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Experimental evaluation of solar integrated water heater

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Power saving;
Cost analysis.

Abstract. Domestic immersion heaters used for heating cold water are characterized by an electrical resistance heating element, which is encased in a tube and directly placed in it. The most common method for heating cold water is the use of portable immersion rod water heater in an open bucket operating in operator control without a controller unit (thermostat). This paper performs an experimental evaluation of portable modified conventional buckets of 10 l capacity. Out of ten portable modified storages, the best three cases are discussed: non-insulated Open Plastic Bucket (OPB), non-insulated plastic bucket top surface covered with a transparent cover (CPB), and insulated plastic bucket closed with a transparent cover (ICPB). Maximum temperatures arising after two hours during OPB, CPB, and ICPB are 29.82%, 47.36%, and 21.49%, respectively, compared to the initial temperatures (22.8°C). At 14:45 hour, CPB temperature reaches 35.6°C, which is 17.88% and 23.61% higher than OPB and ICPB units. Due to the application of solar energy in CPB at 35–50°C, net saving increased by 12.34%, 25.76%, 40.73%, 57.93%, 76.45%, and 97.18% from 2017 to 2022 as compared to the saving in 2016.

1. Introduction

The demand for domestic electrical power consumption is increasing day by day due to the population growth in rural and urban areas of developing nations. A significant portion of domestic power is consumed for heating cold water in winter bathing. A detailed review of several solar water heaters was done by Raisul Islam et al. [1]. Several portable and fixed types of solar water heaters are currently available in the market at different initial investment costs; however, their prices are significantly higher than immersion rods. The role of nano-fluid in the solar water heating system was investigated by Natarajan and Sathish [2]. A parametric study of domestic solar water heaters was conducted by many researchers [3,4]. The utilization of an electrical immersion rod in the bucket for the heating of the cold water in the winter session is the most common practice, especially within the rural and urban areas due to the low initial investment cost of the electric immersion rod. The techno-economic water heating system in a bucket through the immersion rod was evaluated by Sodha et al. [5]. They suggested three different methods for the system improvement: (i) insulating lateral and bottom surfaces, (ii) augmentation with the floating cover over water surface, and (iii) augmentation with both. An experimental evaluation of heat flux and heat transfer coefficient using inverse method was done by Farahani et al. [6]. The water-heating system was designed and simulated by Zhang et al. [7]. Jahangiri Mamouri and Bénard [8] performed

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a case study of a new design of an evacuated tubular water heater performance in the climatic condition of Michigan. The life cycle assessment of domestic water hot water cycle was reported by Moore et al. [9]. An evacuated tube collector water heater with a multi-layer absorber was investigated by Sobhansarbandi et al. [10]. The average economic performance of solar water heater was studied by Ferrer [11].

As in most of the rural areas of different countries, peoples are still using electric immersion rods for water heating. In case of proper motivation for the partial or full application of solar energy using the proposed methodology, the domestic power consumption can be reduced to a large extent.

2. Experimental setup

An real photograph and a schematic view of the portable water heater augmented with the incident solar radiations are shown in Figures 1(a) and 1(b), respectively. The black-colored surface has a better coefficient of absorption than other color surfaces. Hence, the black-colored plastic bucket is characterized by 10 l capacities. Three sets of the portable water heater are made of the following: (1) non-insulated, Open Plastic Bucket (OPB), (2) non-insulated plastic bucket, top surface covered with a transparent cover (CPB), and (3) insulated plastic bucket closed with a transparent cover (ICPB). The schematic arrangement of the CPB along with the floating cover and the immersion rod is that the floating cover gives credence to the variation in volumetric mass water within the bucket. OPB, CPB, and ICPB are fed with 10 l tab water and have been kept exposed to the incident solar radiation for four hours. K-type thermocouples and MDTI -027 temperature indicators are used for measuring and recording the temperature rise. The following observations are recorded as follows:

- Water temperature rising within OPB, CPB, and ICPB at a 15-min interval;
- Ambient temperature;
- Potential difference (voltage) calculated using a voltmeter;
- Current flowing through the immersion rod using an ammeter.

