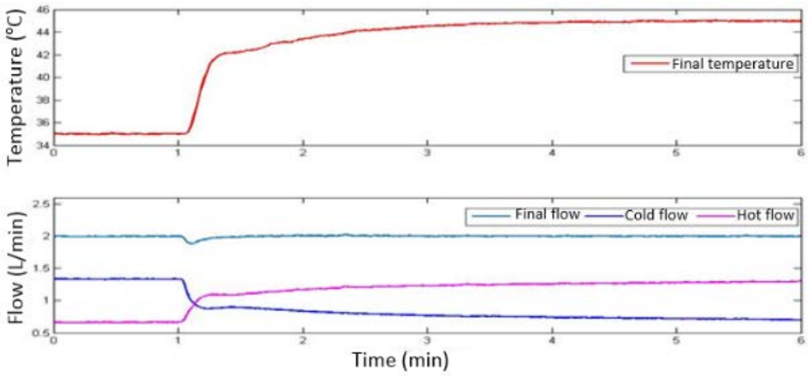

Fig. 6. System behaviour when the final temperature setpoint was changed from 35 °C to 45 °C.

The minor variations in the final flow rate when the temperature was changed are due to temperature and flow rat interaction.

At the 35 °C set point, the cold flow rate dominated the final flow rate since the ambient water temperature was 22 °C, and the hot water tank was set to 60 °C. When the last temperature setpoint changed to 45 °C, the flow in the hotline increased exponentially, whereas the cold line decreased in the same proportion. This allowed the input flow rates to compensate and maintain the final flow rate with minimal influence from their interactions.

3.4.2 Setpoint change in the final flow rate

Analogous to the temperature setpoint change test, a test was conducted that changed the final flow rate setpoint from 1.5 to 2 L/min while maintaining the final temperature. For this test, the hot water stream temperature was 60 ºC, and the cold flow at ambient

was 23 ºC. When changing the desired final flow rate, both streams were increased with more flow in the cold line. The slight increase in hot water was to counterbalance the drop in temperature and to keep the final temperature at the set point. Fig 7 illustrated the changes in the flow rates when the final set point was moved. The final temperature was slightly reduced due to parameter interactions, but it returned quickly to its set point with a small overshoot.

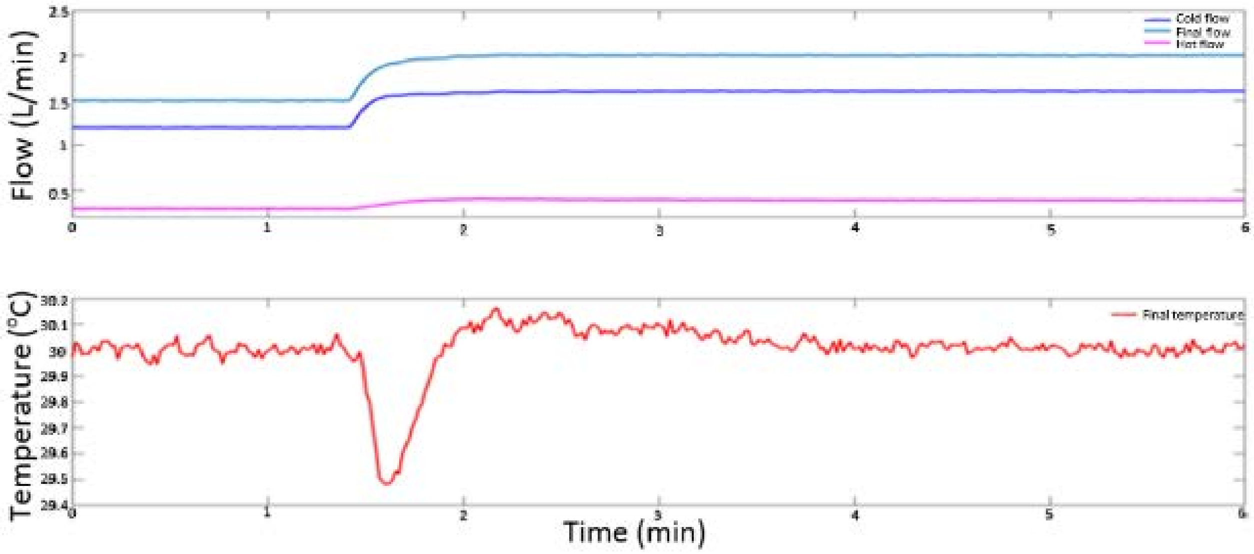

Fig. 7. Setpoint change in the final flow rate from 1.5 to 2 L/min.

