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Original Article

Enhancing Urban Sustainability: An Automatic Rooftop Cooling Mechanism for Smart City

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Abstract *- Greenhouse gas emissions have been the direct offshoot of urbanization, which in turn has raised the temperature of these urban cities. Fans and air-conditioners have been the conventional practice to lower the temperature inside the rooms/buildings in such urban cities. This paper proposes an alternative solution to room cooling using the principle of evaporation through the water-spraying approach from the rooftop to towards the room space. Aptly named an automatic rooftop cooling system, it also attempts to comply with energy efficiency and sustainability. This system has a DHT11 sensor for real-time temperature monitoring, an Arduino microcontroller for automatic actuation, and a Peltier module for cooling water. Here, the cooled water is sprayed on the rooftop, which then cools the room by absorbing the heat of the rooftop, and then this heat absorbed water is collected in a reservoir from where it is sent to the rooftop again after cooling it through the Peltier module. The DHT11 sensor keeps a tab on the temperature, while the Arduino microcontroller actuates the Peltier module when the temperature rises to a certain threshold limit. Experimental results showed that the room temperature dropped for a given period, validating the system's potential to lower the heat buildup in urban settings. The methodology included the calculation of heat conduction, water flow efficiency and the overall system performance.*

Keywords *- Arduino, Evaporative cooling, Peltier module, Rooftop spray, Smart city.*

1. Introduction

Compared to rural regions, urban settings are generally hotter. This is due to the fact that urban cities have too many heat-absorbing materials exposed to the sun, too many human activities, excessive use of power and electricity, and less forests and greenery. While fans and air-conditioners have been in use for decades for a pleasant indoor environment, it is contributing to the emissions of greenhouse gases, further increasing the capacity of heat absorption in these areas. Hence, the loop of rise in temperature in urban cities is consistently getting intense, hence backing global warming. Therefore, the need of the time is to look for alternative solutions to keeping the rooms cooler. Moreover, with the concept of smart cities taking shape, it is all the more important to look for sensible solutions using smart systems like microcontrollers, automatic sensors, etc. The system that this paper proposes utilizes water spraying and evaporation with the integration of Arduino microcontrollers and temperature sensors for real-time temperature monitoring and automated operation of the rooftop cooling system. In the past, there have been several scholarly works and studies exploring alternative cooling methods. A few works on the water spraying system have been briefed here. Mustafa et al. [1] demonstrated that rear-side mist cooling significantly enhances PV efficiency, achieving up to 9.2% gain with forced circulation. Santiko Wibowo et al. [2] showed that using 2 mm full cone nozzles in a water spray system reduced panel temperature and improved efficiency from 10.98% to 14.47%. Zhou et al. [3] in their work concluded that even in buildings that have poor insulation, passive roof spraying systems managed to bring the temperature down. Their study was performed on reinforced concrete buildings. They also suggested the use of rooftop lawns as an additional cooling measure.

Al-Turki & Zaki [4] modeled the thermal response of roofs under different spraying conditions. Their investigation was on intermittent evaporative roof cooling. Through their model, they observed a 40% reduction in cooling loads under hot, dry conditions. Kindangen et al. [5] studied an automatic water spraying system on corrugated galvanized zinc metal - a very common roof material used in Indonesia. Their study observed a surface temperature drop of upto 5°C. They suggested that more research is to be done on water conservation by reusing cooled water. Kondepudi [6] developed an analytical model that estimated roof spray evaporative cooling that considered solar flux exposure, ambient temperature, and humidity.

Water spraying methods and other alternatives have also been studied, two of which are briefed here. Cheikh & Bouchair [7] conducted passive and evaporative cooling in Algeria, demonstrating a temperature reduction of 6°C to 10°C. They suggested that this temperature reduction could further be reduced through natural ventilation during the night. Tijani et al. [8] developed an automatic, cost-effective, domestic, eco-friendly, solar-powered water cooling system using Peltier modules in arid regions.

Cooling through radiation has also been explored by scholars. Zhai et al. [9] developed a metamaterial for daytime radiative cooling that radiates heat into space while reflecting sunlight, attaining a cooling power of 93 W/m² under direct sunlight. Hosseinzadeh and Taherian [10] tested a nocturnal radiative cooling system using unglazed solar collectors. Their system reduced water temperatures by 7°C to 8°C.