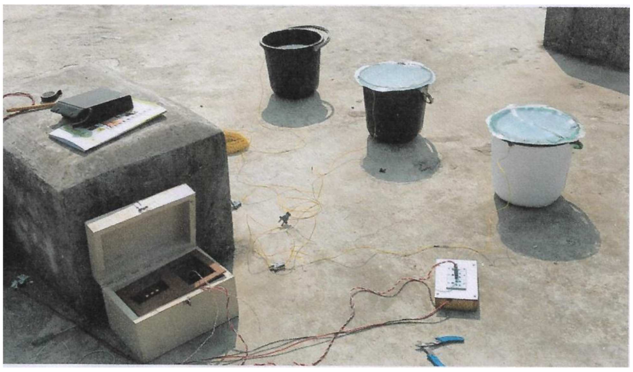

Figure 1a. Actual photographs of OPB, CPB, and ICPB.

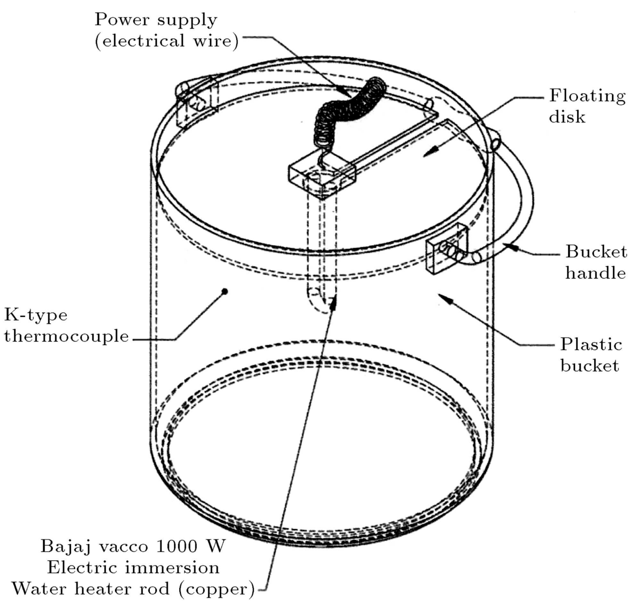

Figure 1b. Schematic representation of CPB along with the immersion rod and floating transparent cover.

3. Mathematical background

Three different configurations of the water heating in a bucket by an electrical immersion rod are shown.

To perform a mathematical evaluation of the system, the following assumptions are considered:

a. Electric power supply at a constant rate;
b. Cylindrical shape of the bucket;
c. Constant mass of water;
d. Uniform temperature of bucket water;
e. Neglecting evaporative losses, covered bucket with transparent material.

The energy balance mathematical relation for the bucket containing water is given as follows:

$$M_w C_w \frac{dT_w}{dt} = E_T - Q_s, \tag{1}$$

where:

$$E_T = E_e + E_s,$$

$$Q_{net\ loss} = Q_c + Q_e + Q_r + Q_s + Q_B.$$

Herein, E_T is the total power supplied to the water through solar radiation (E_s) and electrical immersion rod (E_e) in watts, whereas $Q_{net\ loss}$ is the energy loss through the conduction, evaporation, and radiation through the top, lateral, and bottom surfaces [12]. Various losses may be given below:

$$Q_c = h_c A_T \left(T_w - T_a\right), \tag{2}$$

$$Q_e = 0.013 h_c A_T \left(P_w - \gamma P_a\right), \tag{3}$$

$$Q_r = h_r A_T \left(T_w - T_a\right), \tag{4}$$

$$Q_s = h_s A_s \left(T_w - T_a\right), \tag{5}$$

$$Q_B = h_B A_B \left(T_w - T_a\right). \tag{6}$$

Heat transfer coefficients are given below [13]:

