IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 39, No. 6, December, 2021, pp. 1853-1860
Journal homepage: http://iieta.org/journals/ijht

A Low Cost Intelligent Fuzzy-Controlled Multipass-Multibaffle Dry-Air Sterilizer Device for Small-Sized Surgical Instruments

Ebenezer O. Ige[1,2*], Ojo P. Bodunde[1,3], Solomon O. Akinola[4], Anthony E. Dike[1], Iyadunni A. Anuoluwa[5,6], Ifeoluwatayo A. Ige[7], Agbo Esoso[1]

[1] Department of Mechanical and Mechatronics Engineering, Afe Babalola University, Ado Ekiti 360231, Nigeria
[2] Department of Biomedical Engineering, Afe Babalola University, Ado Ekiti 360231, Nigeria
[3] Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Sha Tin 999077, HKSAR
[4] Department of Computer Engineering, Afe Babalola University, Ado Ekiti 360231, Nigeria
[5] Department of Microbiology, Afe Babalola University, Ado Ekiti 360231, Nigeria
[6] Department of Biological Sciences, University of Medical Sciences, Ondo 351101, Nigeria
[7] Department of Computer Science, University of Ibadan, Ibadan 200284, Nigeria

Corresponding Author Email: ige.olubunmi@abuad.edu.ng

https://doi.org/10.18280/ijht.390620

Received: 2 January 2020
Accepted: 16 December 2021

Keywords:
fuzzy-enabled, multi-baffle convection, alternative energy device, decontamination, low resource application, re-useable surgical tools

ABSTRACT

A major constraint in hospitals and clinics in the interior villages of low resource countries is the access to stable power supply. Decontamination of reusable metal-based surgical tools is an energy-intensive process, the power required for this procedure may not be accessible in many health centres in low resource countries. Hence, decontamination device with low-energy requirements could immensely benefit village clinical settings. The developed sterilizer utilizes a Fresnel lens in a multi-baffle multi-pass chamber to amplify radiation intensity. An intelligent scheme of air passage was achieved using Fuzzy logic control to ensure control of pressure and temperature regime thermal transport within the chamber. The Fuzzy logic controller program was designed on Matlab's fuzzy logic toolbox and simulated with Simulink to evaluate its accuracy. The performance evaluation of the device showed that at an ambient temperature of 27°C and a solar radiation intensity of 1362 W/m^2, the sterilizer was able to sterilize at a temperature of 169.69°C which is within the range for efficient dry heat sterilization to take place (140°C-170°C). This work has demonstrated that fuzzy logic controlled dry air sterilizer could achieve temperature ~ 150°C within the heater chamber which may be suitable for sterilizing used surgical equipment.

1. INTRODUCTION

Decontamination is a vital process in clinical settings, this is because metallic surgical equipment is expected to meet a certain condition of sterility for the safety of patients and clinicians [1]. The advocacy for specialized sterilization systems is dated to the late 1950s [2]. Over the years, decontamination hub for reusable hospital and surgical tools have become a cardinal unit of medical and health care facilities [3-5]. Decontamination involves the physical and chemical process that renders a reusable tool free of harmful microbial life that could constitute a vehicle of disease transmission during usage [3, 6-8]. In large hospitals, sterilization of hand-held surgical sets specifically metallic equipment may be tasking because the chain of processes involved in decontamination include transport, sorting, soaking, washing, and inspection. During this process, time and energy expended in sterilizing of reusable clinical tool accrue to delay in the administration of surgical procedures in tertiary health care facilities [9]. There are several established techniques employed in sterilization namely, chemical washing, Ultrasonic washing, Tunnel washing, cart washing and Thermal washing [10-13]. Most of these techniques rely on specialized equipment maintained at controlled operating conditions. Moreso, sterilization plant is capital intensive and usually out of reach in medical outlets in remote areas of low resource base countries. Besides poor access to energy, huge capital demand makes standard grade sterilization less practicable in low-end part of the world [14-16].

The argument for suitable energy has influenced the design of several medical devices used for various purposes includes decontamination and sterilization process in hospitals [14, 17, 18]. An interesting perspective to low-energy sterilization utilizing commercial solar panel has been demonstrated [17-21]. Nonetheless, there are some limiting issues around the utilization of low-energy sterilization technology. For instance, a solar autoclave device was reported in literature as a cumbersome structure for thermal capture and energy utilization for sterilization concern [22]. This predisposes the device to a high possibility of thermal loss between the solar panel and thermal (dry air) duct which may impair thermal effectiveness. Several attempts at designing low energy sterilization equipment have been reported [23-25]. Utilizing techniques of power electronics, certain improvements to reduce high power requirements for the decontamination process are being explored. Very notable is the down-scaling of sterilizer size as a means of reducing power density during usage [26]. Medium-scale and bed-side sterilizers have been designed following this concept.

