# *Arduino based temperature and humidity control for condensation on wettability engineered surfaces*


Rohit Gupta*
Department of Power Engineering
Jadavpur University
Kolkata 700098, India
*Corresponding author- rohit.ju.pe@gmail.com

Chayan Das
Department of Power Engineering
Jadavpur University
Kolkata 700098, India

Ankit Roy
Department of Power Engineering
Jadavpur University
Kolkata 700098, India

Ranjan Ganguly
Department of Power Engineering
Jadavpur University
Kolkata 700098, India

Amitava Datta
Department of Power Engineering
Jadavpur University
Kolkata 700098, India



***Abstract*—Condensation is a ubiquitous phenomenon which depends on several factors, ranging from the degree of subcooling to the relative humidity of the condensing environment. Characterizing condensation in experimental setups, therefore, requires a proper control strategy of operating parameters. Although industrial vapor chambers are available for carrying out condensation experiments under precisely controlled environments, these setups are prohibitively expensive. Here we have developed a low-cost, prototype vapor chamber that is equipped with advanced control systems. Environmental control aspects of a Styrofoam-made condensation chamber are developed in-house for testing condensation on wettability engineered surfaces. Peltier-heat sink arrangement is used to cool the condenser surface under study and the desired relative humidity is maintained within the chamber by means of spraying deionized water with a nebuliser. In order to automate the process, an Arduino Duemilanove board is amalgamated with the setup. Temperature is controlled by an ON/OFF trigger-driven mechanical relay connected to the Arduino environment, which in turn generates an opportunely amplified signal to control the supply voltage of the Peltier element. A K-type thermocouple is interfaced to the Arduino board with the help of MAX31855K thermocouple amplifier for measuring the plate temperature. For humidity and chamber-temperature monitoring, an SHT35D sensor is used. The relative humidity of the chamber is maintained by a mechanical relay-driven spray arrangement. The time-domain plots of humidity and plate temperature response indicates that the temperature fluctuations are within 0.25°C and RH fluctuations are within 0.5% about the set-point. Transient response of the temperature and RH data are monitored by the Serial Monitor of Arduino software, which indicates that the set values of temperature and RH are obtained approximately within 0 to 1000 seconds.**



***Keywords—Condensation; Temperature Control; Humidity Control; SHT35D; MAX31855K***


## I. INTRODUCTION

Condensation is a phenomenon that is not only omnipresent in nature, but it also plays an important role in wide range of industrial applications including power generation, water desalination, industrial processes, heating ventilation and air conditioning (HVAC). In most of these applications, a high condensation heat transfer coefficient is desired to improve energy efficiency. Typically it has been seen that condensation is highly dependent on physicochemical characteristics of condenser surface, and the thermophysical and conditions of the condensing medium [1]. Primarily there are two modes of condensation heat transfer, dropwise condensation (DWC), which predominantly occurs on hydrophobic surfaces, and filmwise condensation (FWC), which occurs on hydrophilic surfaces. While the literature on influence of condenser surface wettability on DWC and FWC in pure steam has been extensively studied over several decades [2], the literature is still replete with controversial results when it comes to the study of DWC in presence of noncondensable gases (NCG) [3]. For characterizing such condensation process on novel surfaces, controlled temperature and humidity environment chambers (EC) equipped with precise control systems are required. Majority of these studies have used off-the-shelf, proprietary ECs with complex Proportional-Integral-Derivative (PID) control algorithm for controlling the ambient conditions. While these ECs offered reasonably good control, inquiry by us revealed that all these ECs were prohibitively expensive. Here, we attempted to develop a low-cost EC that is custom-designed for condensation experiments under NCG-vapor condition. Such an arrangement would warrant a precise control of the cooling plate (usually a Peltier cooler) and the temperature and relative humidity (RH) inside the chamber.

Several researchers have previously fabricated air de-humidifiers, based on PID that controlled the voltage to the Peltier cooler by Pulse Width Modulation (PWM) of the signal [4,5,6,7,8]. But the Peltier elements need to be operated near their maximum efficiency point. Implementation of PID will increase or decrease the applied voltage too much about the Peltier set-point, which will affect their performance.