Li et al. [11] developed aluminum phosphate-based coatings that reflected 97% of sunlight, resulting in a reduction of rooftop temperatures by 4.2°C. Zhang et al. [12] conducted an economic analysis of a hybrid radiative cooling system in residential buildings. Their study showed a 26% to 46% reduction in annual cooling energy consumption, depending on locations, proving economically feasible with a payback period of 4.8 to 8 years.

Natural insulation materials have also been explored for cooling purposes. Mintorogo et al. [13] tested using coconut fibers as eco-insulation on concrete slab rooftops. They observed a reduction in surface temperature by 13°C and indoor air temperature drops of 2.8°C to 3.1°C, leading to energy savings of 3% to 9%.

The literature discussed above has shown that both active and passive cooling systems, including roof spraying and radiative cooling methods, have successfully reduced indoor temperature and managed energy consumption. However, two critical gaps still exist. One is the lack of close-loop water circulation, and two is the absence of sensor-based duty cycling. Previous spray systems treated water as a single-pass consumable, leading to unsustainable daily usage, and without real-time roof temperature feedback, sprays often operated continuously, potentially overwetting the roof. Hence, this paper proposes to address these gaps by integrating a closed-loop spray circuit and thermoelectric water pre-cooler under threshold-based control to manage both water and energy simultaneously, aligning with the broader framework of smart cities.

The present work, therefore, aims to design a recirculating rooftop spray system, quantify the cooling rate, and benchmark the prototype using both experiment and finite element simulation.

2. Materials and Methods

The central idea behind the proposed roof spray cooling system is to cool the heated roof surface by spraying water on it. Figure 1 shows the block diagram of the working of the automatic rooftop cooling mechanism. Figure 2 shows a schematic of the proposed system. The purpose is to prevent heat from entering the building by cooling the roof before the heat can be absorbed. This system reduces both the temperature of the roof and the amount of heat transmitted indoors from absorbed solar radiation, effectively lowering indoor temperatures.

When the Arduino is connected to the laptop and powered on, the motor valve begins to open, and the 6-volt motor starts drawing water from a filled bucket. The water in the pumping motor is directed to the top of the water block, which functions as a heat exchanger. It then flows through a Peltier module, where a temperature gradient in the water occurs. A 5-volt DC relay module is employed to regulate the water pressure load, ensuring a continuous flow of water over the roof (aluminum foil) for cooling purposes. A digital humidity sensor is installed on the roof to detect heat from sunlight and sends feedback to the Arduino to control the pump motor's actuation. The motor pumps the water again, and this cycle continues until the desired temperature gradient is achieved. Figure 3 shows the flow diagram of the actuator activation.

