ENGINEERED CONTROLLER MODELLING APPROACH FOR TEMPERATURE CONTROL OF HEAT EXCHANGER IN WASTEWATER TREATMENT

K Shanthi[1*], V Bhanumathi[2] &Murugavelh S[3]
[1]Department of Instrumentation and Control Engineering, Sri Krishna College of Technology, Coimbatore, India.
[2]Department of Electronics and Communication Engineering, Anna University Regional Campus, Coimbatore, India.
[3] CO_2 Research and Green Technologies Centre, Vellore Institute of Technology, Vellore, India.

***Corresponding author- k.shanthi@skct.edu.in**

Abstract:

Performance of pilot humidification and dehumidification plant for treatment of textile industry wastewater is analyzed. To keep balance between the industrial growth, water scarcity and industrial effluents, proper treatment technologies for industrial effluents is needed. Drawbacks of the prevailing water treatment technologies are size of the components, land area and source for treatment. The experimentation is carried out in the Kariapudur common effluent treatment plant, Tirupur. Fuzzy Logic Controller (FLC) and Proportion,Integral and Derivative (PID) controller were used for predicting the accuracy of the process. Condensate flow (m^3/hr), feed inlet temperature (°C) and steam flow (kg/cm) for textile effluents were used to predict the output condensate temperature (°C). The accuracy of the developed model was validated using Integral of the Absolute value of the Error (IAE), Integral of the Square Error (ISE), and Integral of the Time weighted Absolute Error (ITAE). Comparison of the models indicated the advantage of FLC model over PID model. The values of PID reported 686,1064 and 2078 of the IAE, ISE and ITAE. Similarly, the FLC reported 443,758 and 1075 of the IAE, ISE and ITAE respectively. Based on simulated results obtained from heat exchanger using Fuzzy model, the solar evacuated tube compact desalination system is developed. The compact desalination system is designed with different size of the tube heat exchanger interlinked together acting as filter, evaporator, and condenser. The solar tube collector is employed as a heat source. FLC model was found to be more effective in predicting the condensate temperature, the results were in line with the experimental data. Maximum of ten liters per day(10L/day) of fresh water is produced from the compact desalination system at the area of 0.4 m^2. The developed hardware set up is tested with same effluent collected from textile industry and it showed 440,762 and 1065 of the IAE, ISE and ITAE respectively. The comparison between the temperature from the experiment and those measured from the simulations shows that the proposed pilot plant is in line with the industry output data. Finally, the economic analysis is also conducted to identify the payback period and is found as 1 year. The treated water could be recycled using this process. Optimization of the process parameters helps in minimizing water consumption and offers economic benefits for wastewater treatment.

Keywords: Desalination, solar thermal, separation process, compact heat exchanger, FLC,PID.
DOI Number:10.14704/nq.2022.20.8.NQ44471 **NeuroQuantology 2022; 20(8): 4379-4401**

4379

Introduction

Industrial development decides a country's growth and there is perpetually a technology transfer between each and every product. Utilization of water is increasing whenever there is a rise in industries, which leads to scarcity of water worldwide. Indirectly there is a high rate of industrial effluents that are rejected out and it pollutes the setting to stay balance between the commercial growth. The knowledge on wastewater treatment and reuse has been accumulated since decades along with the history of mankind. The development of water reuse concept or technology has attained a greater importance in the day-to-day scenario. The prime reason is attributed towards highly pronounced growth in demand and value of water due to exploding global population, rapid industrialization, and urbanization as well as industrial effluents. Water reuse or regeneration implies the process of utilizing the treated or reclaimed wastewater especially from industries for beneficial purpose such as agricultural and land irrigation, processes in industries and several other applications viz. household, fire protection etc. The advent in wastewater treatment processes have substantially enhanced during the last decade. Desalination, one of the types of water treatment process eliminates dissolved and contaminated minerals from treated wastewater. The unique and advent aspect of wastewater treatment based on humidification and dehumidification (HDH) is embarking the latest research challenge in the current era.

Several researchers have reported (Korenak et al. 2019)on reclaimed water reuse specifically in textile industrial segments. The industrial effluents from textile-based factories are discharged at a drastic pace in the environment year by year.(Holkar et al. 2016)discussed different treatment methods for the treatment of textile wastewater, along with the cost per unit volume of treated water. (Mirbolooki, Amirnezhad, and Pendashteh 2017)discussed the sequencing batch reactor which is used to process the textile industry's wastewater. (Liu et al. 2011)reported a detailed review literature on wastewater from the textile units leading to pollution of natural water bodies as it contains higher Chemical Oxygen Demand (COD), complex chemicals, pH, temperature, inorganic salts, Total Dissolved Solids (TDS), turbidity and salinity.(Kocabas et al. 2009) demonstrated detailed demand of 5000 tons of dyeing materials were discharged into the environment every year. Several membranes technology-based treatment of textile effluents viz. Ultra and Nano filtrations are available in(Leaper et al. 2019)&(Jiang et al. 2018). (Dasgupta et al. 2015)an insight into nanofiltration and reverse osmosis were directly reutilised for producing clean softened water and followed by membrane distillation concentrates to bring about zero liquid discharge satisfying techno-economic evaluation.

From the literature survey it is evident that the relevance of water reuse in textile industrial units are scarce. Its increased application has been facilitated by modern wastewater treatment processes that have advanced substantially during the twentieth century. These processes can now effectively remove biodegradable materials, nutrients, and pathogens, so the treated water has a wide range of potential applications. Although non potable water reuse is overwhelmingly dominant on a global scale, reuse as potable water has been accepted for centuries since downstream users virtually produced their potable water from rivers and groundwater that had circulated upstream through multiple cycles of withdrawal, treatment, and discharge.

(Shehata et al. 2019a)presented solar system for water desalination system setup to analyse the productivity of fresh water by using the method of humidification – dehumidification. A comparison study of the shell and tube heat exchanger was done to determine the thermo hydraulic performances with different baffle types and was found that by using helical baffles, the performance of heat and pressure characteristics was good(elMaakoul et al. 2016). (Thakkar et al. 2020)discussed solar desalination system coupled with flash evaporator that improved the distillate output through analyses of two sets and the results found that the distillate output was more in this system when compared with solar desalination using solar still. (Moradi et al. 2019)discussed integrated hybrid power generation in combination with a multi effect desalination that is developed to generate power with higher efficiency by adding a heat source with increased temperature for better performance.(Raj Ranjitha et al. 2018)discussed humidification dehumidification technology is used for small scale desalination system. Further studies in the field of dehumidification were required to control the energetic performance. This research paper describes the advances towards more sustainable desalination and exciting directions that could make this technology more accessible, energy efficient, and versatile. When both the productivity and the cost are taken into consideration, the humidification and dehumidification desalination process is the preferred method.(Zubair et al. 2017) discussed humidification – dehumidification desalination system was operated with solar evacuated tubes for optimum production of heat using a mathematical model with closed air and open water loop to determine various parameters.(Zhu et al. 2007) constructed the shell and tube condenser to evaluate the performances of the steam condensation with the columns of various lengths. The challenge within the desalination at industrial scale is that the size of the processing plant and efficiency of heat exchangers. The utilization of reverse osmosis plant to produce fresh water is energy efficient technology however still it needs power and continuous maintenance.

Heat Exchanger (HE) plays an important role in the industrial waste heat recovery, energy saving, secondary energy utilization, and emission reduction. The innovations in the different control methods used for the HE systems are reviewedin(Kunjuraman and Velusamy 2020).The Proportional Integral (PI) control technique used to control the heat exchanger output temperature is compared with the model-based controller and the results are compared. To compare the outcomes, performance error analysis is used(Raul et al. 2013). (Oravec et al. 2018)presented PID control which was able to ensure better results for low fouling heat exchanger. Both robust model predictive controller and conventional PID controller shows set point monitoring and disturbance rejection according to the integral of the square error measures.FLC has become an active research field for industrial processes that are not suitable for traditional control, especially where there is a lack of quantitative data on the relationship between input and output. It seeks to imitate the human mind to monitor the parameters of the process and to make decisions about the control operation.(Vasičkaninová, Bakošová, and Mészáros 2021) discussed type-1 and type-2 fuzzy logic controllers (FLCs) designed for a small heat exchanger network (HEN) are compared in this paper using simulation results with the PI and PID controllers tuned by conventional methods. (Sridharan 2020) reported two fuzzy models are capable of predicting the outlet temperature of hot and cold fluid. Such predicted values from both systems were compared with the experimental values. (Jamal and Syahputra 2016) discussed feedback controller and fuzzy controller design of heat exchanger, which was developed, and the settling of the process was analysed.(Sridharan 2020) discussed performance analysis of counter flow and parallel flow heat exchanger are analysed using fuzzy logic controller and results are validated. (Kim et al. 2020) presented the proposed model has a much more compact and standard ode representation that makes it useful for control design and analysis. Numerical tests to demonstrate accuracy and reliability of the proposed model are presented. 'If–Then' rules with an appropriate membership function can generate the stipulated input-output pairs by evaluation of model performances(Shamshirband et al. 2015).