$$h_c = 5.7 + 3.8v, \tag{7}$$

$$h_r = \frac{\varepsilon_{eff}\sigma\left[\left(\overline{T}_w + 273\right)^4 - \left(\overline{T}_a + 273\right)^4\right]}{\overline{T}_w - \overline{T}_a}, \tag{8}$$

where σ $\left(= 5.67 \times 10^{-8} W/m^2K^2\right)$ is Stefan's constant, and a bar represents the average (throughout the heating process) of the quantity over it, whereas the effective emissivity of the plate-glazing system can be written as follows:

$$\frac{1}{\varepsilon_{eff}} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_a} - 1\right]^{-1}, \tag{9}$$

$$h_s = \left[\frac{1}{h_{ws}} + \sum_j \frac{2}{K_j r_j} \ln\left(\frac{r_{j+1}}{r_j}\right) + \frac{1}{h_0}\right]^{-1}, \tag{10}$$

$$h_B = \left[\frac{1}{h_{ws}} + \sum_k \frac{L_k}{K_k}\right]^{-1}, \tag{11}$$

where j and k denote the numbers of layers of side and bottom of the bucket, respectively.

It has become clear that the evaporative heat transfer coefficient (h_e) has nonlinear dependency on the temperature. The saturated vapor pressure in a narrow range of temperature variations can be represented by linear temperature dependence.

$$P = R_1 T + R_2, \tag{12}$$

where R_1 and R_2 are the constants evaluated using least-squares curve fitting of saturation. The vapor pressure in a longer range of interest can be evaluated through the following relation:

$$P_w = \exp\left(25.317 - \frac{5144}{T_w + 273}\right), \tag{13}$$

$$Q_e = 0.013 h_c \left[R_1 \left(T_w - \gamma T_a\right) - R_2 \left(1 - \gamma\right)\right], \tag{14}$$

and:

$$\frac{dT_w}{dt} + \alpha T_w = \beta, \tag{15}$$

where:

$$\alpha = \left[\left(H_0 A_T + h_s A_s + h_B A_B\right)/M_w C_w\right]$$

$$\beta = \left[E_T + \left(H_1 A_T + h_s A_s + h_B A_B\right) T_a - 0.013 h_c A_T R_2 \left(1 - \gamma\right)\right] \frac{1}{M_w C_w},$$

$$H_0 = \left(h_c + h_r + 0.013 h_c R_1\right),$$

and:

$$H_1 = \left(h_c + h_r + 0.013 h_c \gamma R_2\right).$$

From Eq. (15), in the initial condition, $T_w = T_{w0}$ and $t = 0$, one can get the following:

$$T_w = \frac{\beta}{\alpha} + \left(T_{w0} - \frac{\beta}{\alpha}\right) \exp\left(-\alpha t\right). \tag{16}$$

In the cooling mode ($E = 0$) from Eq. (15), one can get:

$$\frac{dT_w}{dt} = -\alpha \left(T_w - T_{eff}\right), \tag{17}$$

where:

$$T_{eff} = \left[T_a - \frac{0.013 h_c A_T \left(1 - \gamma\right)\left(R_1 T_a + R_2\right)}{M_w C_W \alpha}\right]. \tag{18}$$

After solving Eq. (17), one can express water temperature:

$$T_w = T_{eff} + \left(T_{w0} - T_{eff}\right) \exp\left(-\alpha t\right). \tag{19}$$

It is analogous to Newton's law of cooling; it can be observed that T_{eff} reduces to T_a at zero heat loss. The thermal performance of the system can be evaluated using the value of α (loss coefficient) for the typical dataset.