This study focused on designing a portable bedside compact dry air heat sterilizer which uses solar energy to sterilize handheld metallic medical/surgical equipment. The design proposed in this report utilizes a combination of baffles and passes (thermal) enhancer for thermal energy by increasing the residence time and flux of air within the enclosure. The need to control the thermal process, vessel pressure and air flux were addressed by using an intelligent fuzzy-controlled architecture. This smart solar fuzzy-enabled dry air sterilizer is made from locally sourced materials to ensure cost reduction and local content inclusion in the fabrication procedure. This study modified the technique of conventional solar air dryer with a combination of Fresnel lens for beam concentration and the incorporation of a fuzzy logic controller to regulate air flux around the baffle-pass arrangement within predetermined temperature boundaries.

2. MATERIALS AND METHODS

Following specified considerations, the construction of the dry heat sterilizer was done in two phases (the fabrication of components and the programming of the controllers).

2.1 Solar air heater utilization for dry heat sterilization

The radiation trapping system utilized in the constructed device is an array of Fresnel lens of dimension 8.3cm×5cm which is equivalent to 41.5cm×25cm for the entire array. The glass cover is of dimension 41.5cm×25cm×0.2cm at 20℃ ambient temperature and solar radiation intensity of 800 W/m^2, the Fresnel lens magnifies temperature at 20℃ to 125℃ which is far higher than the average solar radiation intensity of the ambient which is estimated at 1360W/m^2. Also considering ambient air temperature to be equal to room temperature, and considering solar radiation to be equal to 1360 W/m^2 the magnified temperature becomes 169.7℃. The working temperature for a dry heat sterilizer (electric oven with fan) is between 140 and 170℃. Hence, from the experimental interpolation, it can be seen that the Fresnel lens would be able to achieve the ideal temperature needed for sterilization to take place.

2.2 Thermal controller design hardware components

Power source: The solar panel is used to produce the electric power on which the fans, sensors, and controller are powered. It is connected to a 12V, 7.2Ah battery. Arduino and motor shield: This is the controller used to run the code programmed on the fuzzy logic toolbox and Matlab. The .fis file was converted to a C compiler header and Arduino code. The Arduino receives the inputs from the temperature and humidity probes connected to it and passes the controlled outputs through the Motor Shield to the actuators which are the fans. The sensors required are temperature sensor with a temperature range of 0 – 200℃ and pressure sensor with a range of 15-20 psi. The specifications for the acquired sensors are shown below.

Actuator: 4 fans with heat sinks were adopted as the actuators for this device. All fans have the same specifications, which helps to ensure uniformity in the airflow volumes produced by each fan. The specifications of the fans utilized include fan life – 40,000 hours; Power – 1.44W; Air volume–30CFM; Fan size –80mm×80 mm×25 mm; Heat sink material – aluminum; Fan speed – 3500rpm; Quantity – 4pcs.

The programming phase involved interfacing of sensors and actuators with the controller for specified premises with consideration for flexibility base on stipulated initial conditions, such as thermophysical and fuzzy linguistic variables as contained in Tables 1, 2 and 3.

Table 1. Fuzzy initial conditions

Temp (℃)	Pressure (*psi*)	in_fan_spd (*V*)	out_fan_spd (*V*)
low: T<140	low: p<15	low: V<4	low: V<4
med: 140<T<170	Med: 15<p<20	med: 4<V<8	med: 4<V<8
high: T>170		high: 8<v<12	high: 8<v<12

Table 2. Inlet fan linguistic rules

		Temp		
		Low	med	high
Pressure	low	Med	high	high
	med	Med	med	med
		in_fan_spd		

Table 3. Outlet fan linguistic rules

		Temp		
		Low	med	high
Pressure	low	Low	low	med
	med	Low	low	high
		out_fan_spd		

Membership Function Editor: This provides an environment to defined the membership functions (high mids and lows) for each input and output (Figures 2-4); define their range of values as well as their degree of membership.

The fuzzy architecture was implemented by specifying initial values of the system such as the number of inputs and outputs (i.e., 2 and 2 in this case) as well as the names (temp, pressure, in-fan-spd and out-fan-spd). The AND method, the OR method, the implication, aggregation and the defuzzification is contained in Figure 1. It also made provision for two other functions (membership function editor and real editor).