PID controller was developed using transfer function obtained from the textile data collected from the industry as a function of 3 independent variables such as Condensate Flow (CF),Feed Inlet Temperature (FIT) and Steam Flow (SF). FLC model was developed as a function of the same independent variable to get a dependent variable (Output) Condensate Temperature (CT). The uniqueness of the present paper is the incorporation of heat exchanger subsequent to the membrane process to increase the efficiency of water from the textile effluent. There is a comparison between the temperature of the output obtained from the experiment and those measured from the simulations. Finally, the simulation results were validated to the experimental results. The treated effluent from the treatment process is of high quality and can be reused directly in primary textile activities such as dyeing, which requires a safe and constant supply of soft water. The salt recovered can be employed throughout the dyeing process, and the reclaimed water can be reused in the textile plant.

2. Textile wastewater process

Membrane technologies provide an important solution to environmentalfields such as pollution reduction, water reuse, and recycling valuable components from the waste streams. Microfiltration (MF) is suitable for removing colloidal dyes from the exhausted dye bath and its subsequent rinses. Ultrafiltration (UF) is an effective single step treatment of secondary textile wastewater. Nano Filtration (NF) allows the separation of low molecular weight organic compounds and salts. This permeate produced is usually colorless and low in total salinity. After Nano filtration 15-20% of textile water is wasted and to reuse the remaining wastewater desalination process is used. Heat exchanger acts as a major component in the desalination to control the temperature of the effluent and to get maximum reusable water from the dye water after Nano filtration. The schematic of water reuse plant is shown in figure 1. From textile wastewater treatment process the HE part is used after nano filtration. The 15 % of effluent is entered into the nano filtration. After this process the liquid is divided into two sections product and reject. The product is about 10.78% and the reject is 4.22 %. The 10.78% product is entered into the desalination unit which extracts the reused water by controlling three process parameters like condensate flow, feed inlet temperature and steam flow in the percentage of 7.35 % and the remaining 3.43% into brine. In the reject part total 4.22% dye water entered HE unit and the 3.58% is once again converted into final product. The remaining 0.64% is entered into centrifuge and again this is converted into dry salt. There are various configurations based on which the system inputs are implemented. Due to these diverse investigations, the effect of thermal characteristics provides reliable prediction models which are essential for selecting the optimal configuration and parameters. The 10000 data collected from the textile industry for analysis. The condensate flow, feed inlet temperature and steam flow act as inputs and condensate temperature as output. Heat Exchanger plays a major role as a secondary treatment process. Maintaining the optimal output temperature in a HE is very important to obtain the absolute total dissolved solids (TDS). Based on TDS the wastewater is treated and recycled. The output temperature was controlled by using conventional PID controller and fuzzy logic controller.

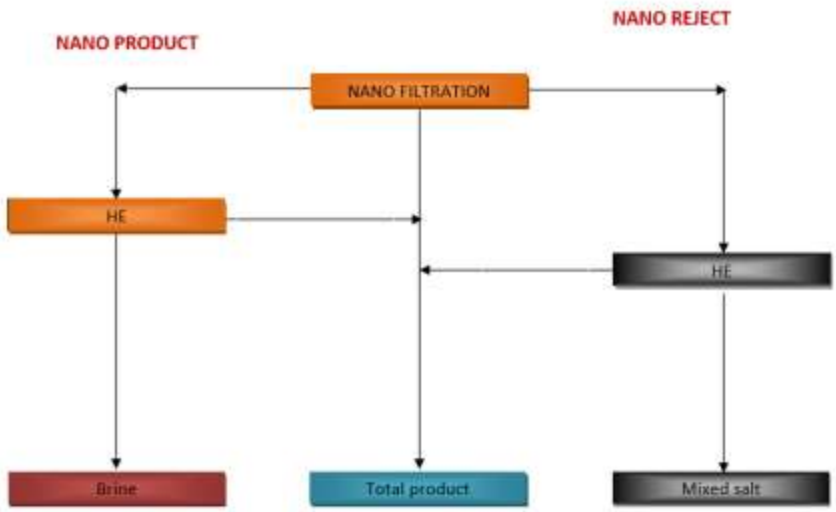

Figure 1. Schematic of water reuse pilot plant

3. Control methodology

3.1 Mathematical modelling

Mathematical modelling of the system is important to design a controller.In this proposed system, the input and output data are collected from the textile industry. The collected data are used to determine the transfer function of the system using a system identification tool. The final process transfer function of the open loop system is

$$G_p(s) = \frac{8.123e^{-37.32}}{73.57s^2+15.465s+4.7} \quad (1)$$

which is in the form of Second Order Plus Time Delay (SOPDT)using system identification tool.

3.2 PID Controller

PID controllers have been widely applied in industrial processes such as refinery systems, wastewater treatment, paper making, etc. In control system, tuning or selection of controller parameters is a crucial task. The popular tuning method developed by Ziegler - Nichols is based on a simple characterization of the frequency response of the process dynamics. Once the process transfer function $G_p(s)$ is obtained from the data collected by the textile industry. The recommended optimum settings for proportional gain (K_P) integral time (T_I)and derivative time (T_D) of PID controller are determined using ultimate gain (K_U) and ultimate period (P_U).Based on the error value, the controller gives the control action, and the system response meets the change of set point.

3.3 FLC Controller

Figure 2 demonstrates the Fuzzy logic controller block diagram approach. In the study of Artificial

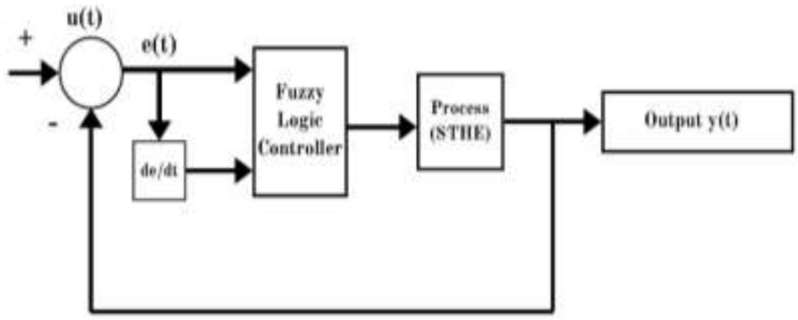

Figure 2 Block diagram of Fuzzy Logic Controller

Intelligence, Fuzzy logic is a specific field of emphasis and is focused on the meaning of the knowledge, which is neither true nor false. Fuzzy logic involves changing the point to control the oscillation below the critical level.

4.Experimental set up

Figure 3 shows the proposed design which included four heat exchangers with different diameter internally merged together viz., sand bed, separator, heater and condenser. The sand bed is the innermost tube that extracts the dust and eliminates the solid particles. The sand bed pipe is surrounded by a thermal separator that aids in the separation of water vapour and industrial waste.

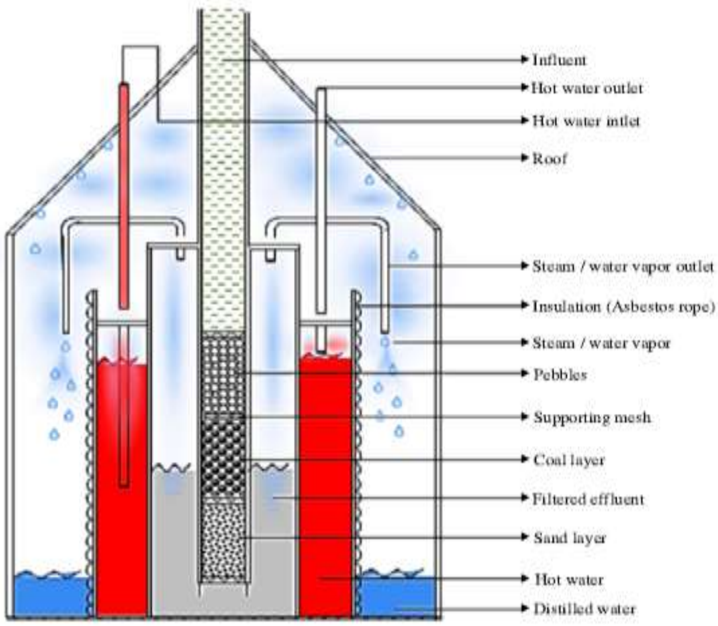

Figure 3 Cross sectional view of proposed compact solar thermal desalination system

The heat energy for separation is continuously fed to third column to heat the effluent in the second column. Since the effluent column heat exchanger and the heat input column heat exchanger have a larger contact surface region, more heat exchange occurs. An inclined outlet pipe is provided at the top of the outlet column, allowing only pure water vapour to pass through. The steam condensing tank is the outermost column, and it can be cooled by natural or forced circulation. Solar energy source can be used to power this device. Thermic fluid from the solar water heater is continuously sent to the third heat exchanger column. Thermic fluids are pumped into the heater from the bottom and then go up after sharing the heat with separator. The heat input column also acts as a thermal storage system and a constant temperature is maintained inside the heat exchanger. It is designed in a way that the

fluctuation in solar radiation does not affect the process of separation of water and salt.
A schematic for the process flow of the proposed system is shown in Figure 4. The continuous heat supplied to the industrial effluents raises the temperature within the chamber, separating the effluent into saturated steam and brine solution due to the difference in boiling point temperatures. The proposed system comprised of an evacuated tube, humidification-dehumidification system, a pump, and a blower. Evacuated tubes are the absorber of the solar water heater. They consume solar energy and convert it to heat, which is then used to heat water. Evacuated Tube Collector (ETC) consists of single tubes that are connected to a header pipe. Each tube in the water-bearing pipes is evacuated to minimise heat losses to the ambient air. A single or several rows of pails make up evacuated tube collectors and the transparent glass tubes supported on a frame. This sealed copper heat pipe transfers the solar heat via convection of its internal heat transfer fluid to a “hot bulb” that indirectly heats a copper manifold within the header tank.