Other influencing parameters can be evaluated through the expressions written below:

i) Time taken to rise the temperature of water from T_{w0} to T_{wf} can be obtained.

$$T_H = -\frac{1}{\alpha} \ln\left(\frac{T_{wf} - \beta/\alpha}{T_{w0} - \beta/\alpha}\right). \tag{20}$$

ii) The efficiency of utilizing solar and electrical energy η can be measured in the following.

$$\eta = \frac{M_w C_w \left(T_{wf} - T_{w0}\right)}{\int_0^{t_{h1}} E_s dt + \int_{t_{h1}}^{t_{ht}} E_s dt}. \tag{21}$$

4. Cost analysis

The total annual cost of the system can be expressed in response to the corresponding initial investment as follows [14]:

$$C_{TA} = C_B f_1 + C_H f_2 + C_E \int_0^{1Year} E_T dt, \tag{22}$$

where f_1 and f_2 are the annuity factors that can be obtained as follows:

$$f_1 = \frac{q^L B (q-1)}{q^L B - 1}, \tag{23}$$

$$f_2 = \frac{q^L H (q-1)}{q^L H - 1}, \tag{24}$$

where $q = \left(1 + \frac{Z}{100}\right)$.

Annual amount of useful energy (kWh) is obtained below:

$$Q_u = \int_{Year} M_w C_w \left(T_w - T_{w0}\right) dt. \tag{25}$$

The cost of 1 kWh of useful energy can be determined as follows:

$$C_u = \frac{C_T}{C_u}. \tag{26}$$

5. Result and discussion

All the experiments were carried out in January 2017 at Jaypee University of Engineering and Technology, Guna (24.4348° N, 77.1606° E). Maximum and minimum incident solar radiations on the horizontal surface were recorded as 890 and 640 W/m^2, respectively, during the experimentation. Variation in incident solar radiation was recorded, as shown in Figure 2. At the beginning of the experimentation, the incident solar radiation was recorded at 792 W/m^2, which increased at 13:00 hour by 12.37%. After 13:00 hour, it started to decline by 28.09% at 14:45 hour during the experimentation.

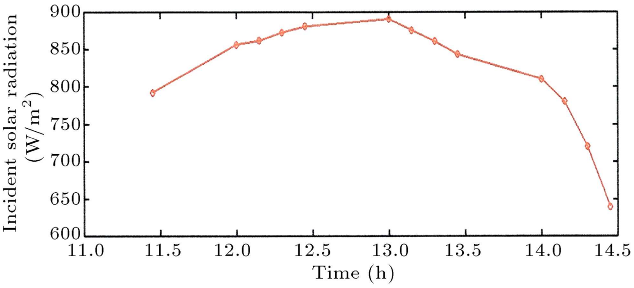

Figure 2. Variation of incident solar radiation with respect to time.

At the beginning of the experimentation, OPC, CPB, and ICPB were filled with the cold water (10 l each) at a temperature of 22.8°C, and the results of the experimentation and theoretical evaluation and its variation due to the incident solar radiation as a function of time are shown in Figure 3. Maximum temperatures rising after a two-hour time interval in OPB, CPB, and ICPB are 29.82%, 47.36%, and 21.49%, respectively, as compared to the initial temperatures (22.8°C). Water temperature of OPB, CPB, and ICPB was determined at its highest value at 14:45 hour during the experimentation, whereas the obtained results of the theoretical models slightly decreased after 14:00 hour due to a reduction in the incident solar radiation.

Water temperature rise in CPB has maintained its lead throughout the experimentation as compared with the OPB and ICPB, whereas ICPB lags behind as compared with OPB and CPB due to the lateral surface insulation. Temperature rise in OPB is more moderate than that in CPB and ICPB.

Temperature increase by water within OPB and CPB due to the Bajaj Vacco (Immersion Water Heater Rod) of 1000 W capacity.

The temperature rise in both cases was recorded at an interval of two minutes and is shown in Figure 4. Water within the CPB retains more heat as it is covered from the top surface, which is the reason why the temperature rise recorded in CPB maintains its lead as compared to the OPB throughout the heating process. Due to the presence of the top cover during water heating by means of the immersion rod, the time required to rise unit degree temperature is shorter than that in the OPB and power consumption has reduced in CPB to a greater extent than that in OPB.