4 STEADY-STATE PERFORMANCE TESTING

Several tests were performed to measure the unit performance and determine compliance of the final process variables, temperature, and flow rate with the standard. Multiple temperature setpoint values were considered, whereas the final flow rate mainly was kept at 2 L/min due to limitations in the inlet flow rates of the supply tanks. The data were logged once every second, and, after reaching steady-state conditions, the data were collected for an additional 30 minutes. Table 3 shows the statistical analysis for two different experiments at different temperature setpoints.

Table 3. Statistics of the measured values for final flow rate and temperature at steady state.

Statistical Parameters	Temperature 30oC	Flow 2L/min	Temperature 50oC	Flow 2L/min
Mean	29.999	1.999	49.995	2.000
Standard Deviation	0.019	0.002	0.023	0.003
Min	29.933	1.991	49.91	1.969
Max	30.064	2.011	50.075	2.018
ISE	0.729	0.012	1.064	0.028
Range	0.131	0.02	0.165	0.049
Number of Samples	1833	1833	1869	1869
Violations	0	0	0	0

The outcome of the two tests in Table 3 lies within the boundary limits required for the project. In the first test at 30 ºC, both the temperature and flow rate adhered to the standard requirements. The mean values are close to the setpoints with minimal deviations, as indicated in the standard deviation values for both temperature and flow rate. Since there is no drift, the maximum and minimum values range within the boundaries, and the violation is zero for both process variables. This test was performed when the cold water at ambient temperature was 24 ºC and the hot water temperature was set to 50 ºC. The graph in Fig 8 (a) illustrates the temperature and flow rate at a final set point of 30 ºC.

A second test was performed when the temperature set point was 50 ºC. As shown in Table 3 and illustrated in graph Fig 8 (b), the performance of measured values adhered completely to standard limitations. The maximum and minimum of the recorded temperature values at a steady state for 30 minutes were 49.91 ºC and 50.07 ºC, respectively. The results indicate a slightly higher integrated square error for the temperature and flow rate than the 30 ºC set point test. The test was conducted when the cold water temperature was 23 ºC and the hot water was 60 ºC.

The steady-state values for both tests were recorded within limits and specified testing time. In addition, the system's development in the system demonstrates that the solar collector efficiency control unit could supply fluid to test solar collectors according to the Australian and New Zealand Standard AS/NZS 2535.1.2007.