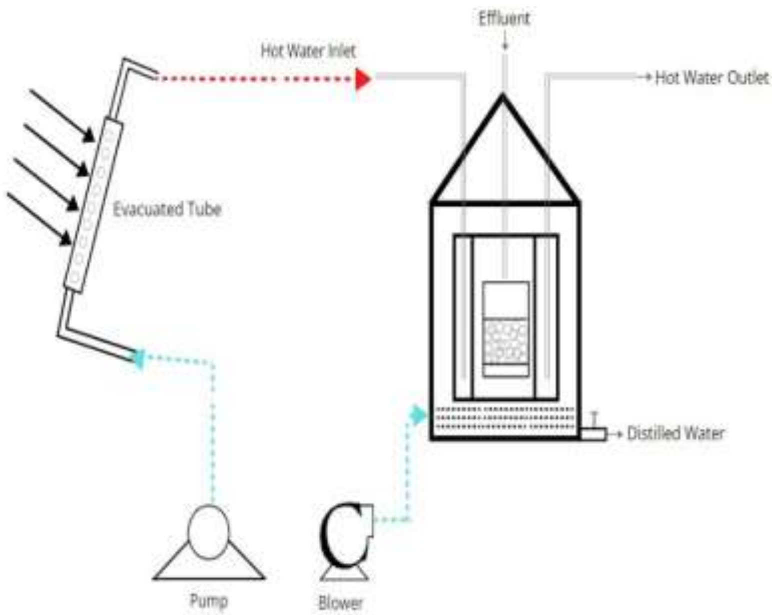

Figure 4 Layout of desalination plant

From the top of the humidifier and dehumidifier arrangement, a pump is connected to the evacuated tube, resulting in hot water entering the humidifier and dehumidifier arrangement. A blower delivers air (20 kg/h) at atmospheric condition to the humidifier where simultaneous heat and mass transfer takes place between hot saline water and air. After heating and humidification in a humidifier, the rejected brine is re-circulated or collected and safely disposed based on its salinity level. The humidifier emits hot humid air with a high relative humidity, which reaches the dehumidifier.The steam was released through an inclined pipe that was in direct contact with the condensing heat exchanger. Steam condenses in the fourth column, where it is stored as output.
As shown in Figure 5 the experimental setup consists of evacuated tube collectors, a HDH desalination unit, a blower and pumps.

Figure 5 Experimental setup of evacuated tube collector driven humidification dehumidification system.

5.Result and Discussion

In this present work heat exchanger behaviour is analysed with three inputs and one output using the PID and FLC modes. To control the temperature of a shell and tube heat exchanger system different controllers are used and the simulated studies of the controller performance is discussed in this section.

The HE thermal performance is strongly influenced by three input parameters (CF, FIT & SF) and the model is developed using data from textile industry. The three inputs are directly related to the enhancement transfer, which provides increased effective heat transfer. Oscillations in process control loop is determined using different parameters summarized below. The three measuring errors such as IAE, ISE, and ITAE were used to compare the performance of PID and FLC.The design specification of pilot plant and their results is analysed.

5.1 Performance of FLC and PID

The output temperature of a heat exchanger is predicted by controlling its input parameters using PID and FLC model. In the Figure 6 the Simulink schematics of PID controller is shown. The gain values for PID controller are calculated with Zeigler Nichol 's tuning rules. Simulink schematics of fuzzy logic controller is shown in Figure 7. The FLC knowledge base includes two elements such as the rule base and the data base. Rule base having if - then rules and a data base have membership function of fuzzy sets used in fuzzy rules. The core component of the FLC is the rule base. The rule base is used to define the control of the goals and to control the strategy of deciding the linguistic element of the control of the rules.

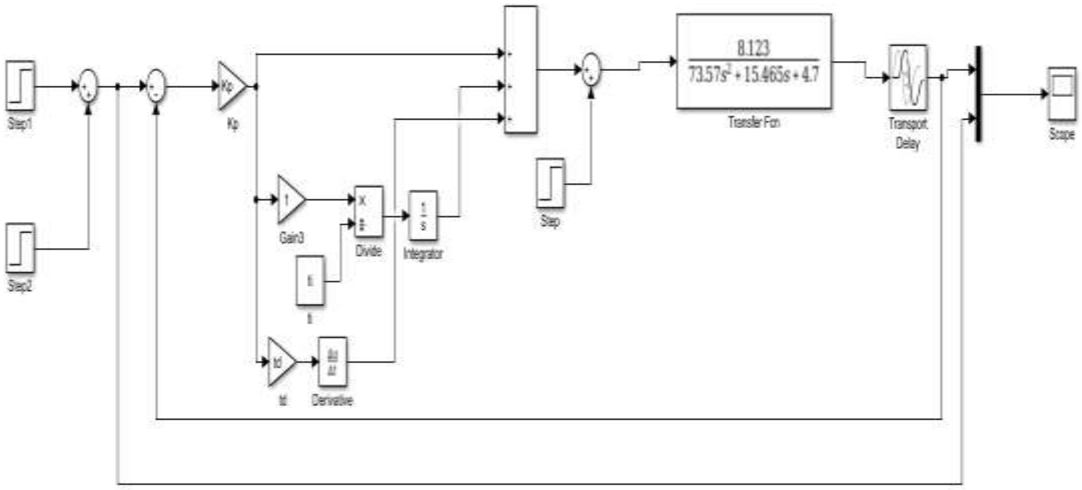

Figure 6 Simulink design of PID controller

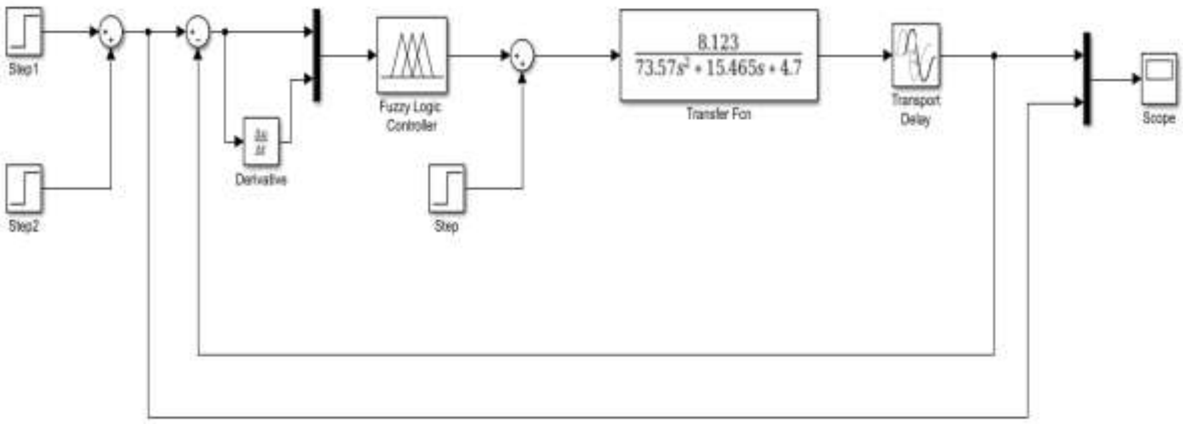

Figure 7 Simulink design of Fuzzy Logic controller

The rules that connect the input and output variables are given here. It consists of several rules that provide a connecting between the input error(e), change in error $\frac{de}{dt}$ and the output $y(t)$ of the controller. In this system triangular membership functions are used. For the FLC, the two inputs (error, change in error) and output are divided into 5 fuzzy membership function such as NL-Negative Large, NS-Negative Small, ZE-Zero, PS-Positive Small, PL-Positive Large. Figures 8 and 9 shows the inputs and output membership function. Based on linguistic variables there are 25 rules are formed, and the output is defuzzified by using the centroid method.

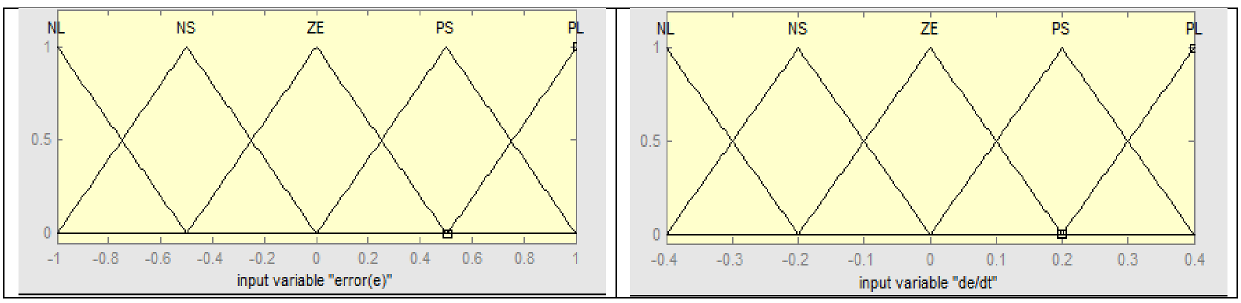

Figure 8 Input membership function - Input 1(error (e)) and Input 2(change in error (de/dt))

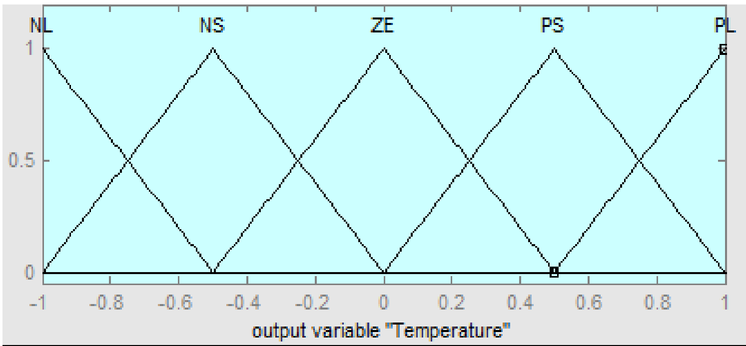

Figure 9 Output membership functions (Temperature)

The temperature monitoring of HE has been established with the help of fuzzy logic controller designed. The FLC adjusts to rectify the errors between the obtained output and the desired value by minimizing the error. The difference of temperature has been minimized by the appropriate rule selection. Fuzzy inference system has been developed for the mapping of the input to the fuzzy logic.