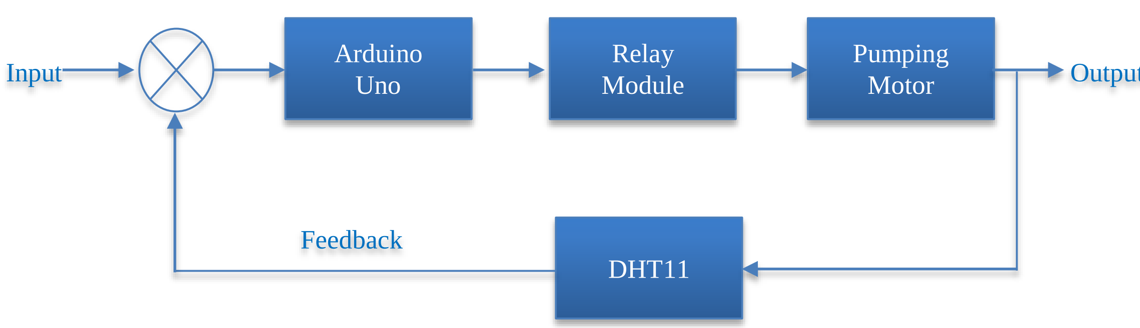

Fig. 1 Block diagram of working of automatic rooftop cooling mechanism

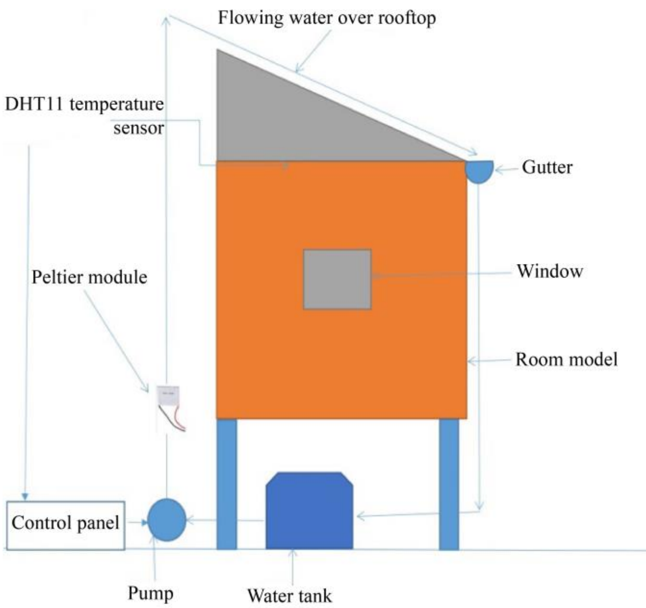

Fig. 2 Schematic diagram of automatic rooftop cooling mechanism

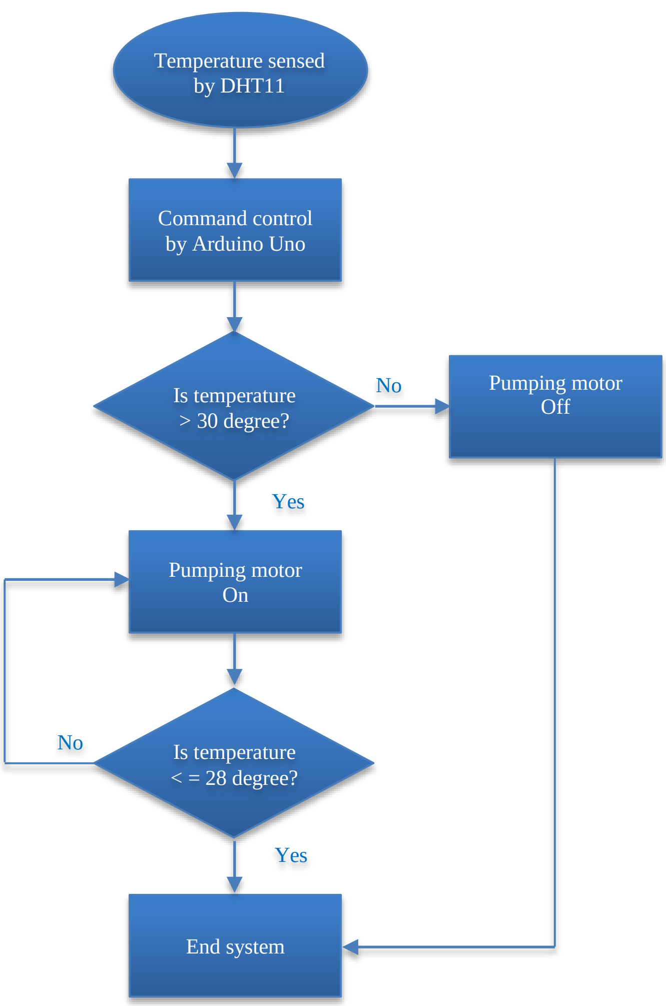

Fig. 3 Flow diagram of the actuator activation

The temperature measured by the DHT11 (digital humidity sensor) is relayed to the Arduino as feedback. The code specifies that if the temperature detected by the DHT11 is greater than or equal to 30°C, a command is issued to open the motor valve, allowing water to flow. When the temperature drops to 28°C, the DHT11 sends feedback to the Arduino, prompting it to close the valve. The desired temperature gradient is achieved by running the cycle for 164 seconds.

2.1. Analysis using ANSYS

ANSYS is available in three varieties, with this work primarily focusing on thermal analysis and computational fluid dynamics. The three types include structural analysis, thermal analysis, and computational fluid dynamics. The theoretical data generated by ANSYS software will be compared with data obtained from actual physical experiments. Figure 4 shows the ANSYS model.

ANSYS Workbench R21 was utilized for the analysis. First, a 3D image of the house dimensional model was imported from CATIA V5. The aluminum material was created within the software, with the inner surface (box/outer roof) temperature set at 303 Kelvin (30°C) and the wall (inner roof) temperature set at 301 Kelvin (28°C). The roof thickness was taken as 1 mm (0.001 m).