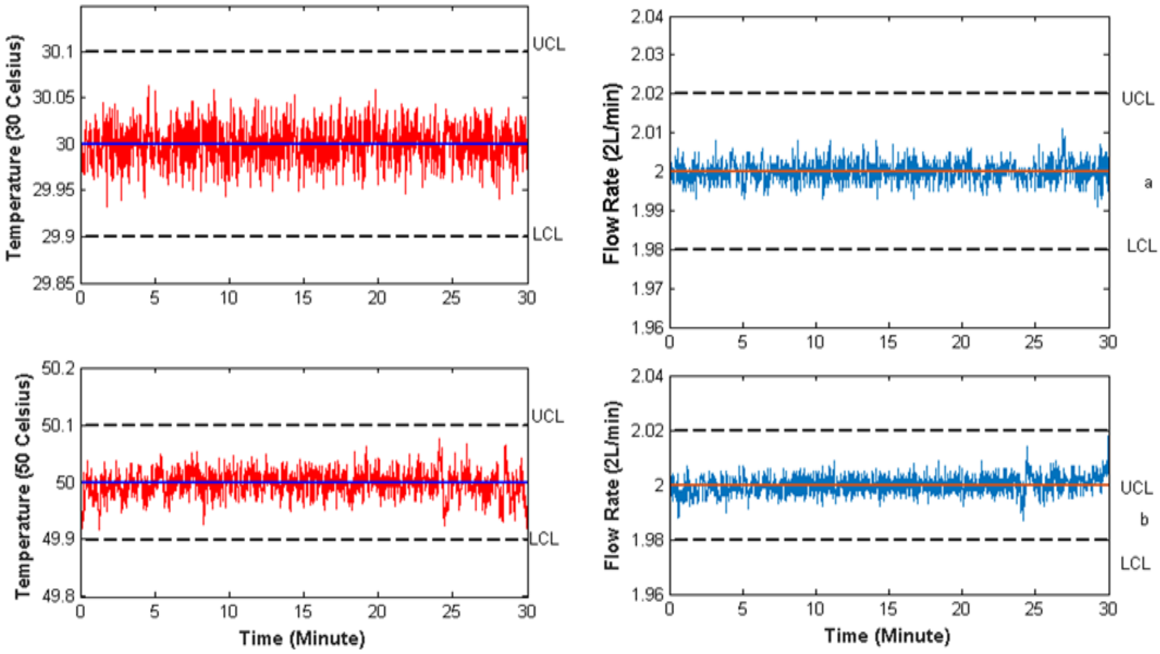

Fig. 8. Final flow rate and temperature at steady state for (a) a temperature of (a) 30 oC and (b) 50 oC with a flow rate of 2 L/min in both cases.

5 PROJECT OUTCOME ANALYSIS

Achieving the desired results in this unit resulted from several modifications and enhancements conducted during this research. These modifications are listed below.

- Adding the water supply tank assisted in keeping the water head pressure constant. The instability in the flow rate was analysed in [15], which blamed the fluctuations on the supply pressure. However, this problem was not present in the developed unit.
- Calibrating the instruments in the unit, which included temperature transmitters and flow meters to ensure accurate signals were obtained that exactly match the actual values.
- Replacing the old controller NI Field-Point DAQ, which is no longer supported by National Instruments, with a new, highly developed NI CompactDAQ. The analogue input has an accurate signal reading. Also, the digital output has a rapid speed response to manipulate the valve through stepper motors across the digital signals.
- The stepper motors were Operated in the valve by sending four digital signals to each motor as a unique and precise method. Jitter and spiking were experienced in the stepper motor movements due to utilising an external microprocessor in previous works with this unit. However, this problem was not confronted in the presented research.
- Modifying the decoupler block by implementing a cascade controller that adjusts the final setpoint temperature in the decoupler to help eliminate the previously observed offset.
- A LabVIEW software application was Developed and utilised the software's ability to execute a swift time update.

All these factors played a significant role in enhancing the unit's performance to meet the standard.

6 CONCLUSION

The developed unit can provide water for testing a solar collector's effectiveness according to the demand. A new control strategy was implemented, and a highly sophisticated data acquisition system was utilised. The complex heating system was varied using a unique temperature tuning system. Moreover, applying a decoupler eliminated the interactions between the final process variable control loops. It attained a smooth transition when the setpoint was changed—modifying the decoupler by adding the cascade PI controller to the final temperature assisted in removing the encountered offset in the final temperature. Eventually, the unit can be trusted to be employed in measuring the efficiency of solar collectors in industrial or academic research.

7 FUTURE DEVELOPMENT

Further enhancements are recommended to improve the performance of the designed unit. These could include additional equipment or additional steps in the control strategy to fulfil a more flexible operation. Precisely, the recommendations are as follows.

- Installing a pump at the inlet of the water supply tank: Since the water supply flow rate to the tank from the university water system is 2 L/min, increasing the outlet flow rate would fluctuate the head pressure on the unit. Therefore, adding the pump can provide more flexibility in changing the set point of the final flow rate while maintaining the head pressure.
- Implementing a feedforward control loop on the heating system could help reduce the response time to disturbances. Since the heating system control loop dynamics are slow, responding to disturbances when the outlet flow rate changes take a relatively long time. Implementing a feedforward controller can help address this issue[16].
- Installing two pressure sensors on both sides of the mixing valve could help provide knowledge of the differential pressure across the valve, which is necessary to investigate cavitation's probability.

Further research can be performed by implementing a higher performance control strategy [17], or a model predictive controller MPC can be constructed for this unit. All process variables, including the temperature of the hot tank, the final temperature and the final flow rate, can be handled in the MPC as a single package[17]. This MPC would overcome the disturbance rejection delay response in the heating system and increase the overall performance. LabVIEW has a valuable and comprehensive toolbox to perform predictive controlling [18].

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