The triangular membership function has been chosen for defining the input and output variable. In order to assign the values to membership function the following settings have been done to input variables: error in the range of (-1 to 1), change in error (-0.4 to 0.4) and the output range of (-1 to 1). The fuzzy rules table with the mentioned values has been shown in Table 1.

Table 1 Fuzzy Rule Table with the linguistic expressions

$\frac{de}{dt}$ \ e	**NL**	**NS**	**ZE**	**PS**	**PL**
NL	NL	NL	NL	NS	ZE
NS	NL	NL	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PL	PL
PL	ZE	PS	PL	PL	PL

The fuzzy controller designed has been validated by implementing on the SOPDT model.The simulation results have been found satisfactory. The real time HE controls using designed FLC has been implemented and the performance of the same has been evaluated with conventional PID controller tuned with ZN rule. In this simulation, testing of temperature control in the heat exchanger system with combined type PID and FLC is shown in Figure 10. It has been observed that the PID controller is settling after sufficiently long time and produce large overshoot.

As shown in the graph of figure 10, it can be seen that the FLC is already delivering results that are slightly better than the results with previous controller. This is indicated by the signal response of the system is approaching the reference signal, which takes 50 seconds to get up to the magnitude of the desired temperature. Furthermore, oscillation occurs until the 122 to reach temperature stability at a desired magnitude (700).In the application of this control overshoot as high as 22% of the magnitude of the expected temperatures, although only occur in a relatively short time span of 25 seconds to lead a stable condition.

Response results FLC is relatively fast compared to the response of PID feedback control, because the work is purely feedback controllers always have to evaluate each of the previous output in the loop. Thus, the computation required is relatively shorter than the feedback PID controller.

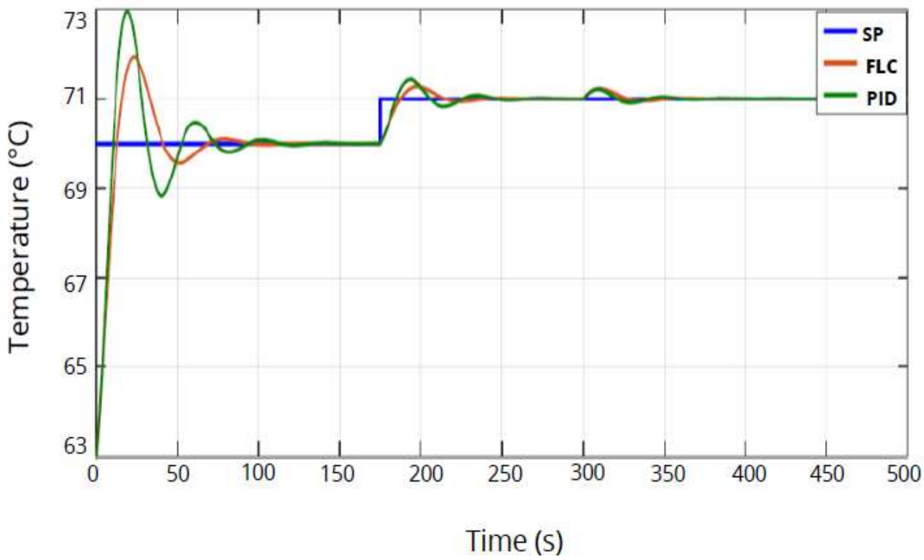

Figure 10 Simulated results of process with PID controller and FLC graph comparison

The PID and FLC response for varied load changes are captured as shown in Figures 11 and 12 respectively.

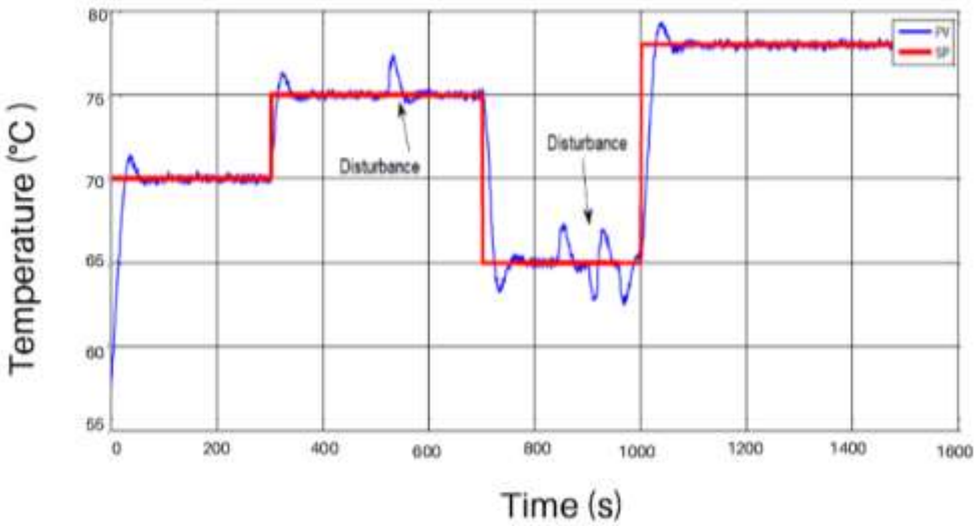

Figure 11 FLC action with disturbances

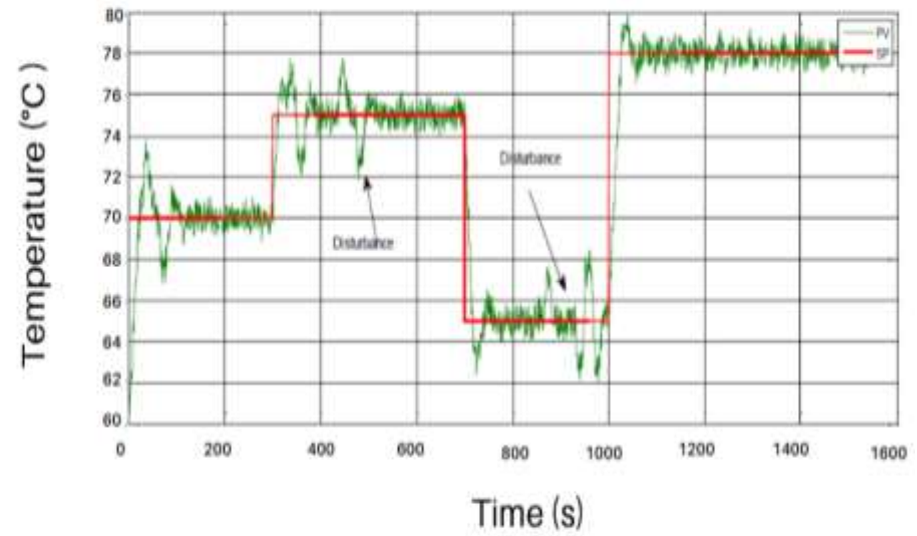

Figure 12 PID Control action with disturbances

The feedback PID controller shows 11.6 % of maximum peak overshoot and 114 seconds of settling time. Due to the high overshoot of classical PID controller, FLC is modelled.The fuzzy logic controller reduces the overshoot to 5.5% and 79 seconds of settling time is shown in Figure11. Integral Error based performance indices viz. ISE, ITAE and IAE performance indices are calculated along with time response characteristics using step input. The transient response (Maximum peak overshoot and settling time) in step response of all the controllers (PID and FLC) is summarized in Table 3. The error response of all the controllers (PID and FLC) is summarized is tabulated in Table 2.The rejection of disturbances at various instances is noticeable in the responses shown and both the controllers have tracked the set-point. However, fuzzy controller provided faster response with lesser overshoots. The error criteria performance used to validate the proposed method was ISE, IAE and IATE is depicted in Table 3.

5.2 Validation

In every feedback control system, there is an implicit purpose to reduce errors and thus to always keep track of errors from zero to infinity and to constantly minimize them by defining a performance metric in terms of IAE, ISE and ITAE. These are generally used performance criteria in stability analysis. Performance measure minimization would ensure the minimization of errors. The detailed time-integral parameters allow the comparison of various controller designs.

The fuzzy controller performance has been evaluated using standard performance measures which are compared with the PID controller.