Eight sets (23–50°C, 24–50°C, 28–50°C, 30–50°C, 34–50°C, 36–50°C, 38–50°C, and 40–50°C) of the experiment are considered for analyzing the electrical power consumption in OPB and CPB during water heating through an electrical heater. The obtained results of the experimentation are shown in Figure 5.

Estimated cost saving on the basis of expected

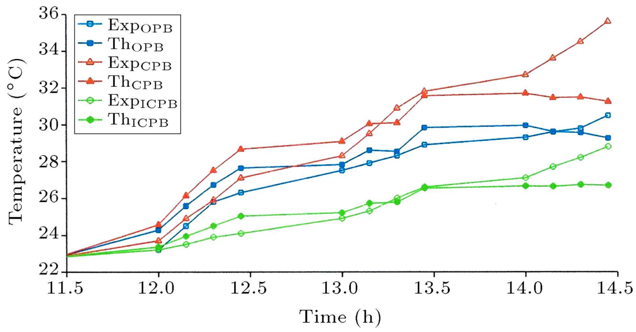

Figure 3. Variation of bucket water temperature due to incident solar radiation with respect to time.

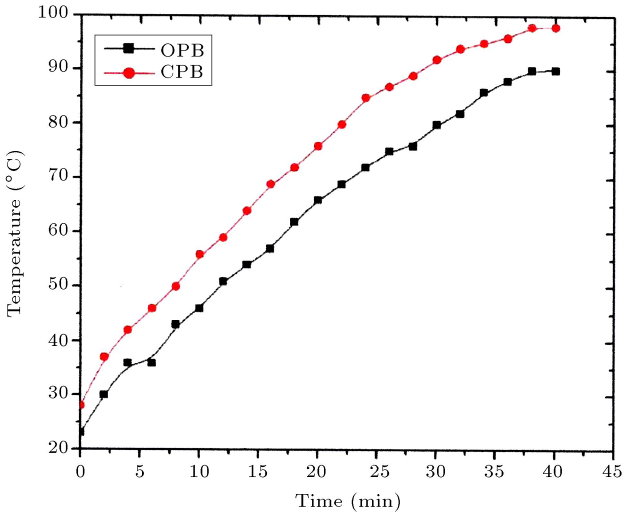

Figure 4. Variation of water temperature in OPB and CPB due to the immersion rod with respect to time.

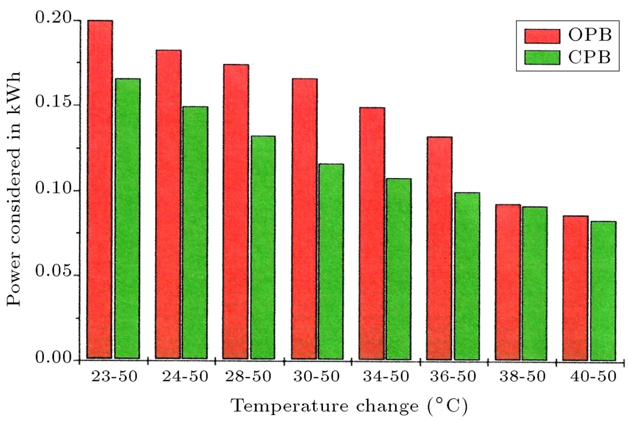

Figure 5. Variation of power consumption with respect to the temperature range.

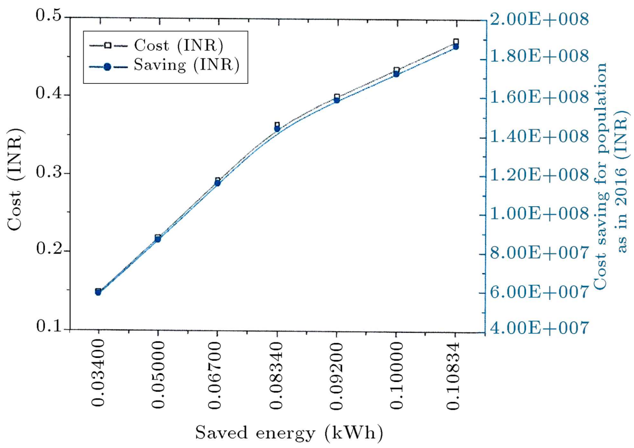

Figure 6. Variation of energy saving and estimated cost as per the domestic rate of Madhya Pradesh (MP) India with respect to saved energy.