To circumvent this problem, the authors have developed a robust, low cost, yet accurate EC which can perform condensation experiments over a wide range of RH (from 60 to 98 %) and a surface temperature ranging from 3 to 15 °C. The chamber is fabricated in such a way that it enables optical imaging and Schlieren imaging of the condensation surface in order to study the influence of vapor-NCG boundary layer profile on DWC or FWC heat transfer. The whole environment control process is automated and monitored in real-time by an Arduino processor. The paper is structured as follows: in section II the proposed experimental setup and its subcomponents are described. The control strategy and connection diagrams are detailed in section III. In Section IV the accuracy of the adopted control algorithm is discussed and a set of successful condensate collection data is also tabulated. Finally in section V and VI the observed results are summarized and some future possible developments are suggested, respectively.

## II. Experimental Setup

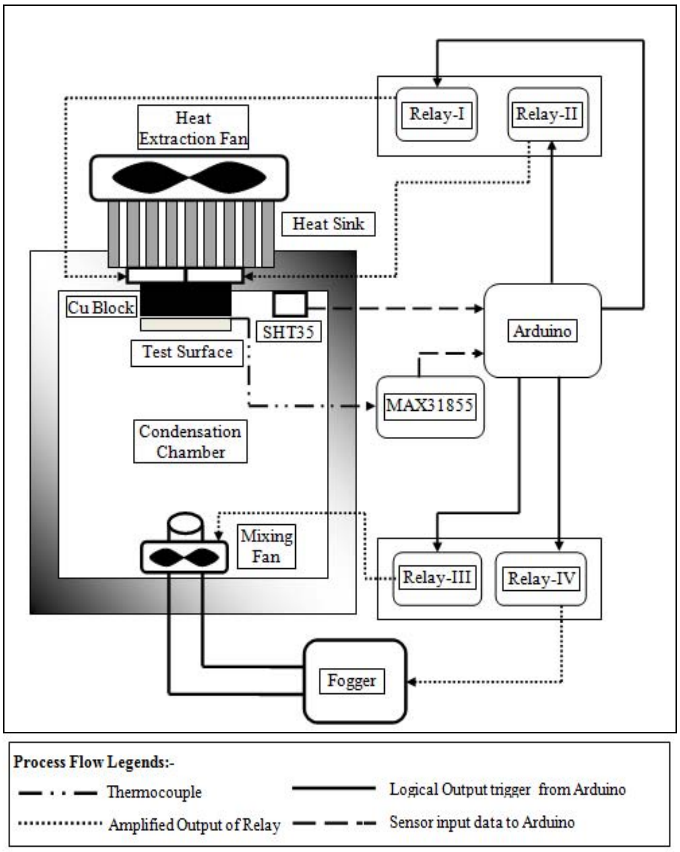


**Fig. 1.** Schematic of the experimental setup

In the proposed experimental setup for characterizing condensation, the cold side of the TEC-12706 (Make – Hebei I.T co. ltd) Peltier element (having dimensions 4×4×0.39 $cm^3$) is attached to a copper block (Dimension – 6×6×5 $cm^3$) using a thermal paste (Omegatherm 201, Omega). The opposite face of the copper block is exposed to the interior of a Styrofoam chamber of inner dimension 31×35×22 $cm^3$ and 6 cm wall thickness. The four side-faces of the copper blocks are insulated using double-sided Teflon tapes. In order to maintain the cold side of the copper block at a nearly isothermal condition (thus ensuring one-dimensional steady heat conduction through the block), the heat generated by the hot side of the TEG is continuously removed by an aluminum heat sink of and a brushless DC (BLDC) fan. The thermal contact between the Peltier element and heat sink is also established by the same thermal paste. The arrangement (see Fig 1) is such that the heat sink is exposed to the atmosphere whereas the TEG is placed within the thick wall of the EC. An aluminum substrate (Dimension - 6.5×6.5 $cm^2$) of known wettability is mounted (using thermal paste) on the inner face of the copper block, which experiences a drop in temperature as the Peltier element is powered. When surface temperature on the test plate drops below the dew point temperature corresponding to the environment inside the EC, condensation of water vapor begins on the test plate. A fiber-glass window is installed on the opposite (to the test plate) wall of the EC for optical imaging of the test plate. Two windows in Line of Sight (LOS) grazing over the condenser surface are also provided for Schlieren imaging purpose. An effervescent atomizer-based nebulizer (Model NE C25S) and a mixing fan arrangement is used to supply required amount of deionized water within the EC in order to emulate different relative humidity (RH). A K-type thermocouple (Make - Omega) is used for measuring the plate temperature whereas SHT35D (Make - Sensirion) sensor module provides the temperature and RH data of ambient condition within the EC. For comparing the accuracy of the temperature readings of the copper block, another K-type thermocouple is connected to a standard DAQ (Make - Agilent). The temperature and humidity control process is automated and monitored by an Arduino Duemilanove development board. The details and working principle of the different components of the controller will be discussed in the following sub-sections.