A total of 515 iterations were performed to achieve accuracy in the chart and results. The contour surface of the roof (1 mm thickness) illustrates the temperature variation from the outer surface of the roofing material to the inner surface. The internal heat production of the roofing material is zero (0). The red area of the model indicates the highest temperature exposure of the roof, followed by the yellow area and then the green area.

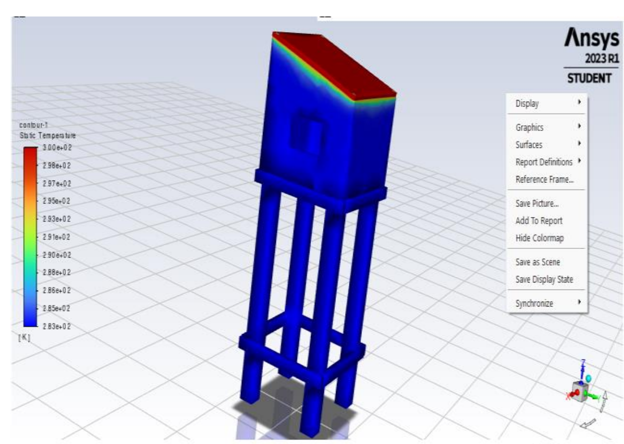

Fig. 4 ANSYS model

2.2. System Design and Components

The cooling system was conceptualized as an automated solution integrating a smart city's infrastructure. Table 1 has the list of the components used in the physical model.

Table 1. Components used

Component	Description
Breadboard and Jumper Wires Set	A solderless breadboard for semi-permanent prototyping of electronic circuits and jumper wires used to connect components without soldering.
Digital Humidity Sensor	A sensor that measures absolute or relative humidity and converts it into electrical signals, capable of detecting environmental changes.
Digital Thermometer Sensor	A thermometer that uses a thermistor or pyroelectric sensor to detect temperature changes and provide digital output.
SMPS Power Supply	A Switched-Mode Power Supply is used for efficient electrical power conversion from DC or AC sources to DC loads.
Thermo-electric Peltier Refrigeration Cooling System	A cooling system using the Peltier effect, where electrical current induces a temperature gradient to cool objects.
Water Cooling Block Head	A heatsink alternative used in water-cooling systems is commonly employed to cool electronic components such as CPUs or GPUs.
Peltier Module	A semiconductor module that creates a temperature gradient between two plates using the Peltier effect allowing for heating or cooling.
Arduino Uno	A low-cost, programmable microcontroller board controls electronic components and systems like LEDs, relays, or motors.
5V DC Relay Module	A relay module is used to control high-voltage systems like lighting, motors, or solenoids, with specifications for switching between AC and DC voltages.
Water Pump	A 12-volt DC water pump is used for low-voltage, energy-efficient applications, including water cooling and recirculation in the system.
Heat Sink Compound	A compound used to improve heat transfer from device components to heatsinks, optimizing performance and lifespan.
Wood	Plywood and timber are used for constructing test cells, with plywood forming the walls and timber used for durable legs.
Nails	1-inch and 2-inch nails are used to fasten wood and other components during construction.
Aluminium Sheet	Lightweight, corrosion-resistant aluminium panels used for roofing. Aluminium has a high strength-to-weight ratio, ideal for energy-efficient and durable roofing in industrial and residential settings.
Bucket	A plastic bucket is used as a water reservoir to collect and transport water within the system.
PVC Hard Pipe	Rigid PVC pipes used in plumbing and drainage systems are strong, durable, and corrosion-resistant. In this system, it is used to catch and drain water from the roof.
PVC Flexible Tube	A flexible plastic tube made from PVC is used to transport water from the bucket to the rooftop for spraying.
Control Panel	A panel housing the control components, including the motor, Peltier module, Arduino Uno, relay module, breadboard, and SMPS, is assembled for operational control of the system. Placed within a thermocol box for insulation and safety.

2.3. Model Fabrication

Figure 5 shows the CATIA model of the system, illustrating how a roof absorbs heat. The dimensions of the test cell are 32 cm in length, 32 cm in width, and 32 cm in height. The walls and floor are constructed from plywood, while the roof consists of aluminum sheets. The floor of the test cell is also made of plywood and raised approximately 80 cm off the ground.