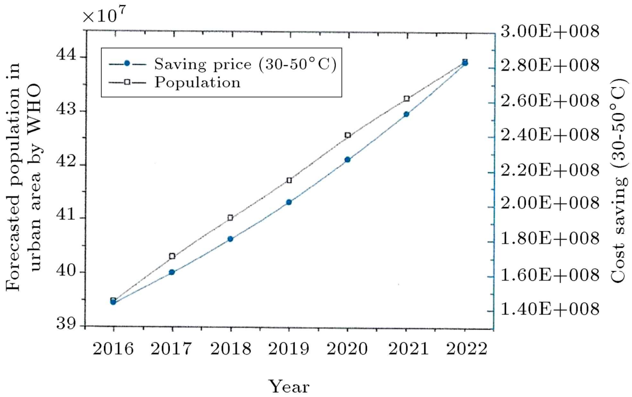

Figure 7. Variation of estimated population growth of urban area by World Health Organization (WHO) and cost saving with respect to the associated year.

population growth by World Health Organization (WHO) is shown in Figure 6 due to recorded and expected growth rates in the population of rural and urban areas.

Figure 7 shows the estimated saving from 2016 to 2022 on the basis of the estimated population and 10% price hike on electricity. Estimated population growth has been recorded at rates of 2.13, 3.39, 5.74, 7.86, 9.63, and 11.4%, which are higher than the rates recorded in 2017 to 2022, compared to the population living in 2016. However, net saving resulting from the utilization of solar energy in CPB in a temperature range of 35–50°C increased by 12.34, 25.76, 40.73, 57.93, 76.45, and 97.18% from 2017 to 2022, compared to saving in 2016.

6. Conclusions

Based on experimental theoretical investigations, the following conclusions are drawn:

- Open bucket water heating using immersion rod is an inefficient process;
- Use of transparent plastic cover mater helps reduce the consumption of electrical power significantly;
- The transparent floating cover can also be a cost-effective solution to cost reduction;
- For dry climatic conditions, the electrical heating system operates more uneconomically;
- The application of solar energy for heating of water reduces electric power consumption significantly;
- To reduce heat loss, an immersion rod of higher power rating can be used.

Nomenclature

A_B	Bottom surface area of the bucket, m^2
A_T	Top surface area of water, m^2
A_S	Area of sides, m^2

C_B	Initial investments in bucket, insulation, and cover, INR
C_E	Electricity rate, INR/kWh
C_H	Initial investment cost of an immersion rod, INR
C_T	Total system annual cost, INR
C_u	Overall cost of useful energy, INR/kWh
C_w	Specific heat of water, J/kg°C
C_{TA}	Total annual cost of the system, INR
E_e	Electrical energy supplied through immersion rod, W
E_s	Solar energy received, W
E_T	Total energy supplied to the bucket through the solar and electrical sources, W
h_B	Total heat transfer coefficient from the water to the ground through the bottom, W/m^2°C
h_c	Convective heat transfer coefficient from top surface /water to ambient air, W/m^2°C
h_r	Radiative heat transfer coefficient from cover surface /water to ambient air, W/m^2°C
h_s	Total heat transfer coefficient from water to the ambient air through sides, W/m^2°C
M_w	Mass of water, kg
P_a	Partial pressure of saturated water vapor at ambient temperature, N/m^2
P_w	Partial pressure of saturated water vapor at water temperature, N/m^2
T_w	Temperature of water, °C
T_a	Ambient temperature, °C
Q_c	Convective heat loss from water/ top surface to the surrounding, W
Q_e	Evaporative heat loss from water/ top surface to the surrounding, W
Q_r	Radiative heat loss from water/ top surface to the surrounding, W
$Q_{net\ loss}$	Heat loss through lateral surface of bucket, W
Q_u	Annual useful energy, kWh
Z	Percentage rate of interest
ε_{eff}	Effective emissivity of cover/ water surface
v	Velocity of air, m/s
σ	Stefan-Boltzmann coefficient (= 5.67×10^{-8} W/m^{2}K^4)
γ	Relative humidity