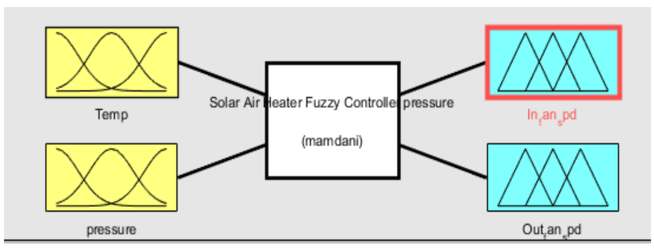

Figure 1. Fuzzy logic designer

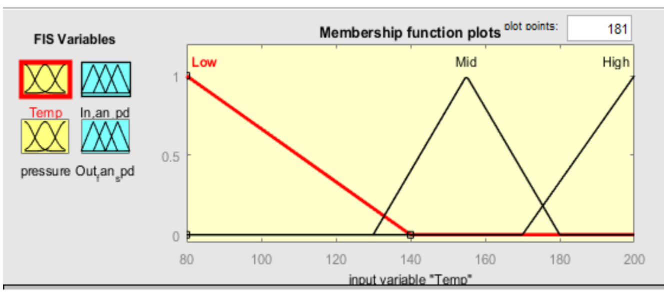

Figure 2. Temp membership function

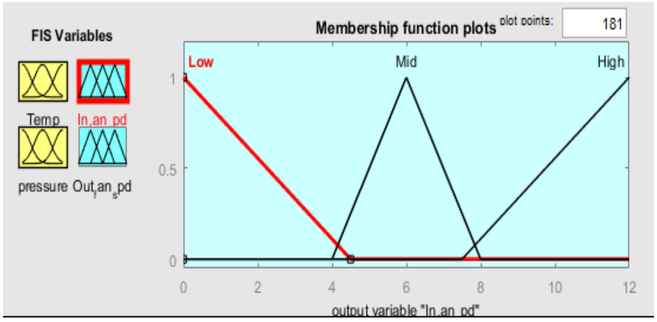

Figure 3. In fan speed membership function

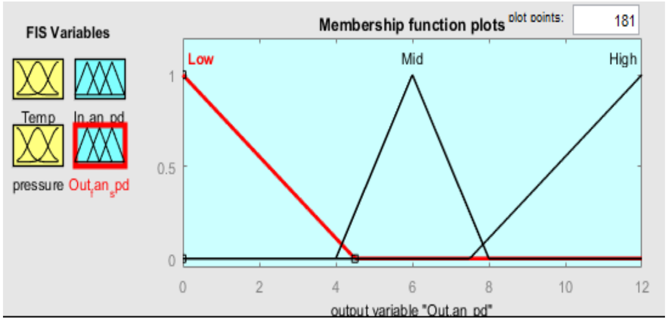

Figure 4. Out fan speed membership function

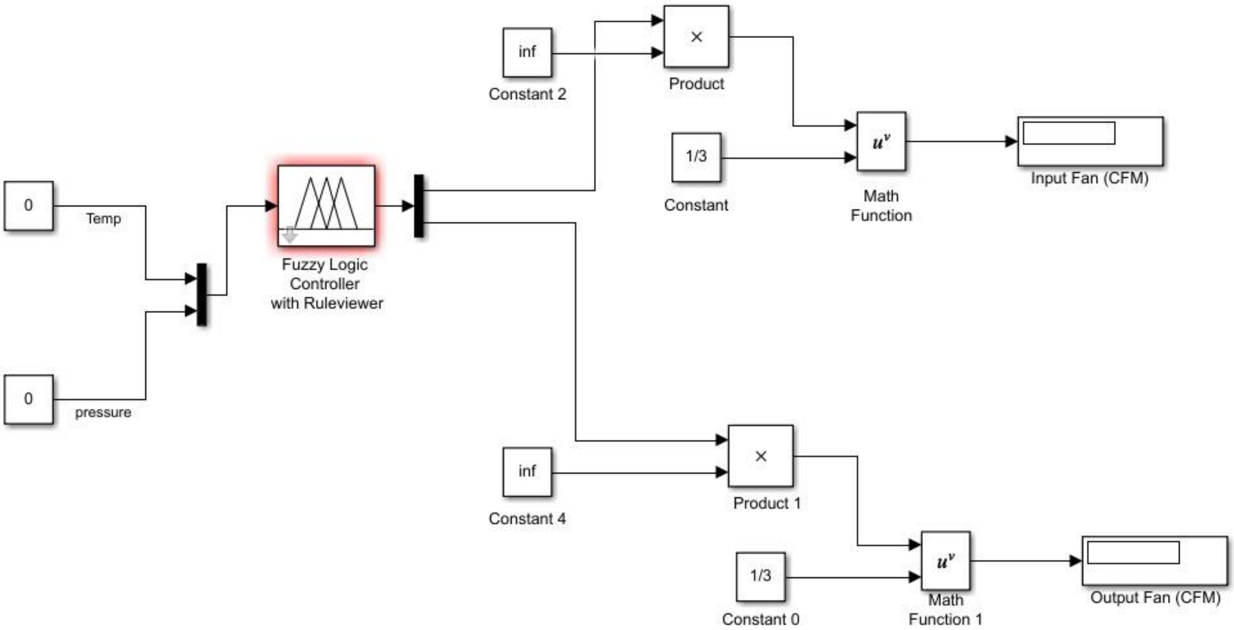

Figure 5. Simulink model of fuzzy logic controller

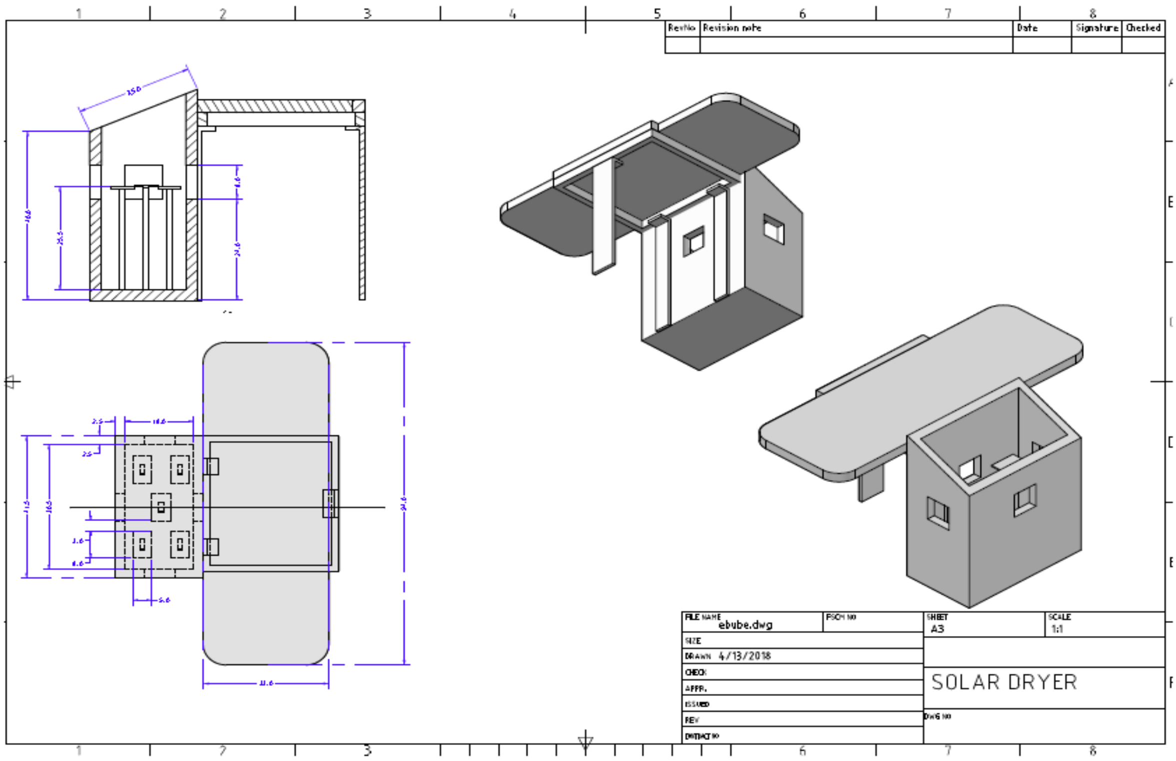

Figure 6. Proposed solar air heater design of the sterilizer device

2.3 MATLAB Simulink

Simulink toolbox in MATLAB is used to simulate the solar heater system with the fuzzy logic controller (which has the program imported from the fuzzy logic toolbox). The transfer function gotten from the mathematical model developed for the solar air heater and Fan Laws [4]. It was used to stimulate the working of the system under various conditions for analytical purposes. The simulation shows the changes in airflow volume of the fans relative to the change in temperature and pressure as shown in Figure 5.