This structure has no ceiling, and the roof slopes in a single direction. Openings on the right and left sides (north and south) of the cell measure 10 cm × 8 cm. The test house should be positioned outdoors, in the garden, to receive as much direct sunlight as possible during the morning or afternoon. Figure 6 illustrates the fabricated model.

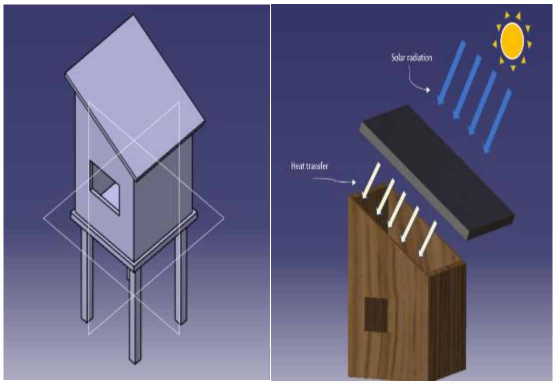

Fig. 5 CATIA model

Fig. 6 Front, side and isometric views of the fabricated model

A digital temperature sensor that detects temperature is used to evaluate the cooling system's effectiveness for the Peltier module. One sensor is applied as a reference temperature for incoming water, which must be at a higher temperature and is installed in the roof gutters that channel water after spraying. At the end of the pipe, a data logger is set up to monitor changes in the water temperature as it exits the cooling system.

A data logger is mounted to the interior of the aluminum roof to measure and record the temperature of the roof surface. A bucket containing water serves for cooling, with the suction pipe submerged. A 5-liter/minute DC pump circulates water from the tank. Water is poured into the distribution pipe, which sprays onto the roof's surface.

The design of the automatic roof spraying mechanism is divided into several subsystems, consisting of a controller, sensors, and actuators. Each component of the system requires a voltage source; the DHT11 and DS18B20 sensor probes need a supply voltage of 5V, while the Arduino UNO microcontroller and relay module require a supply voltage of 12V at an electrical current of 10A. The DS18B20 sensor probe records water and air temperatures, while the DHT11 sensor monitors the roof's surface temperature. These sensors are easy to integrate with an Arduino microcontroller, providing consistent and accurate readings for effective temperature monitoring.

If the roof surface temperature exceeds the specified limit, the Arduino activates the relay and the DC pump, spraying water on the roof. The device is set as a temperature limit parameter at a specific roof surface temperature. Likewise, the controller disables the actuator if the roof temperature is lower than or equal to the specified degree.

3. Results and Discussion

The developed automatic rooftop cooling system underwent several runs during the testing phase. The Arduino microcontroller analyzed data from the DHT11 sensor, accurately monitoring temperature changes. When the temperature exceeded the predetermined threshold, the Arduino activated the pumping motor, initiating the cooling process. Figure 7 illustrates the experimental setup.

Fig. 7 Experimental setup

The efficient heat transfers of water resulted in a gradual decrease in the rooftop surface temperature. Once the temperature fell below the predetermined threshold, the Arduino deactivated the pumping motor, which was continuously monitored by the DHT11 sensor. The Peltier module cooled the water at this point, enhancing the overall cooling effect. Table 2 presents the experimental data.

Table 2. Experimental data

Sl. No.	Time	Humidity [g/m^3]	Temperature [°C]
1	07:03:25 AM	54	28
2	07:03:27 AM	54	28
3	07:03:29 AM	54	29
4	07:03:31 AM	55	29
5	07:03:33 AM	55	29
6	07:03:35 AM	55	29
7	07:03:37 AM	55	29
8	07:03:39 AM	55	29
9	07:03:41 AM	55	30
10	07:03:43 AM	56	30