1. Integral of the Square Error (ISE) - This criterion gives more weight to larger deviation.
   The mathematical equation for this criterion is
   $$ISE = \int_0^\infty e^2(t)dt \quad (2)$$
   Where $e(t) = y_{sp} - y(t);\ y_{sp} = set\ point, y(t) = output$
2. Integral of the Absolute value of the Error (IAE) - It is the best criterion for the process control.
   $$IAE = \int_0^\infty |e(t)|dt \quad (3)$$
3. Integral of the Time weighted Absolute Error (ITAE) – These criteria weights deviations more heavily as time increases.
   $$ITAE = \int_0^\infty t|e(t)|dt \quad (4)$$

The corresponding results are presented in Table 2 and Table 3, which clearly indicates better performance from FLC.Performance evaluation of FLC has been listed with standard performance measures in Table 3. This validates the hypothesis that FLC gives better performance than conventional controller.

Table 2 Comparison of Fuzzy controller and PID controller with the error criteria

Performance Index	PID	FLC
IAE	686	443
ISE	1064	758
ITAE	2078	1075

Table 3 Performance Comparison of PID controller and FLC

PID CONTROLLER		
Control action	**Maximum Peak Overshoot Mp(%)**	**Settling time (sec)**
Nominal (70^{0}C)	11.6	114
Step change (5^{0}C)	5.5	79
FLC CONTROLLER		
Control action	**Maximum Peak Overshoot Mp(%)**	**Settling time(sec)**
Nominal (70^{0}C)	5.1	55
Step change (5^{0}C)	3.9	46

The resulting graph for the conventional PID controller and FLC is shown in Figures 10. Figure 10 shows that high overshoot and higher settling time values are achieved in the system with PID controller. Further improvement in the characteristic response of the system the FLC used and it shows that the system's response has improved significantly with the aid FLC. The overshoot of the system using FLC has been reduced; the settling time, the peak amplitude of the system also appreciable reduction as analysed. Table 3 reveals that the overshoot and settling time with the FLC controller was substantially reduced compared to standard PID.

Output condensate temperature obtained from experimental results using PID and FLC was compared with the textile industry data and the performance was evaluated using three parameters of error measurements like IAE, ISE, and ITAE for different input sets and the values were tabulated in Table 2. From the IAE, ISE, and ITAE values, the stability and reliability of both FLC and PID models can be viewed

5.3 Experimental analysis

Separator load of 2.23 kW is required for 56 g/kg of seawater inlet and 85 g/kg of brine solution concentration, while cooling load of 0.82 kW is required for 10 LPD of water vapour condensation. Table 4 shows that producing 10 LPD of fresh water requires 77.68 LPH of hot fluid supply temperature at a temperature of 378.15 K. The collector area can be constructed according to the type of solute.

Table 4 Design parameters of the system for 10 LPD of fresh water

Description	Load
Seawater concentration, g/kg	56
Brine Concentration, g/kg	85
Seawater mass flow rate, LPH	29.54
Brine mass flow rate, LPH	19.48
Hot fluid mass flow rate, LPH	77.68
Hot fluid temperature, K	378.15
Solar Global radiation, W/m^2	950

Separator, kW	2.23
Condenser, kW	0.82

5.3.1 Uniqueness of the compact desalination system

The proposed compact desalination device operates on a different concept than thermal desalination. The technique takes a different approach, with fresh water being divided by a difference in boiling point temperature. Hence operation at high temperature is possible. The seawater is continually fed into the separator, and the freshwater vapour and brine solution are isolated due to the high temperature. The freshwater vapour and brine solution temperatures are believed to be constant, and the brine concentration can be regulated by adjusting the separator temperature and pressure. Figure 13 depicts the study of a proposed compact desalination device for a fixed 1000 LPD of freshwater production at various brine concentrations and hot fluid supply temperatures for a fixed 1000 LPD of freshwater output. Table 4 shows the design parameters for producing 10 LPD of fresh water from the proposed compact desalination system at a constant hot fluid supply temperature of 378.15 K.

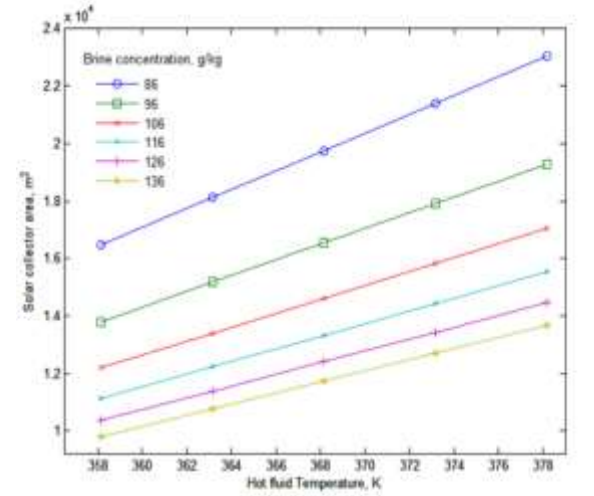

Figure13 Effect of Brine concentration at different hot fluid supply temperature

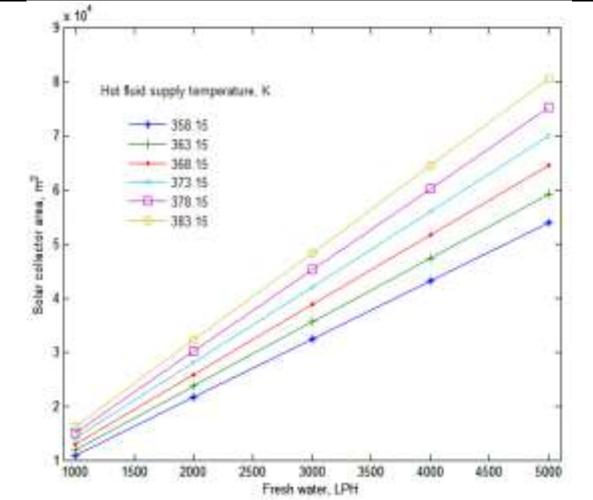

Figure 14 Measurement of solar collector area for different quantity of fresh water

5.3.2 Effect of inlet concentration, operating temperature on the collector area

Based on the input parameters of constant seawater inlet temperature of 303.15 K, salt concentration of 56 g/kg, and thermal temperature difference between the hot fluid and separator of 25 K, the necessary solar collector area is calculated. When the device is operated at a high temperature, the necessary collector area is high, while the solar collector area is reduced when the brine concentration is increased. The compact desalination system is simulated to determine the amount of solar collector area needed for the supply of fresh water in the range of 1000-5000 LPH at various hot fluid supply temperatures, with a fixed seawater concentration of 56 g/kg and a brine concentration of 120 g/kg. The solar collector area is increases when the need of freshwater quantity is increases and it is lies in the range of 10000-80000 m^2 for 1000-5000 LPH of freshwater production as shown in the Figure 14. Whereas the area required for installation of separation system is low compared to existing desalination system.The solar collector area can be reduced by increasing the brine solution concentration for the fixed hot fluid temperature,but it wills leads to vacuum in the separator. The solar collector area can be reduced by introducing a heat recovery heat exchanger between the exit of hot solution brine concentration and the inlet seawater.

5.3.3 Significance of global radiation on collector area

The proposed compact desalination system can be powered by biomass, solar, geothermal, and other heat sources. Solar energy is plentiful and renewable, but solar radiation is constantly changing, so the effect of solar radiation is studied and depicted in Figure 15. It is well known that as solar radiation increases, the hot fluid temperature production increases, reducing the required solar collector region. It is simulated here for solar global radiation of 700-1000 W/m2 at various hot fluid temperatures between 358.15 and 383.15 K. The solar collector area required for successful operation of 1000 LPD is 8000 m^2 at solar global radiation of 1100 W/m^2 whereas14000 m^2 of solar collector area is required when the global radiation is around 700 W/m^2. The parameters of influent water concentration, freshwater concentration, and hot fluid supply temperature affect/decide the system's efficiency, according to the study. The complexity in designing the heat exchanger for the proposed system is reduced by setting the exit brine solution concentration and hot fluid supply temperature. Due to the internal coupling of the heat exchanger, variations in solar radiation have little effect on the separation process. The developed batch process having hot water flow of 10 LPD and outlet water temperature of 67 ^{0} C to 73 ^{0} C. The plant which was developed in the laboratory was considered as a prototype of a real water treatment plant. The laboratory-based water treatment plant was designed and fabricated based on the specification given in Table 4. The heat exchanger in the textile plant is simulated at the designed size and the results are validated with the experimentation on pilot plant. The results are proved the benefit of keeping all the input parameters in a desired level.

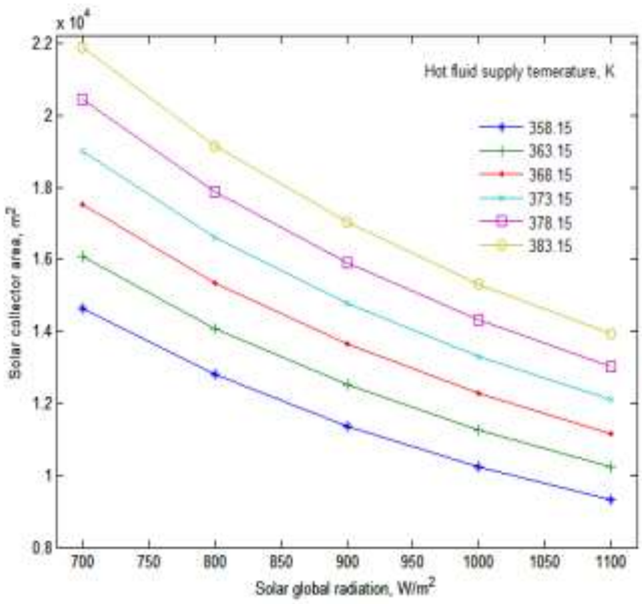

Figure 15Effect of solar global radiations in the proposed compact desalination system

In this study, a large-scale textile plant was selected as a as an industry plant for the implementation of the FLC. The results of the study clearly indicated that the application of FLC measures is essential to reduce water and energy consumption. In this proposed system, the input and output data are collected from the pilot plant. The collected data are used to find the transfer function of the system using a system identification tool. The final process transfer function of the open loop system is

$$G_p(s) = \frac{7.69\, e^{-35.88}}{84.62s^2+12.412s+7.88} \qquad (5)$$

Simulation of FLC controller for proposed plant is shown in Figure 16.