The structural design of the solar heater was first designed via CAD software AutoCAD to give a better understanding of the design and to readjust the design to fit the optimum standard. The design consists of an assembly of the housing, the baffle, the Fresnel lens array, fan and heat sink, battery, control and solar panel as shown in Figure 6.

2.4 Modeling of heat transfer rate using heat exchanger analogy

The following assumptions were made:

i. Both fluids are single phased and mixed as they come in contact with each other.
ii. The heat exchanger shell is adiabatic.
iii. A constant uniform fluid inlet temperature.
iv. Diffusion and longitudinal conductance are neglected.
v. No transverse temperature.
vi. The velocity/flow rate of the inlet fluid is given by the velocity of the flow inside the system and is a component of flow rate emanating from both fans [5].

Considering the inlet, I1 and outlet, O1 to obtain similarity with a cross-flow heat exchanger as shown in Figure 7.

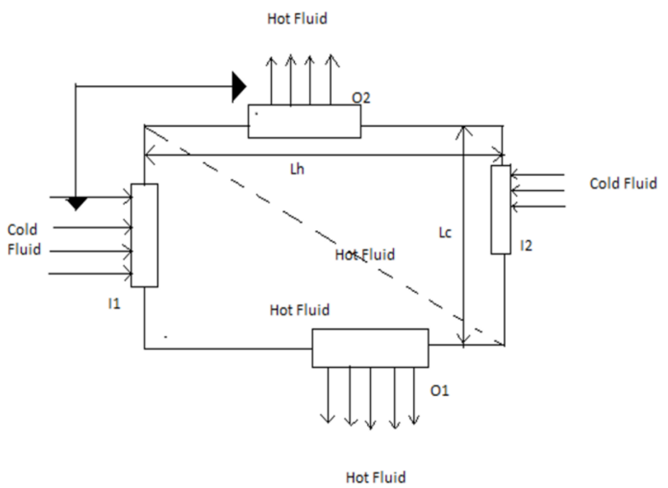

Figure 7. Schematic model of solar heater

Due to the non-isolation of fluid, there is no wall separating the hot and cold fluid stream.