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Biographies

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Hrishi Jain is pursuing his MTech in Ocean Technology from IIT Madras. He was born on September 21, 1994 at the Tikamgarh district of M.P. India and has completed his higher secondary school from Hope Academy Tikamgarh and secured 80%. He completed his BTech in Mechanical Engineering at Jaypee University of Engineering & Technology in 2017 and worked as a Design Engineer for the ATV (All-Terrain Vehicle) in college team Ardent Clan and ATV at Gautam Buddha University Noida in Off Road Challenge competition. He is currently pursuing his MTech in Ocean Technology at IIT Madras and completed his thesis titled "development of thermally rechargeable ARGO float using ocean thermal gradient" with National Institute of Ocean Technology (NIOT) Chennai. He has an affiliation with the startup Terero Mobility mentored by Lockheed Martin at IIT Madras a Finite Element Analysis (FEA) lead. He has published two international research articles in peer-reviewed international conferences/journals.

Nishant Kumar works with Shrota Enterprises Pvt. Ltd. as a Production Planning & Control (PPC) officer. He was born on November 11, 1993 in the Patna district of Bihar India. He has completed his higher secondary school from R.K.S College, West Champaran and received his BTech degree in Mechanical Engineering from Jaypee University of Engineering & Technology in 2017. He has worked as a Fabrication Engineer and Steering Incharge for the ATV (All-Terrain Vehicle) in college team Ardent Clan and raced our ATV at Gautam Buddha University Noida in Off Road Challenge competition and published two international research articles in peer-reviewed international conferences/journals.

Mahendra Singh Sodha is a visiting Professor at the Department of Education and Physics, Lucknow (UP). He was born in Ajmer district of Rajasthan on February 8, 1932. He pursued his higher education at the University of Allahabad. After receiving his D Phil in "Theory of Spectroscopy Instruments" in 1955, he joined Defense Science Laboratory in Delhi for a short period of time. From 1956 to 1964, he worked in Canada and the USA at different capacities. He was appointed a Professor at the Department of Physics at the Indian Institute of Technology Delhi, New Delhi, 1964. Professor Sodha has made outstanding contributions in the areas of energy, plasma, solid state physics, optics, combustion, and ballistics. He has published more than 500 research papers in reputable national and international journals. He has to his credit 13 books and 12 reviews. He has also supervised more than 65 PhD students from IIT Delhi and other Universities. Professor Sodha was awarded the prestigious S.S. Bhatnagar award in 1974, Hari Om Ashram Prerit Shri S.S. Bhatnagar award in 1978, and Padmashri award in 2003 for his outstanding contributions in science and engineering. He is a fellow in many professional bodies including Indian National Science Academy and National Academy of Science, India. He has been a member of the editorial board of national and international journals. Professor Sodha served IIT Delhi at many capacities including Head of the Department of Physics (1966–1968); Head of the Centre for Energy Studies (1978–1982); Dean (Science, Students, PG Studies) (1970–76), and Deputy

Director (1982–1985). He has also served as the Vice-Chancellor of Lucknow University, Lucknow (1992–95) and Barkatullah University, Bhopal (1998–2000). He has played an active role in the promotion of higher education in India. He has been instrumental in setting up the Centre for Energy Studies at IIT Delhi and Faculty of Engineering Sciences at Indore. He is currently a Ramanna Fellow and a Visiting Professor at the Department of Education and Physics, Lucknow (UP).