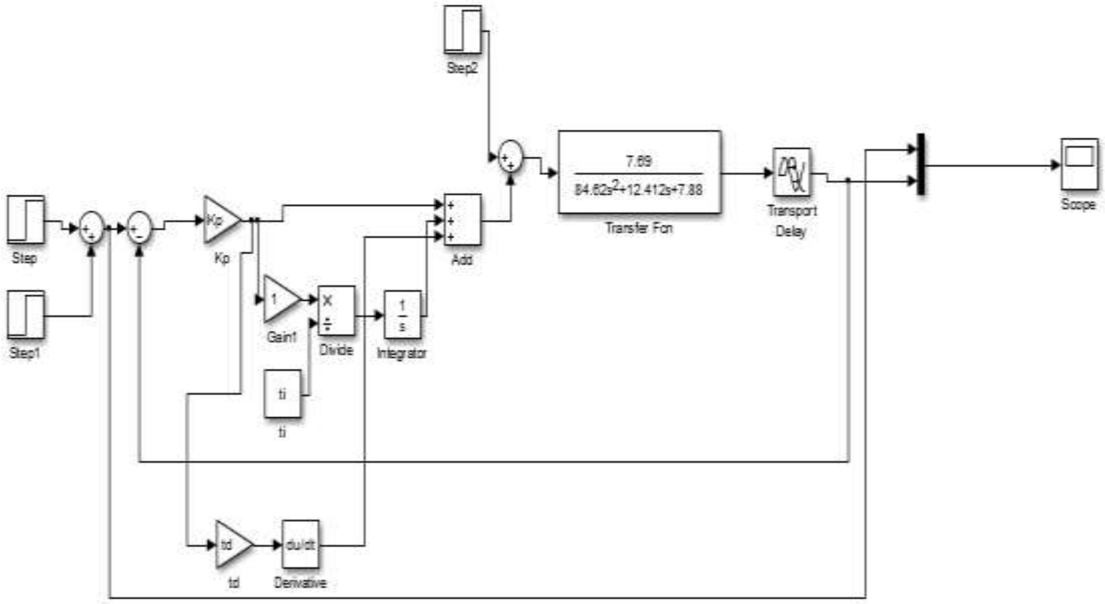

Figure 16 Simulation of FLC controller for proposed plant

Figure 17 shows the relation between output temperature of heat exchanger from textile industry data and predicted temperature from pilot plant by FLC.

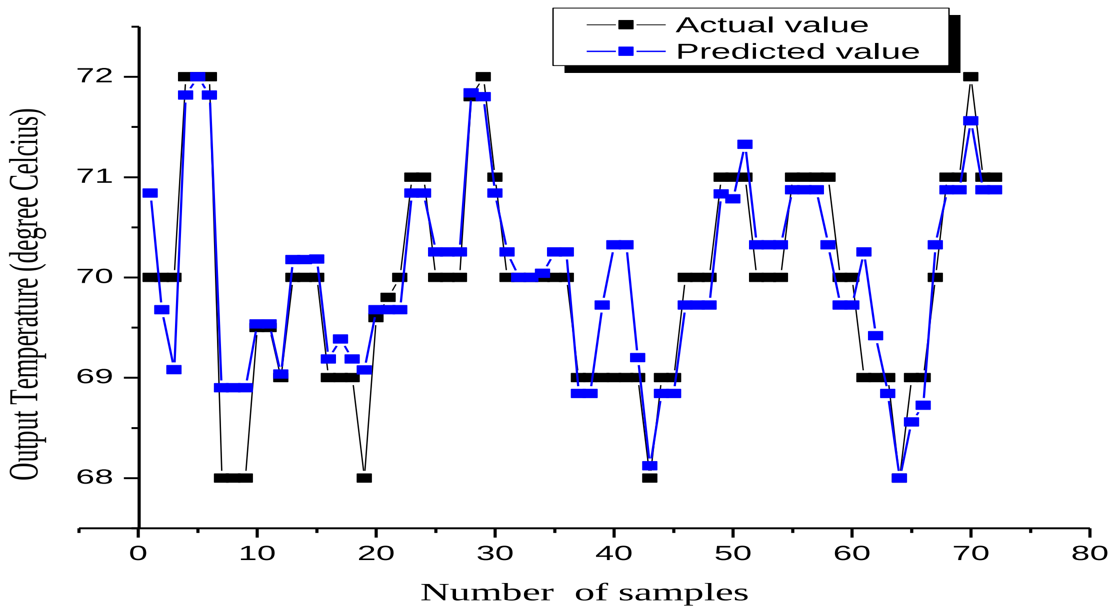

Figure 17 Response graph

Graphical and numerical error analyses were employed to determine the models' ability in predicting the condensate temperature. Graphical error analysis demonstrated that the predicted values are appropriately aligned with the trends observed in experiments.The purpose of conducted research work is to expose the modern model: FLC, which investigated as a best modern model to prediction the results of compact heat exchanger on input parameters.

Before finalizing the FLC model structure the performance of the model is tested taking different kinds and number of membership functions. The performances are evaluated on the basis of error criteria such as IAE, ISE and ITAE. The FLC model is also compared with the conventional PIDmodelling technique. The FLC model is able to predict the heat transfer coefficient within an error of ±2%, whereas the error is ± 7% in the case of the PID model.

It is observed from the results that Fuzzy Logic controller for textile plant data and experimental FLC model output exactly match with input configurations. Table 5 shows the error criteria comparison of proposed system FLC and textile industry data FLC. All the error criteria data of pilot plant is in line with the real time textile data.

Table 5 Comparison of proposed system FLC and textile industry data FLC with the error criteria

Performance Index	Proposed FLC	Industry data FLC
IAE	443	440
ISE	758	762
ITAE	1075	1065

6.Economic Evaluation

An economic model of the proposed evacuated tube operated tri-generation plant is carried out to identify the cost of fresh water and payback period. The annual production of fresh water, electricity and cooling outputs are assessed for the monthly averaged environmental data of Vellore, India shown in Figure 18. The economic analysis was made adapting the method used by (Anand and Murugavelh 2020). During the evaluation following assumptions are considered,

Assumptions

- The interest rate is set at 9% since it ranges between 9% and 14 percent in Indian banks.
- The service life of the project expected to be 20 years.

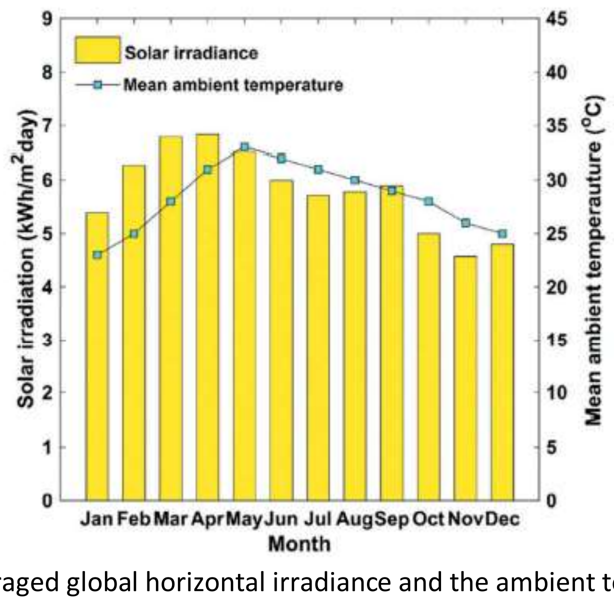

Figure 18Monthly averaged global horizontal irradiance and the ambient temperature of Vellore, India.

- Future salvage value of the plant is 20% of the total capital cost of the plant.
- Operation and maintenance cost of the plant excluding energy cost is 15% of the annual capital cost.
- The unit cost of electricity as per the regulations of TNEB (Tamil Nadu Electricity Board) is ₹.8.00 /kWh for the II-B category of consumers (Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO).

The unit cost of fresh water (C_{dw}) generated from the proposed system is the ratio of annual total cost of the plant (ATC_p) to annual fresh water yield (DW_y) from the plant.

$$C_{dw} = \frac{ATC_p}{DW_y} \qquad (6)$$

where, annual total cost of the plant includes annual capital cost (AC_p), annual operation and maintenance cost (OMC_p) and annual salvage value (ASV)

$$ATC_p = AC_p + OMC_p - ASV \qquad (7)$$

Annual capital cost is calculated as

$$AC_p = M(CRF) \qquad (8)$$

M is the cost used for material such as evacuated tube, humidifier, and dehumidifier, piping cost, other auxiliary system components cost, installation cost, transportation cost, insurance and contingency cost. The detailed description of components used in the plant and its cost is given in Table 6.