The energy conservation was computed thus using the conservation equation for hot and cold fluid streams in Eq. (1).

$$C_c \frac{dT_c}{dt} - (h^1 A)_c (T_s - T_c) + (M^1 Cp) \frac{dT_c}{d\left(\frac{x}{l_c}\right)} = 0 \tag{1}$$

$$C_h \frac{dT_h}{dt} - (h^1 A)_h (T_h - T_s) + (M^1 Cp) \frac{dT_h}{d\left(\frac{y}{l_h}\right)} = 0 \tag{2}$$

where:
C_c is the heat capacitance of cold fluid;
C_h is the heat capacitance of hot fluid;
h^1 is the changing heat transfer coefficient;
A is the area of heat transfer;
T_s is the temperature inside the system (working temperature);
T_c is the temperature of the fluid at the inlet;
T_h is the temperature of the fluid at the outlet;
M^1 is the changing mass flow rate;
C_p is the specific heat capacity of the fluid at constant pressure;
x,y are the heat exchanger's physical length and dimension; and,
L is the length of the heat exchanger.

Considering turbulence in the baffles with thickness d_b with w_b and length l_b and considering air flowing perpendicular to the thickness of the baffle [6],

Reynolds number,

$$Re = \frac{u\, d_b}{v} \tag{3}$$

where, Re is the Reynolds' number; v is the kinematic viscosity. The flow is turbulent when the air hits the baffle.

Nusselt's number,

$$Nu = 0.037\, Re^{1/2} Pr^{1/3} \tag{4}$$

$$\text{But } Nu = \frac{h\, d_b}{k} \tag{5}$$

$$\therefore h = \frac{0.037\, Re^{1/2}\, Pr^{1/3}\, k}{d_b} \tag{6}$$

where, Pr is the Prandtl's number.

The energy equation is given by:

$$Q_{conv\, I_1} = (h^1 A)_c (T_s - T_c) \tag{7}$$

where, $Q_{conv\, I_1}$ is the convective heat flow rate at the inlet.

Considering the Fresnel lens solar concentrator [7].

The energy equation is given by:

$$Q_u = Q_i - Q_o = I\tau\alpha \cdot A_c - U_l A_c (T_c - T_a) \tag{8}$$

where:
Q_u is the useful energy gain of the solar concentrator;
Q_i is the collector heat input;
Q_o is the heat loss;
I is the intensity of the solar radiation;
τ is the transmission coefficient for glazing;
α is the absorption coefficient of the plate;
A_c is the collector Area;
T_c is the collector average temperature; and
T_a is the temperature at ambient.

It is also known that the rate of extraction of heat from the collector may be by means of heat taken away by the collector may be by means of the amount of heat taken away by the fluid passed through it.

$$Q_u = MC_p(T_h - T_c) \quad (9)$$

where, M is the mass flow rate Eq. (8) proves to be inconvenient because of the difficulty in defining the collector average temperature (T_c). It is convenient to define a quantity that relates to the actual useful energy gain of the collector to the useful gain if the whole collector temperature was at the fluid temperature. This quantity is known as the collector heat removal factor (F_r) and is given by:

$$F_r = \frac{MC_p\,(T_h - T_c)}{A_c[I\tau\alpha - U_l\,(T_s - T_a)]} \quad (10)$$

where:

C_c is the heat capacitance of cold fluid;

C_h is the heat capacitance of hot fluid;

h^1 is the changing heat transfer coefficient;

A is the area of heat transfer;

T_s is the temperature inside the system (working temperature);

T_c is the temperature of the fluid at the inlet;

T_h is the temperature of the fluid at the outlet;

M^1 is the changing mass flow rate;

C_p is the specific heat capacity of the fluid at constant pressure;

x,y are the heat exchanger's physical length and dimension; and,

L is the length of the heat exchanger.

2.5 Temperature and pressure detection and control in the system

Since the temperature and pressure are not elements that can be directly controlled due to the fact that they are subject to the outside environment; fans and heat sinks are adopted for this control. This is to ensure that the line between the prescribed range and the rules programmed to the fuzzy logic controller. It is also used to control the fans based on the reference and target temperatures at that point in time. There are two inlet fans in opposite directions and two outlet fans as well as making four fans in total.

At a medium speed of inlet fan, dissipation of heat is minimal and even, at the same time pressure build-up while the outlet fans are kept low to reduce the heat and pressure loss. At the optimum working temperature while the pressure is low; the inlet fans are set to high speed to build the pressure in the chamber as rapid as possible while the outlet fan is set to low to reduce pressure loss during this period. At high speed of the inlet fan, the temperature would have exceeded the working temperature while the pressure in the chamber is still low. Therefore, the inlet fan speed is set to high to build the pressure as rapid as possible while the outlet fan speed is set to medium in order to expel the excess heat in the system.

A situation where pressure is minimal and the temperature is low implies that the temperature in the chamber is still building while the pressure is within the optimum working condition. The inlet fans act to dissipate the building heat in the system while maintaining the pressure. The outlet fans act to prevent heat loss and pressure reduction during this period. When both thermal and pressure fields within the chamber are at minimal condition. It implies that the temperature and pressure in the system are at the ideal working condition and hence should be kept at that.

The inlet fan speed is set to medium to maintain constant distribution of temperature and pressure, while the outlet is set to low to prevent losses. The inlet fan speed is set to medium to help distribute the heat and pressure evenly while the outlet fan speed is set to high to help remove the excess fan heat as quickly as possible. The fuzzy-controlled architecture is designed to maintain temperature and pressure at optimum working conditions. High pressure is not taken into account because the fans do not have the power high enough to increase the pressure above the working pressure, and the pressure sensor does not measure above the working pressure as well.