### A. *ArduinoDuemilanove Development Board*

The controller board used here is an Arduino Duemilanove development board equipped with ATMega328 running at a clock speed of 16 MHz. The communication protocols feature UART/USART TTL (5V) Serial communication, SPI, $I^2C$. The board also has 14 digital I/O pins among which 6 pins can provide PWM outputs of 8-bit/16-bit and 6 pins have a special feature of taking analog inputs of 10-bit resolution. An FTDI FT232RL on the board channels this serial communication over USB.

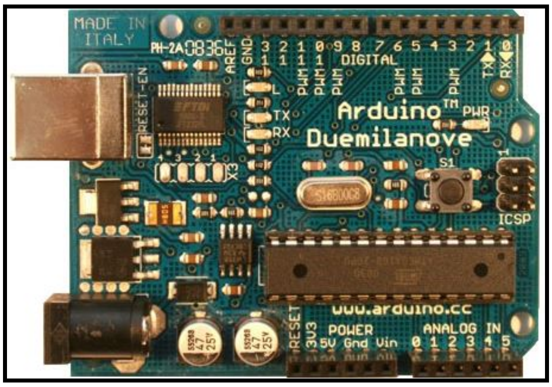


**Fig. 2.** Arduino Duemilanove development board.

## B. SHT35D RH and temperature sensor

The SHT35D (see Fig. 3) is a combined temperature and relative humidity sensing breakout board which communicates with ATMega328 using $I^2C$ protocol which can speed up to 1 MHz. It has a typical accuracy is ±1.5 % for RH and ±0.2°C for temperature readings. The SDA and SCL pins of the breakout board are connected to the A4 and A5 pins of the Arduino board respectively. The sensor monitors the ambient temperature and RH % inside the vapor chamber. An SF2 filter cap is used to prevent penetration of water droplets inside the sensor.

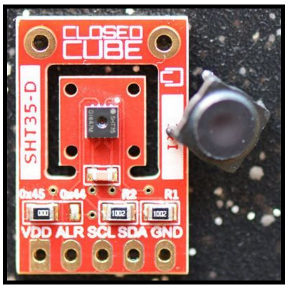


**Fig. 3.** SHT35-D RH and temperature sensor module (by Sensirion)

## C. K-type thermocouple and MAX31855K amplifier

In order to monitor and control the temperature of the wettability-engineered test surface of condenser, a K-type thermocouple is installed at the interface of cold side exposed to the vapor chamber and test surface with the help of thermal paste. The thermocouples provide a differential voltage across its terminals for each degree of temperature change. In order to decode that change a MAX31855 (see Fig. 4) cold-Junction Compensated Thermocouple-to-Digital Converters by Maxim Integrated were used to acquire the generated Seebeck voltages. This converter exhibits a 14-bit resolution (or 0.25°C) and a thermocouple accuracy of ±2°C for temperatures ranging from -200°C to +700°C for *K*-type.

The communication between ATMega328 and the MAX31855K module is based on SPI (Serial Peripheral Interface), a synchronous interface ideal for short-distance communication. In our case we have a single master - single slave configuration where the master is the Arduino UNO board while the two slaves are the two MAX31855K, selected acting on the respective ChipSelect pin. Every second, using the SPI interface of the Arduino Duemilanove board, a vector of temperature values is acquired and used for further computations in the control loop.

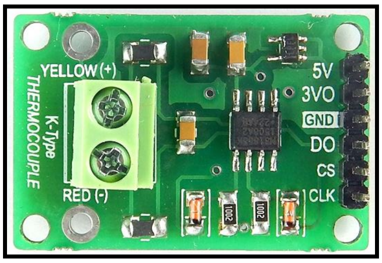


**Fig. 4.** MAX31855K thermocouple voltage level booster.

## D. Peltier Element

The copper block is cooled by two Peltier elements (TEC-12706). It has maximum current and voltage ratings of 6.4 Amps and 16.4 Volts. Heat is continuously extracted from the hot side of the Peltier by dual-fin arrangement equipped with a brushless DC Fan.