11	07:03:45 AM	56	30
12	07:03:47 AM	56	30
13	07:03:49 AM	56	30
14	07:03:51 AM	56	30
15	07:03:53 AM	56	30
16	07:03:55 AM	56	30
17	07:03:57 AM	56	30
18	07:03:59 AM	56	30
19	07:04:01 AM	57	30
20	07:04:01 AM	57	30
21	07:04:03 AM	57	30
22	07:04:05 AM	57	30
23	07:04:07 AM	57	30
24	07:04:09 AM	57	30
25	07:04:11 AM	57	30
26	07:04:13 AM	57	30
27	07:04:15 AM	57	30
28	07:04:17 AM	58	29
29	07:04:19 AM	58	29
30	07:04:21 AM	58	29
31	07:04:23 AM	58	29
32	07:04:25 AM	59	29
33	07:04:27 AM	59	29
34	07:04:29 AM	59	29
35	07:04:31 AM	59	29
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37	07:04:35 AM	59	29
38	07:04:37 AM	59	29
39	07:04:39 AM	59	29
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41	07:04:43 AM	59	29
42	07:04:45 AM	60	29
43	07:04:47 AM	60	29
44	07:04:49 AM	60	29
45	07:04:51 AM	60	29
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53	07:05:03 AM	61	29
54	07:05:05 AM	61	29
55	07:05:07 AM	61	29
56	07:05:09 AM	61	29
57	07:05:11 AM	61	29
58	07:05:13 AM	61	28
59	07:05:15 AM	61	28
60	07:05:17 AM	61	28

Table 3. Calculated data

Conductivity [W/mK]	Area [m2]	Thickness [m]	Temperature difference [^{0}C]	Heat conduction [W]
180	0.1216	0.001	30 – 29 = 1	0.02188
180	0.1216	0.001	29 – 28 = 1	0.02188
180	0.1216	0.001	28 – 29 = –1	– 0.02188
180	0.1216	0.001	29 – 30 = –1	– 0.02188

3.1. Heat Conductive Rate

Using the formula Q = (k * A * ΔT) / d, the rate of heat conduction was calculated. Here, Q is the heat conduction rate (in W). The roofing material's thermal conductivity is k (in W/mK). A is the roof's surface area (in m2). T is the difference in temperature (in °C) between the outside and the roof. The roof's thickness is d (in m). The heat conductivity rate was determined by measuring the roof's surface temperature before and after cooling, taking into account the known values of k and d for the aluminium roof. Table 3 has the calculated data.

3.2. Water Flow through Pipe

The cooling efficiency of the system is significantly influenced by the flow rate of water through the pipe, as it determines how quickly water is distributed across the rooftop. This flow rate can be calculated based on the pipe's diameter, pressure, and other hydraulic factors or measured directly with a flow meter. Figure 8 shows the arrangement.

Fig. 8 Water flowing through the pipe

3.3. Observations

The automatic rooftop cooling system demonstrated promising results in reducing surface temperature. The heat from the roof was effectively dissipated through conduction between the aluminum roof and the water. Since water has a higher thermal conductivity than air, applying water to the rooftop enhances heat transfer. An integrated temperature sensor and Arduino microcontroller enabled real-time monitoring and control of the cooling process. The cooling mechanism was activated as needed and deactivated once the temperature reached the desired limit, demonstrating the system's responsive nature to temperature changes. As shown in Table 2, results indicated that the automatic rooftop cooling system could lower the surface temperature by approximately 1°C every 1.5 minutes. It is important to note that the cooling rate may vary based on factors such as ambient temperature, humidity, and solar radiation. The Peltier module setup, which cooled the water, further improved cooling efficiency by maintaining a lower water temperature and providing a consistent cooling effect on the rooftop surface.

To understand the heat conduction rate through the roof, the efficiency of the conduction process was assessed by calculating the heat conduction rate. Increased heat conduction meant efficient heat transfer from the roof surface to the water. To validate the mechanism of the cooling system, the calculated numerical results were compared with the theoretical data. Figure 9 shows a comparison of experimental temperature data and ANSYS simulation results. The graph includes 38 data points tracking time, ANSYS temperature, and experimental temperature. Initially, both stayed steady at 27°C and 30°C. Over time, the ANSYS temperature remained about 1°C lower than the experimental value. The experimental temperature stayed mostly at 30°C, except for a drop to 28°C at the end, while the ANSYS temperature slowly fell from 27°C to 23°C. These differences could be due to minor errors, simulation assumptions, or variations in material properties. Despite the 1°C difference, the ANSYS results closely match the experimental data. The steady temperatures suggest that the system's thermal behavior was well predicted.