2.6 Testing for the ability of the sterilizer to achieve sterility

This test was carried out to ascertain the efficacy of the sterilizer in sterilizing used surgical equipment (see Figure 8). This was carried out by sterilizing used surgical equipment in an autoclave at 121℃ for 15 minutes having close similarity with the report of the study [9] and some other used surgical equipment were sterilized in the dry-heat sterilizer with average temperature for 2 hours respectively while some used surgical equipment was left unsterilized to be used as control. Following the method described by Olutiola et al. [27], agar medium (nutrient agar) was prepared and sterilized and left in the molten form by placing in a water bath that had its temperature regulated to 45℃ to keep the agar warm so as to be used for pour plate later. Sterile distilled water was used in rinsing the sterilized and unsterilized surgical equipment separately and serial dilution was carried out following the method described by Olutiola et al. [27]. The stock and 10-1 dilutions were plated out using the pour plate technique. The plates were incubated for 18-24 hours in after which the plates were observed for microbial growth.

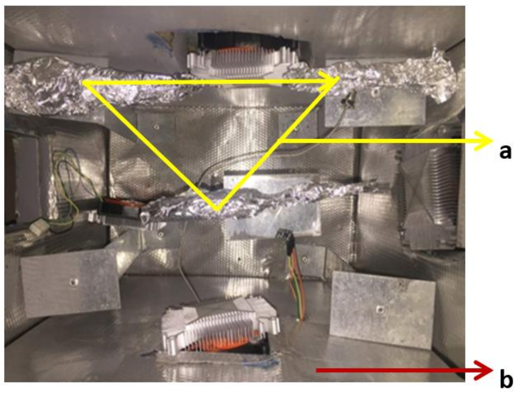

Figure 8. Surgical equipment on baffles during sterilization in the dry air

a: samples of contaminated reusable surgical tool

b: interior of sterilizer device furnished with stainless steel

3. RESULTS AND DISCUSSIONS

With the aid of the structural setup and programming, the system was able to reach its targeted working potential by the controller using its logic to regulate the relatively analog temperature and pressure signals and as such, the results were analyzed. After the control has been programmed, the rule viewer is a means of running the program, helping the user to view the resulting implications on the outputs based on the varying input signal (Temperature and Pressure) and the fuzzy rule set. Figure 10 shows the regulated temperature and pressure values and the equivalent fan speeds at that point while the view for these temperature regimes are captured in Figure 9 The Simulink model serves as a means of monitoring the airflow volume of the fan (in CFM) as it acts to regulate the varying input signals and tries to maintain them at Ideal conditions for sterilization as shown in Figure 5.

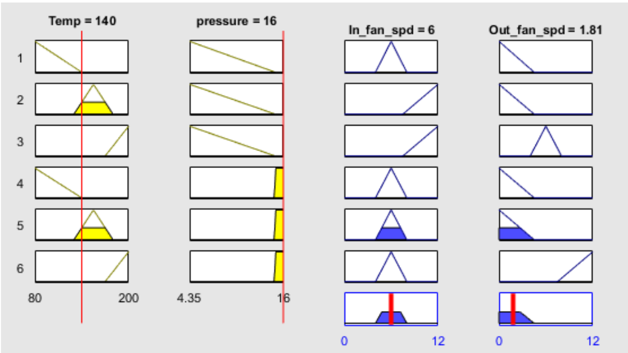

Figure 9. Rule viewer for temperature regimes

This plots a 3-dimensional graph producing a surface that represents all possible outcomes of the system based on all possible outcomes of varying input by joining different points based on the rules to show the deviation the rules make in a more visual form. For this controller, there are two surface diagrams because there are two outputs. The x-axis represents the temp, the y-axis represents the pressure, and the z-axis shows the output (in-fan-spd or out-fan-spd as the case may be) as contained in Figure 10 and Figure 11.

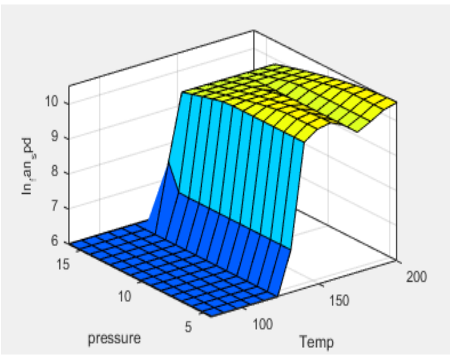

Figure 10. Distribution of fuzzy-enabled fan input with temperature and pressure

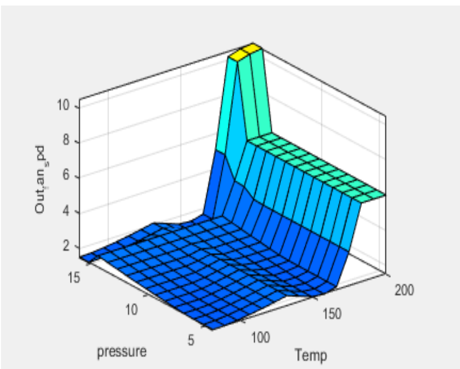

Figure 11. Distribution of fuzzy-enabled fan output with temperature and pressure