## E. Relay Modules

Two relay breakout boards (see Fig. 5) are used, each having two relays. One of the breakout board controls the supply to the Peltier elements based on the temperature set-point whereas the other board controls the stirring fan and fogger arrangement. The Peltier relays control inputs from two DC power supplies which are operated at 7 volts and can supply up to 5 Amps. The Mixing fan relay bypasses 12 volt, 500 mA from another DC supply module whereas the fogger control relay directly bypasses the 230 V, 50 Hz household AC supply. All the relays are capable of handling the different supply lines.


**Fig. 5.** Relay Module.

## F. Power supply modules

In order to perform ground isolation for obtaining uninterrupted thermocouple readings, the development board, sensors, and logic trigger side of the relays are powered by a 5 volt, 10000 mAh battery. The supply trigger sides are connected to two separate variable DC supplies. The mixing fan relay is fed with a 12 volt, 500 mA DC supply. The Heat sink cooling fan is driven by a 12 volt, 1 amp DC adapter.

# III. CONTROL STRATEGY

## A. Connection layout and control sequence :-

The detailed discussion in previous section indicates that the SHT35D should be interfaced to the $I^2C$ bus, MAX31855 to the SPI bus and the relays will use digital output pins of ATMega328 for their logical voltage trigger side. Fig. 6 represents the connection diagram. The adopted control algorithm is represented in Fig. 7. The control loop for surface temperature is a single layer cascaded system whereas for humidity control it is a double layer cascaded control loop.