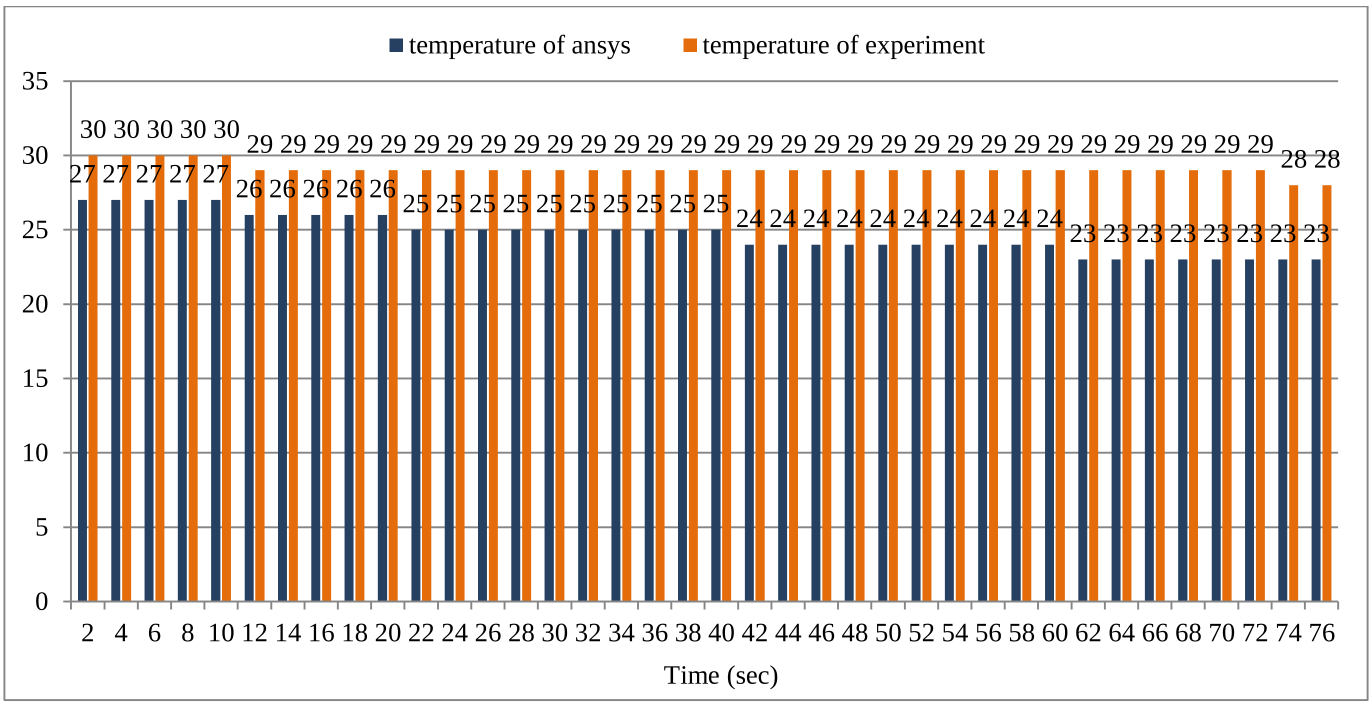

Fig. 9 Theoretical temperature vs experimental temperature

4. Conclusion

This work developed an automatic rooftop cooling system proposed to be installed in buildings in urban settings under the framework of smart city infrastructure. The system uses water spray and evaporation techniques to lower the rooftop temperatures, which in turn reduces the indoor room temperature. The units of this mechanism have Arduino microcontrollers, temperature sensors, and water-cooling Peltier modules, which continuously monitor the conditions and adjust temperature as needed. This makes this system both efficient and responsive. The proposed model was simulated in ANSYS, and the results were obtained. Experimental tests of this study showed that this cooling method could lower rooftop temperature by about 1°C every 1.5 minutes. This result is in close proximity with the simulated results, validating the method. Optimizing factors like heat conduction rates and water flow efficiency could further enhance the performance. As more and more cities are growing and urban living is increasing, solutions like this may be a way to forego the excessive use of power-consuming air-conditioners. This study adds to the possible inputs needed in smart city infrastructural projects and the body of literature in the context of urban sustainability. Future research can focus on optimizing water usage, potentially through recycling techniques or non-drinkable water. Integrating add-on renewable energy technologies, such as hybrid solar-thermal systems or automated control mechanisms, could further enhance efficiency. However, limitations such as consistent water availability needs, system maintenance requirements, and varying climatic conditions across regions need to be carefully considered before broader implementation.

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