3.1 Analysis of sterility experiment

The analysis depicts sensitivity experiment of multibaffle hot-air chamber during the contamination process. Plates containing from rinse water from sterilized surgical equipment using both the autoclave and the dry air sterilizer respectively, showed no microbial growth whereas in plates containing diluents from rinse water from unsterilized used surgical equipment had microbial growths in them. This shows that the designed sterilizer is capable and fit to be used for sterilizing used surgical equipment in clinics without adequate supply of power. The shortfall in chamber temperature during sterilization could be attributed to some of these factors:

i. The glass used with the solar concentrator was too thick and as a result, there was energy loss by reflection and absorption by the glass plate.
ii. Presence of unaccounted openings and cracks resulted from flawed construction of the housing causing heat loss from non-isolation of the system.
iii. Fluctuating weather conditions leading to a large variation in solar radiation intensity with time thereby affecting the temperature.

3.2 Technological and environmental impact analysis

The development of this intelligent sterilizer has set the pace for the addition of modern technological advancements into the area of biomedical engineering research. Hence, facilitating the development of more sensitive and efficient technologies that adopt a mechatronic approach to solving problems into the field. The development of this sterilizer would help ensure the utilization of renewable energy while reducing the dependence on electrical power sources for the sterilization process which is most relevant in clinics and hospitals in remote parts of third world countries.

4. CONCLUSION

In this report, low-cost dry air sterilizer for small-sized medical tools has been presented. Fresnel lens solar collector was employed to amplify radiation intensity. Fuzzy-based controller architecture built on the Arduino platform supports intelligent control of pressure and thermal transport. Specially designed multi-baffle and multi-pass arrangement was incorporated in the heating chamber to increase the residence time of the thermal regime in the sterilizer chamber. This work has demonstrated that fuzzy logic controlled dry air sterilizer could achieve temperature ~ 150°C within the heater chamber which may be suitable for achieving sterility in the used surgical tools. Non-dependence on electricity and utilization of solar radiation as feed energy asserts the environmental friendliness of the device. The use of high-grade stainless steel for device fabrication improves a contamination-free environment in the chamber. Our observation showed that used surgical equipment sterilized using the device indicated considerable decontamination while the chamber temperature is recorded within the literature range of convectional autoclave and sterilizer device. A very unique feature of our device is its low cost, ease of operation, compact-size, and incorporation of intelligent controller scheme for optimized temperature delivery in the chamber.

ACKNOWLEDGMENT

This work was supported by the Department of Mechanical and Mechatronics engineering and the Department of Microbiology, Afe Babalola University Ado-Ekiti (ABUAD) Nigeria. The authors also appreciate the technical support team of the College of Engineering ABUAD.

REFERENCES

[1] Pittet, D., Ducel, G. (1994). Infectious risk factors related to operating rooms. Infection Control & Hospital Epidemiology, 15(7): 456-462. https://doi.org/10.1086/646951

[2] Perkins, J.J. (1959). Principles and Methods of Sterilization. Springfield Illinois.

[3] Leiss-Holzinger, E., Felbermayer, K., Ismic, D., Rankl, C., Hillmann, J., Brandstetter, M. (2017). A localized analysis of the sterilization process by direct steam monitoring. IEEE Access, 5: 19961-19970. https://doi.org/10.1109/ACCESS.2017.2753940

[4] Sopwith, W., Hart, T., Garner, P. (2002). Preventing infection from reusable medical equipment: A systematic review. BMC Infectious Diseases, 2(1): 4. https://doi.org/10.1186/1471-2334-2-4

[5] Fast, O., Fast, C., Fast, D., Veltjens, S., Salami, Z., White, M.C. (2017). Limited sterile processing capabilities for safe surgery in low-income and middle-income countries: Experience in the Republic of Congo, Madagascar and Benin. BMJ Global Health, 2(4): e000428. https://doi.org/10.1136/bmjgh-2017-000428

[6] Sehulster, L.M. (2004). Prion inactivation and medical instrument reprocessing: challenges facing healthcare facilities. Infection Control & Hospital Epidemiology, 25(4): 276-279. https://doi.org/10.1086/502391

[7] Rodrigues, C.S., Madeira, L.M., Boaventura, R.A. (2014). Decontamination of an industrial cotton dyeing wastewater by chemical and biological processes. Industrial & Engineering Chemistry Research, 53(6): 2412-2421. https://doi.org/10.1021/ie402750p

[8] Sehulster, L.M. (2015). Healthcare laundry and textiles in the United States: review and commentary on contemporary infection prevention issues. Infection Control & Hospital Epidemiology, 36(9): 1073-1088. https://doi.org/10.1017/ice.2015.135

[9] Chessesbrough, M. (2006). Distinct Laboratory Practical in Tropical Countries. https://www.medbox.org/preview/5255d6e1-05d4-41a9-beb2-02b60e695ecc/doc.pdf.