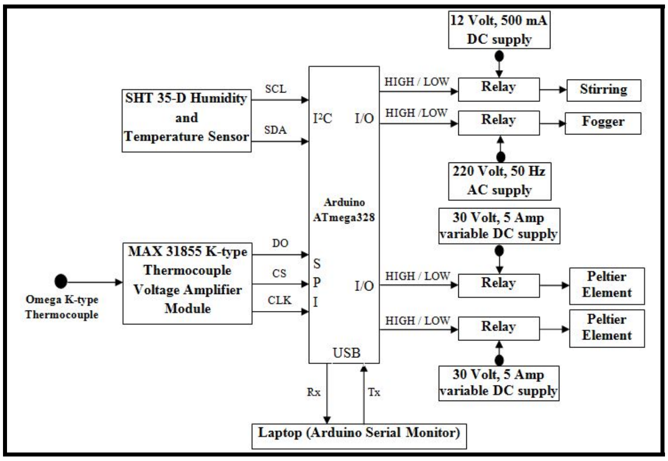


**Fig. 6.** Detailed connection layout.

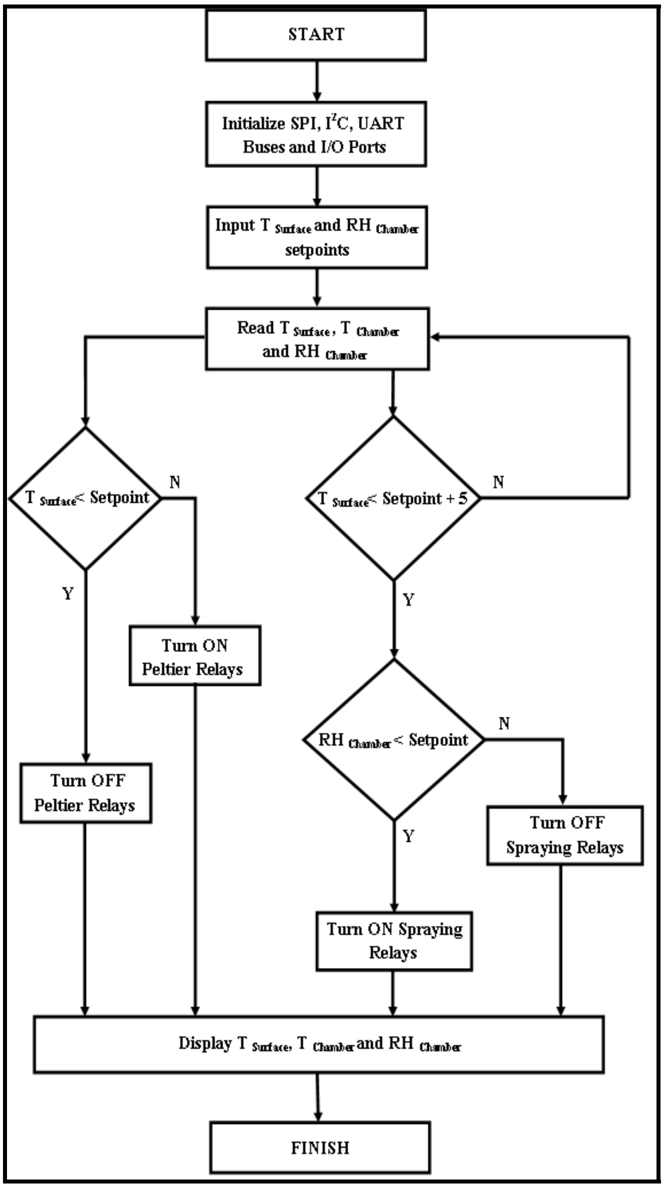


**Fig. 7.** Process control algorithm.

## IV. Results and Discussion

### *A. Time-domain plot of condenser surface temperature:-*

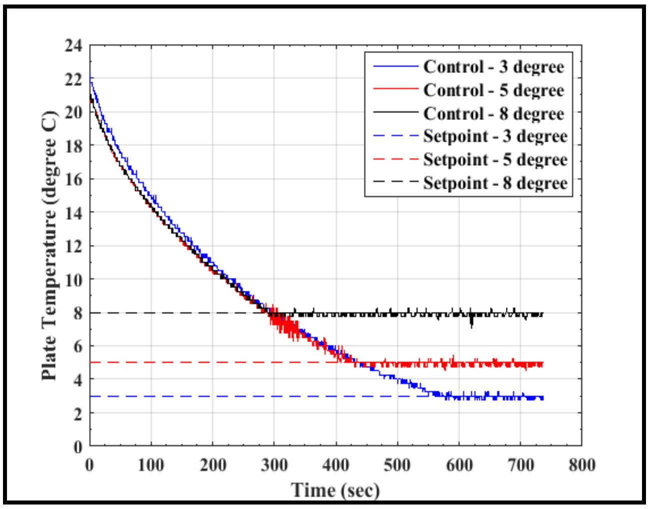


**Fig. 8.** Time domain response of temperature.

The time response (see Fig. 8) of condenser surface temperature sensor output was plotted at different set-points at which the condensation experiments are to be performed. The sensor shows a nearly constant ramp down rate of 2.1°C/min for wide range of set-points. It also quantifies the time at which the condenser surface reaches the set-point from the start of experiment. This time can be termed as the start-up time for the condensation experiments.

### *B. Time domain plot of chamber RH:-*

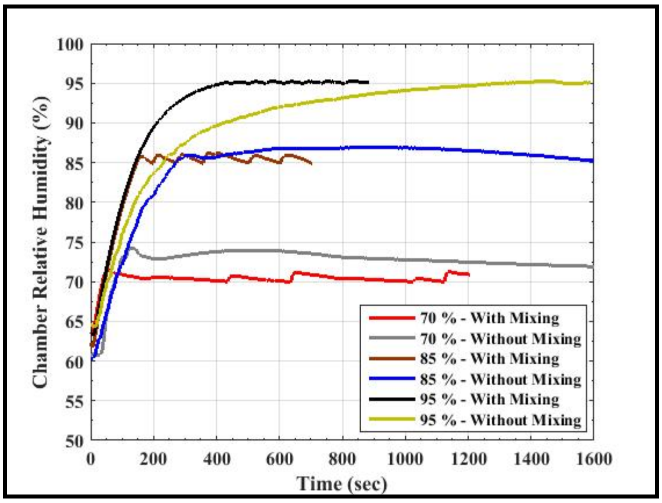


**Fig. 9.** Time domain response of RH without condensation : Effect of mixing.

For maintaining desired RH within the chamber, two methods are adopted and compared with the help of time domain response of RH. First method is by directly spraying a fog of deionised water within the chamber and allowing diffusive transport to homogenize the vapor concentration within the EC. In the second method, a low-speed BLDC fan is used to augment mixing of the sprayed fog droplets within the EC. The fog-inlet port and the mixing fan are installed far away from the condensing surface in order to have minimal flow disturbance near the condenser plate and ensure natural convection at the vicinity of condenser plate. Clearly, the time domain curve (see Fig. 9) indicates that mixing fan arrangement increases the chamber humidity at a much faster rate and also minimizes the large amplitudes of RH overshoot about the set-point. Therefore, the mixing fan arrangement is chosen for the final experimental setup.