Capital Recovery Factor (CRF) is expressed as

$$CRF = \frac{i(1+i)^n}{(1+i)^n-1} \qquad (9)$$

where i and n are interest rate per year and service life of the project in years. Annual operation and maintenance cost of the plant (OMC_p) includes periodic cleaning, removal of salt deposition, electricity consumption cost, labour cost, etc. The annual electricity consumption of the plant (AEC_p) is the product of electrical power consumption per hour and total operating hour in a year.

$$OMC_p = C_c(AEC_p - AEG_p + AER_c) + .15(AC_p) \qquad (10)$$

where, AEG_p is annual electricity generation from plant, AER_c is annual equivalent electricity required to generate the annual cooling output of the proposed tri-generation plant using conventional air conditioning unit.

Assuming Co-Efficient of Performance (COP) of conventional air conditioner (COP_{ac}) as 2.5, the equivalent electrical energy required to generate the cooling output from the plant is calculated as

$$AER_c = \frac{AQ_c}{COP_{ac}} \qquad (11)$$

Annual Salvage Value of the plant (ASV_p) is expressed as

$$ASV_p = SV_p(SFF_p) \qquad (12)$$

Considering future salvage value of the plant (SV_p) as 20% of M, Sinking Fund Factor (SFF_p) is calculated as

$$SFF = \frac{i}{(1+i)^n-1} \qquad (13)$$

4396

Annual desalination yield, electricity production, and cooling output are estimated by assuming the plant which is operated 8 h /day for all 365 days in a year. Monthly averaged solar irradiance and mean ambient temperature of typical meteorological year data for the location Vellore, India is shown in Figure 23. The annual output of desalination, electricity and cooling output are 4.2 m^3/year, 1095 Wh/year and 250 Wh/year, respectively. The estimated total capital cost of the plant is ₹ 67,375.00, which includes transportation, installation, insurance and contingency, cost (Table 6). By considering all the economical parameters mentioned above, unit cost fresh water generated from the plant is calculated as ₹ 10/L. The Payback period (PB_p) of the plant is the time required to recover the initial expenditure of the plant.

$$PB_p = \frac{\ln\left(\frac{C_F}{C_F-(MXi)}\right)}{ln(1+i)} \qquad (14)$$

Where C_F is the cash flow, and it is expressed as

$$C_F = DW_y \; X \; C_{dw} \qquad (15)$$

When the cost of fresh water and electricity price are ₹ 10 /L and ₹ 8.0 /unit, the estimated payback period of the proposed plant is 1 year.

Table 6 Plant equipment descriptions and its cost

Components	**Description**	**No of components**	**Cost (₹)**
Evacuated tube water heater	100LPH	1	16,500.00

Humidifier and Dehumidifier	Shell and tube heat exchanger Shell and tube material: SS 304 Material thickness: 0.004 Tube diameter and length 0.020m and 0.6m Shell length 0.6m	1	33,000.00
Air blower	Centrifugal blower Discharge capacity:500m^3/h Power consumption: 0.37kWh	1	3,000.00
Pump	½ HP	1	3,000.00
Others	Gasket (Compressed Asbestos jointing sheet):2m^2	1	1,000.00
	SS 304 Bolt and Nut	20	500.00
	Ball valve	5	1,250.00
	Rotameter	2	3,000.00
Total direct capital cost of the evacuated tube operated plant			61,250.00
Transportation cost (from local dealer to site) and insurance 5% of direct capital cost			3,062.50
Contingency cost 5% of direct capital cost			3,062.50
Total capital cost of the evacuated tube operated plant			67,375.00
Unit cost of the fresh water			₹10/L
Payback period			1 year

Table 6 shows the capital cost incurred in the different components of the desalination. It shows that the distilled water cost is lower in the humidification dehumidification desalination. The superior distillate is obtained in the humidification dehumidification desalination due to uninterrupted constant heat supply.

Table 7 shows the comparison of the present study with results reported in previous work. The plant performance is compared in terms of maximum desalination output. The integration of solar evacuated tube with HDH desalination provides much higher heat energy to operate desalination plant than the conventional system.

Table 7 Comparison of present system with various HDH systems powered by Evacuated Tube Collector(ETC)

S. No	Collector area	Maximum yield (L/day)	Reference
1	2m^2	44	(Hamed et al. 2015)
2	2m^2	12.32	(Sharshir, Peng, Yang, El-Samadony, et al. 2016)
3	4.13m^2	9.36	(G. P. Li and Zhang 2016)
4	14m^2	332.8	(X. Li et al. 2014)
5	2m^2	56.24	(Sharshir, Peng, Yang, Eltawil, et al. 2016)
6	3m^2	10.4	(Hermosillo, Arancibia-Bulnes, and Estrada 2012)
7	2m^2	188.8	(Kabeel, Abdelgaied, and El-Said 2017)
8	12m^2	400	(Yuan et al. 2011)
9	2.5m^2	45	(Shehata et al. 2019b)
10	0.8 m^2	9.04	(Xiao et al. 2021)
11	2.5m^2	28.8	(Rahimi-Ahar and Hatamipour 2021)

12	$0.4m^2$	**10**	**Present work**

In (Hamed et al. 2015),preheating the incoming water at the humidifier section increases the HDH system's fresh water generation capacity while drastically reducing operation time with the collector area of $2m^2$and the yield of 44L/day.(Sharshir, Peng, Yang, El-Samadony, et al. 2016) presented the humidifier unit's rejected warm water can be used as preheated feed water for a solar still with a 12.32 L/day of yield with evacuated HDH system and a $2m^2$ unit area.In membrane-based HDD systems, hollow porous fibre membranes consisting of dense polyvinyl alcohol(PVAL) and porous polyvinylidene fluoride (PVDF) can effectively contribute to the humidification process. The yield is 9.36 L/day and the unit area is $4.13m^2$.((G. P. Li and Zhang 2016).Parallelly linked dual wall evacuated glass tubes with a capacity of $14m^2$ and 332.8 L/day can efficiently contribute to preheating the air medium entering the humidifier unit. The relative humidity and temperature of the humidifier's intake water spray increases. The rate of condensate and enthalpy increases as the temperature and relative humidity of the dehumidifier's incoming air increases is discussed in (X. Li et al. 2014). (Sharshir, Peng, Yang, Eltawil, et al. 2016)presents, the fresh water yield grows at a rate of 56.24 L/day and a unit area of $2m^2$ as the number of parllelly connected solar stills for re-use of rejected warm water from humidifier units increases..

(Hermosillo, Arancibia-Bulnes, and Estrada 2012)uses $1.3m^2$ of collector area with maximum yield of 10.4 L/day. HDD system with evacuated tube collector could produce 50-70% more yield per day than a solar still with same collector area.(Kabeel, Abdelgaied, and El-Said 2017) produces 188.8 L/day with the collector are of $2m^2$. Here Recirculation of air from condenser to evaporator unit through forced circulation enhances the fresh water yield of the system predominantly.(Yuan et al. 2011)presented Polyurethane foam with SS could be an effective insulating material for humidifier and dehumidifier units to avoid heat lossfor 400 L/day yield.The maximum productivity is 45 L/day with unit area of $2.5m^2$ in (Shehata et al. 2019b)with ultrasound humidifier.By increasing heat input, the operative temperatures of the bubbling HDH desalination system can be raised, resulting in increased freshwater productivity of 9.04 L/day with 0.8 m^2 is presented in(Xiao et al. 2021).The highest desalination rate of 28.8 L/day was achieved using 2.5 m^2 of solar water heater area. In comparison to air temperature and feed salinity value, the parametric analysis demonstrated that decreasing the humidifiers pressure and increasing the water temperature improved the system performance more considerably in (Rahimi-Ahar and Hatamipour 2021).

As Table 7 demonstrates, some available data for comparison were collected at different operating conditions. The thermal efficiency of the device and the freshwater productivity can be compared on the basis of per m^2 collector area and fresh water yield. Based on the available data, the accumulated yield of the proposed HDH desalination system can reach 10L/day with $0.4m^2$ collector area under actual weather, which is better and the water productivity.

Conclusions

Two common methods of PID and FLC are introduced in this article. The two methodologies are described in detail. Then the key procedures and the implementation of the two techniques are applied in order to predict and optimize the heat transfer of the heat exchangers. The pilot plant was designed based on controller results and finally validate the results.

The main conclusion are as follows:

- FLC and PID models were developed for HE for predicting the output condensate temperature with respect to the condensate flow, feed inlet temperature and steam flow. The amount of produced reused water (product) was directly related to the controlling three input parameters. Controlling 3 parameters has a bigger effect on the output variable (condensate temperature). The performances were evaluated on the basis of error criteria performance IAE, ISE and ITAE.