[10] Crawford, T.C., Allmendinger, C., Snell, J., Weatherwax, K., Lavan, B., Baman, T.S., Kune, D. (2017). Cleaning and sterilization of used cardiac implantable electronic devices with process validation: the next hurdle in device recycling. JACC: Clinical Electrophysiology, 3(6): 623-631. https://doi.org/10.1016/j.jacep.2016.12.007

[11] Rutala, W.A., Weber, D.J. (2004). Disinfection and sterilization in health care facilities: what clinicians need to know. Clinical Infectious Diseases, 39(5): 702-709. https://doi.org/10.1086/423182

[12] Ling, M.L., Ching, P., Widitaputra, A., Stewart, A., Sirijindadirat, N. (2018). APSIC guidelines for disinfection and sterilization of instruments in health care facilities. Antimicrobial Resistance & Infection Control, 7(1): 25. https://doi.org/10.1186/s13756-018-0308-2

[13] Alfa, M.J., Nemes, R. (2004). Manual versus automated methods for cleaning reusable accessory devices used for minimally invasive surgical procedures. Journal of Hospital Infection, 58(1): 50-58. https://doi.org/10.1016/j.jhin.2004.04.025

[14] Franco, A., Shaker, M., Kalubi, D., Hostettler, S. (2017). A review of sustainable energy access and technologies for healthcare facilities in the global south. Sustainable Energy Technologies and Assessments, 22: 92-105. https://doi.org/10.1016/j.seta.2017.02.022

[15] Adair-Rohani, H., Zukor, K., Bonjour, S., Wilburn, S., Kuesel, A.C., Hebert, R., Fletcher, E.R. (2013). Limited electricity access in health facilities of sub-Saharan Africa: A systematic review of data on electricity access, sources, and reliability. Global Health: Science and Practice, 1(2): 249-261. https://doi.org/10.9745/GHSP-D-13-00037

[16] Essendi, H., Johnson, F.A., Madise, N., Matthews, Z., Falkingham, J., Bahaj, A.S., Blunden, L. (2015). Infrastructural challenges to better health in maternity facilities in rural Kenya: Community and healthworker perceptions. Reproductive Health, 12(1): 103. https://doi.org/10.1186/s12978-015-0078-8

[17] Al-Akori, A. (2014). PV Systems for Rural Health Facilities in Developing Areas: A completion of lessons learned. Berlin, Report IEA-PVPS T9-15.

[18] Ngounou, G.M., Gonin, M., Gachet, N., Crettenand, N. (2015). Holistic approach to sufficient, reliable, and efficient electricity supply in hospitals of developing countries: Cameroon case study. In Sustainable Access to Energy in the Global South, pp. 59-77. https://doi.org/10.1007/978-3-319-20209-9_6

[19] Kaseman, T., Boubour, J., Schuler, D.A. (2012). Validation of the efficacy of a solar-thermal powered autoclave system for off-grid medical instrument wet sterilization. The American Journal of Tropical Medicine and Hygiene, 87(4): 602-607. https://doi.org/10.4269/ajtmh.2012.12-0061

[20] Ahmed, T.M., Rajagopalan, P., Fuller, R. (2015). A classification of healthcare facilities: Toward the development of energy performance benchmarks for day surgery centers in Australia. HERD: Health Environments Research & Design Journal, 8(4): 139-157. https://doi.org/10.1177/1937586715575910

[21] Dhankher, A., Drake, G., Haytko, J., Patel, Y., Sidoti, C., Song, G. (2014). A solar sterilization and distillation unit for water in resource-poor settings. In IEEE Global Humanitarian Technology Conference (GHTC 2014), pp. 469-473. https://doi.org/10.1109/GHTC.2014.6970324

[22] Li, X., Lin, R., Ni, G., Xu, N., Hu, X., Zhu, B., Zhu, J. (2018). Three-dimensional artificial transpiration for efficient solar waste-water treatment. National Science Review, 5(1): 70-77. https://doi.org/10.1093/nsr/nwx051

[23] Ha, T.M.H., Yong, D., Lee, E.M.Y., Kumar, P., Lee, Y.K., Zhou, W. (2017). Activation and inactivation of Bacillus pumilus spores by kiloelectron volt X-ray irradiation. PLoS One, 12(5): e0177571. https://doi.org/10.1371/journal.pone.0177571

[24] McCreanor, V., Graves, N. (2017). An economic analysis of the benefits of sterilizing medical instruments in low-temperature systems instead of steam. American Journal of Infection Control, 45(7): 756-760. https://doi.org/10.1016/j.ajic.2017.02.026

[25] Neumann, O., Feronti, C., Neumann, A.D., Dong, A., Schell, K., Lu, B., Nordlander, P. (2013). Compact solar autoclave based on steam generation using broadband light-harvesting nanoparticles. Proceedings of the National Academy of Sciences, 110(29): 11677-11681. https://doi.org/10.1073/pnas.1310131110

[26] Doona, C.J., Feeherry, F.E., Setlow, P., Malkin, A.J., Leighton, T.J. (2014). The portable chemical sterilizer (PCS), D-FENS, and D-FEND ALL: Novel chlorine dioxide decontamination technologies for the military. JoVE (Journal of Visualized Experiments), 88: e4354. https://doi.org/10.3791/4354

[27] Olutiola, P.O., Famurewa, O., Sontag, H.G. (2000). An introduction to general microbiology (A practical approach). Measurement of Microbial Growth, pp. 101-111.