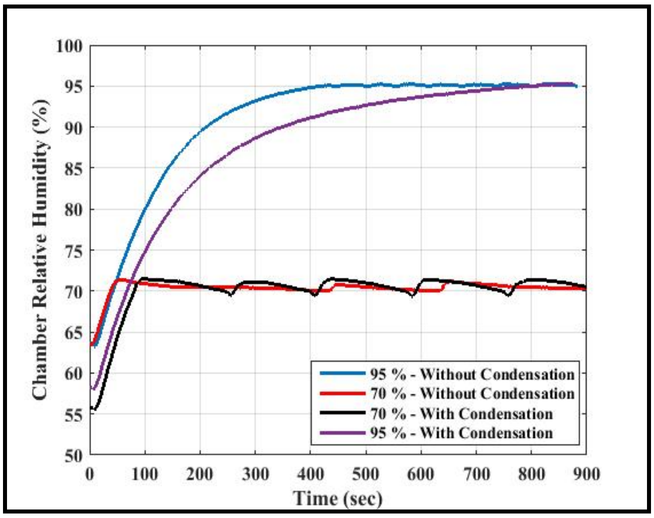


**Fig. 10.** Time domain response of RH : Effect of condensation (With Mixing)

The comparison of chamber humidity response for runs with and without condensation (see Fig. 10) is made to ensure that the start-up time is minimal even when there is a constant consumption of water (i.e., condensation takes place) while the surface temperature is ramping down to reach the set-point. For an RH set-point of 70% the increment of charging time is nearly 50 seconds when there is simultaneous humidity charging and plate temperature ramp down. The same for an RH set-point of 95% is approximately 400 seconds, which is negligible with respect to total experimental time of 4 hours. A few random time sampling was done for measuring the time duration of spray (water addition time) and condensation (water consumption time) with a stopwatch. The spray time is nearly equal to 20 seconds irrespective of the surface temperature but the consumption time is a strong function of the difference of chamber and surface temperature (the degree of subcooling). Increasing the degree of subcooling will decrease the water consumption time and will result in frequent humidification of the chamber.

### *C. Condensate collection data:-*

Condensation experiments were performed at different environment and surface wettability (varying contact angle) conditions. The measured quantity to characterize condensation under various conditions is the amount of condensate collected over a particular time. The area of the condensation surface is 6.5×6.5 cm$^2$. The salient data are tabulated in Table-1.

Table- 1

| Surface Type | Time of test (hrs) | Plate Temp (°C) | Chamber Temp (°C) | RH (%) | Water collection (gms.) |
|---|---|---|---|---|---|
| Hydrophilic CA-81°± 1 | 4 | 8± 0.2 | 18±0.4 | 70±0.5 | 0.12 |
| Hydrophilic CA-81°±1 | 4 | 8± 0.2 | 18±0.4 | 85±0.5 | 1.3 |
| Hydrophilic CA-81°±1 | 4 | 8± 0.2 | 18±0.4 | 95±0.5 | 1.68 |

## V. CONCLUSION

A simple, yet accurate control system without implementing PID algorithm has been implemented to design a low cost controlled humidity environment chamber, custom-designed to perform condensation experiments at user defined surface temperature and humidity set-points. An Arduino Serial Monitor acquired the real time data of the chamber humidity, chamber temperature and condenser surface temperature. The accuracy and stability of the experimental setup for characterizing condensation depended on the environment. The time response plots indicate that the temperature fluctuations are within 0.25° C and RH fluctuations are within 0.5% about the set-point, which is adequate for the experimental accuracy for the study of condensation on wettability engineered surface in presence of noncondensable gases.

## VI. FURTHER DEVELOPMENT

The future aspects of improving the environment chamber include varying the ambient dry bulb temperature with a help of a convective strip heater with the help of PID algorithm. Further, for on-board process parameter monitoring, a 16×2 LCD module can be interfaced with the Arduino. Lastly for real time condensate collection measurement a strain gauge load cell is to be installed.

## *Acknowledgment*

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