- A compact type of HDH is designed to produce fresh water from seawater as well as in industrial effluents. It is operated based on the principle of separation process by boiling point temperature difference and suitable for all solar thermal collectors. The compact desalination system is simulated to find the quantity of solar collector area for need of fresh water.
- The comparison between the experiment's temperature and that of the simulations shows that the proposed pilot plant was in line with the industry's production results. In humidification-dehumidification desalination, the decrease in distilled water cost with the increase in lifetime is important compared to other solar collectors. The cost of ₹. 10/L of fresh water and the economic analysis is also carried out and the payback period is approximately 1 year. The minimum distilled water cost is observed with the HDH connected with the solar water heater contains evacuated tubes. It is suitable for places where standalone Desalination plants are needed owing to its cost benefit and lower operation cost.
- the proposed HDH desalination system can reach 10L/day with 0.4m^{2}collector area under actual weather.
- The control algorithm calculated the parameters of the heat exchanger input process and thus maintained the temperature of the condensate output and the TDS water, ensuring the year-round supply of good reuse water quality. It is possible to use the control algorithm and the prototype in any form of raw water treatment and thus minimize water scarcity.

Acknowledgment

The authors would like to thank M/s. Karaipudur common effluent treatment plant, Eco pure technologies private limited,Tirupur for providing the necessary facilities to carry out the experimental work.

REFERENCES

Anand, B., and S. Murugavelh. 2020. “Performance Analysis of a Novel Augmented Desalination and Cooling System Using Modified Vapor Compression Refrigeration Integrated with Humidification-Dehumidification Desalination.” *Journal of Cleaner Production* 255: 120224. https://doi.org/10.1016/j.jclepro.2020.120224.

Dasgupta, Jhilly et al. 2015. “Remediation of Textile Effluents by Membrane Based Treatment Techniques: A State of the Art Review.” *Journal of Environmental Management* 147: 55–72. http://dx.doi.org/10.1016/j.jenvman.2014.08.008.

Hamed, Mofreh H., A. E. Kabeel, Z. M. Omara, and S. W. Sharshir. 2015. “Mathematical and Experimental Investigation of a Solar Humidification-Dehumidification Desalination Unit.” *Desalination* 358: 9–17.

Hermosillo, Juan Jorge, Camilo A. Arancibia-Bulnes, and Claudio A. Estrada. 2012. “Water Desalination by Air Humidification: Mathematical Model and Experimental Study.” *Solar Energy* 86(4): 1070–76.

Holkar, Chandrakant R. et al. 2016. “A Critical Review on Textile Wastewater Treatments: Possible Approaches.” *Journal of Environmental Management* 182: 351–66.

Jamal, Agus, and RamadoniSyahputra. 2016. “Heat Exchanger Control Based on Artificial Intelligence Approach.” *International Journal of Applied Engineering Research* 11(16): 9063–69.

Jiang, Mei et al. 2018. “Conventional Ultrafiltration As Effective Strategy for Dye/Salt Fractionation in Textile Wastewater Treatment.” *Environmental Science and Technology* 52(18): 10698–708.

Kabeel, A. E., Mohamed Abdelgaied, and Emad M.S. El-Said. 2017. “Study of a Solar-Driven Membrane Distillation System: Evaporative Cooling Effect on Performance Enhancement.” *Renewable Energy* 106: 192–200.

Kim, Donghun, Jiacheng Ma, James E. Braun, and Eckhard A. Groll. 2020. "Fuzzy Modeling Approach for Transient Vapor Compression and Expansion Cycle Simulation." *International Journal of Refrigeration*. https://doi.org/10.1016/j.ijrefrig.2020.10.025.

Kocabas, A. Merve, HandeYukseler, Filiz B. Dilek, and Ulku Yetis. 2009. "Adoption of European Union's IPPC Directive to a Textile Mill: Analysis of Water and Energy Consumption." *Journal of Environmental Management* 91(1): 102–13.

Korenak, Jasmina, Claus Hélix-Nielsen, Hermina Bukšek, and Irena Petrinić. 2019. "Efficiency and Economic Feasibility of Forward Osmosis in Textile Wastewater Treatment." *Journal of Cleaner Production* 210: 1483–95.

Kunjuraman, Shanthi, and BhanumathiVelusamy. 2020. "Performance Evaluation of Shell and Tube Heat Exchanger through ANN and ANFIS Model for Dye Recovery from Textile Effluents." *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 00(00): 1–20. https://doi.org/10.1080/15567036.2020.1832627.

Leaper, Sebastian, Ahmed Abdel-Karim, Tarek A. Gad-Allah, and Patricia Gorgojo. 2019. "Air-Gap Membrane Distillation as a One-Step Process for Textile Wastewater Treatment." *Chemical Engineering Journal* 360: 1330–40.

Li, Guo Pei, and Li Zhi Zhang. 2016. "Investigation of a Solar Energy Driven and Hollow Fiber Membrane-Based Humidification-Dehumidification Desalination System." *Applied Energy* 177: 393–408.

Li, Xing et al. 2014. "Experimental Study on a Humidification and Dehumidification Desalination System of Solar Air Heater with Evacuated Tubes." *Desalination* 351: 1–8.

Liu, Meihong et al. 2011. "Comparison of Reverse Osmosis and Nanofiltration Membranes in the Treatment of Biologically Treated Textile Effluent for Water Reuse." *Desalination* 281(1): 372–78. http://dx.doi.org/10.1016/j.desal.2011.08.023.

elMaakoul, Anas et al. 2016. "Numerical Comparison of Shell-Side Performance for Shell and Tube Heat Exchangers with Trefoil-Hole, Helical and Segmental Baffles." *Applied Thermal Engineering* 109: 175–85.

Mirbolooki, Hanieh, Reza Amirnezhad, and Ali Reza Pendashteh. 2017. "Treatment of High Saline Textile Wastewater by Activated Sludge Microorganisms." *Journal of Applied Research and Technology* 15(2): 167–72.

Moradi, M. et al. 2019. "Developing of an Integrated Hybrid Power Generation System Combined with a Multi-Effect Desalination Unit." *Sustainable Energy Technologies and Assessments* 32(February): 71–82. https://doi.org/10.1016/j.seta.2019.02.002.

Oravec, Juraj et al. 2018. "Robust Model Predictive Control and PID Control of Shell-and-Tube Heat Exchangers." *Energy* 159: 1–10. https://doi.org/10.1016/j.energy.2018.06.106.

Rahimi-Ahar, Zohreh, and Mohammad Sadegh Hatamipour. 2021. "Performance Evaluation of a Solar and Vacuum Assisted Multi-Stage Humidification-Dehumidification Desalination System." *Process Safety and Environmental Protection* 148: 1304–14.

Raj Ranjitha, P., R. Ratheesh, J. S. Jayakumar, and Shankar Balakrishnan. 2018. "Theoretical Modelling and Optimization of Bubble Column Dehumidifier for a Solar Driven Humidification-Dehumidification System." *IOP Conference Series: Materials Science and Engineering* 310(1).

Raul, Pramod R. et al. 2013. "Comparison of Model-Based and Conventional Controllers on a Pilot-Scale Heat Exchanger." *ISA Transactions* 52(3): 391–405. http://dx.doi.org/10.1016/j.isatra.2012.12.002.

Shamshirband, Shahaboddin et al. 2015. "Performance Investigation of Micro- and Nano-Sized Particle Erosion in a 90° Elbow Using an ANFIS Model." *Powder Technology* 284: 336–43.

Sharshir, S. W., Guilong Peng, Nuo Yang, M. O.A. El-Samadony, et al. 2016. "A Continuous Desalination System Using Humidification - Dehumidification and a Solar Still with an Evacuated Solar Water Heater." *Applied Thermal Engineering* 104: 734–42.

Sharshir, S. W., Guilong Peng, Nuo Yang, Mohamed A. Eltawil, et al. 2016. "A Hybrid Desalination System Using Humidification-

Dehumidification and Solar Stills Integrated with Evacuated Solar Water Heater." *Energy Conversion and Management* 124: 287–96.

Shehata, Ali I. et al. 2019a. "Achievement of Humidification and Dehumidification Desalination System by Utilizing a Hot Water Sprayer and Ultrasound Waves Techniques." *Energy Conversion and Management* 201.

Shehata, Ali I. et al. 2019b. "Achievement of Humidification and Dehumidification Desalination System by Utilizing a Hot Water Sprayer and Ultrasound Waves Techniques." *Energy Conversion and Management* 201.

Sridharan, M. 2020. "Predicting Performance of Double-Pipe Parallel- And Counter-Flow Heat Exchanger Using Fuzzy Logic." *Journal of Thermal Science and Engineering Applications* 12(3): 1–11.

Thakkar, Hemin et al. 2020. "Comparative Analysis of the Use of Flash Evaporator and Solar Still with a Solar Desalination System." *International Journal of Ambient Energy*.

Vasičkaninová, Anna, Monika Bakošová, and AlajosMészáros. 2021. "Fuzzy Control Design for Energy Efficient Heat Exchanger Network." *Chemical Engineering Transactions* 88: 529–34.

Xiao, Jianwei et al. 2021. "Experimental Investigation of a Bubbling Humidification-Dehumidification Desalination System Directly Heated by Cylindrical Fresnel Lens Solar Concentrator." *Solar Energy* 220: 873–81.

Yuan, Guofeng, Zhifeng Wang, Hongyong Li, and Xing Li. 2011. "Experimental Study of a Solar Desalination System Based on Humidification-Dehumidification Process." *Desalination* 277(1–3): 92–98.

Zhu, A. M. et al. 2007. "Effects of High Fractional Noncondensable Gas on Condensation in the Dewvaporation Desalination Process." *Desalination* 214(1–3): 128–37.

Zubair, M. Ifras et al. 2017. "Performance and Cost Assessment of Solar Driven Humidification Dehumidification Desalination System." *Energy Conversion and Management* 132: 28–39.

*e*ISSN1303-5150