Experimental Study and Engineering Validation of Fountain Cooling Using Biomimetic Nozzle Arrangement

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Abstract: This paper proposes a biomimetic nozzle arrangement strategy and an integrated approach of experimental investigation and engineering validation to evaluate a model of heat and mass transfer for water columns previously proposed. A 50.24 m², circular dry fountain was tested for the cooling effect under the typical summer weather conditions in Zhangjiakou. The average temperature difference of the cooling water measured was 3.95 °C and the predicted value of the model was 4.2 °C, with a relative error of only 6.3 %. Based on these findings, the model was then implemented on a large-scale rectangular dry fountain with an area of 850.5 m² having 180 nozzles and the nozzles were arranged according to the Fibonacci sequence. The heat dissipation capacity of the system was calculated to be 3,218.76 kW with the cooling water temperature decreased by 4.5°C, which showed a great cooling effect from 32 °C to 26 °C when the system was operationally deployed. These results validate the model's performance and applicability to laboratory experiments and large-scale engineering problems. Comparing the fountain system to traditional cooling towers, under the same thermal load conditions the fountain system has a lower cooling water flow rate. Moreover, both systems reduce cooling water temperatures by similar amounts at the same flow rate, suggesting a possibility of using a fountain condenser as an alternative or supplement to the traditional cooling tower.

Keywords: Fountain Cooling; Heat and Mass Transfer; Biomimetic Arrangement; Experimental Validation; Engineering Application.

1. Introduction

As part of our previous work [1], we had created an extensive macroscopic model which described the whole process of heat and mass transfer in one free falling water jet. Considering the Fibonacci spiral and the structure of the arrangement of tree canopies, we proposed a new biomimetic arrangement with 3D water columns. The present work is a basic work that has been done both theoretically and by using engineering cases to validate the feasibility of the model. But despite these positive results, there is still a lack of systematic experimental validation of the accuracy of the model. To bridge this gap, the present study is developed based on our previous research work which used an integrated approach combining experimental investigations with engineering validation for more rigorous verification [2,3].

2. Fountain Cooling Performance Experiment

2.1 Experimental Objectives

(1) To measure water inlet and outlet temperature of the fountain when it is in operation, outdoor environmental parameters, calculate the heat dissipation and cooling effect of the fountain; (2) To input the measured data into the established mathematical model of heat and mass transfer of water column [1] and do the calculation to compare with the empirical results, so as to verify the accuracy and reliability of the mathematical model; (3) To compare the cooling performance of the fountain and the cooling tower under the same outdoor meteorological conditions, and evaluate the feasibility and practical applicability of the fountain as an air-conditioning cooling apparatus.

2.2 Experimental Setup

The experimental platform, which is called “Renewable Energy Thermal (Cooling) Storage and Heating (Cooling) Engineering and Landscape Integration Compatibility Test System”, is located on the west side of the logistics building at a University in Zhangjiakou. The cooling area in the logistics building includes a four-story office space of about 1000 m² with a cooling load density of 85 W/m², resulting in a summer air-conditioning cooling load of 85 kW. The fountain used is a dry-type circular fountain with a diameter of 8 m, area of 50.24 m² and flow rate equal to 54.42 m³/h. It is located in an open area and has excellent heat-dissipating conditions. This fountain's nozzle configuration is biomimetically designed after the Fibonacci spiral and the arboreal canopy, and features 32 nozzles configured in the Fibonacci spiral intersection distribution on the horizontal plane [4]. In the vertical direction, the nozzles are set in a gradient, with the nozzle in the center being higher than the nozzles on the outside, and the height of the nozzle in the center is 3 m, the opening angle of the nozzle is 60° and the canopy is formed. This system can be used as a campus landscape feature and as an auxiliary cooling system for central air-conditioning water systems.

2.2.1 Cooling system

(1) Air Conditioning Unit: Heating capacity of 95 kW and cooling capacity of 90 kW. (2) Settling Tank: Size 1 m × 2 m × 2 m, it is used to let the sediments in the return water settle, to prevent the impurities from harming the pump. Also, the cooling water circulates freely in the tank by gravitational head difference, after which the water pump recirculates it to the air conditioning unit for a closed circuit system. (3) Water Pump: Pump to draw water from the fountain, flow rate 65 m³/h, head 20 m, rated power 4.3 kW. (4) Cooling Tower: 24 m³/h circular counter flow cooling tower. (5) Piping: The pipes in the machinery room are made of seamless steel pipe, while the pipes in the fountain are made of PE pipe hot melt fittings. Nozzles: The nozzles are installed locally on locally installed blind flanges with apertures that can be adjusted as necessary. Figure 1 shows a sectional view of a nozzle.

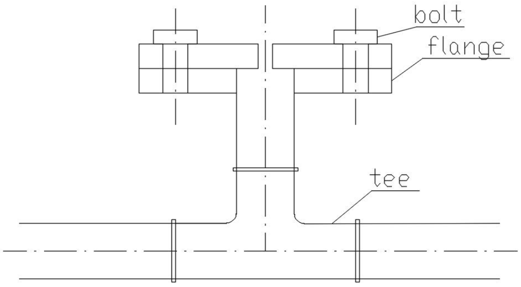

Figure 1. Sectional View of a Nozzle

2.2.2 Operating modes

(1) The fountain serves solely as a water feature without passing through the machine room. Pump No. 1 is activated, and valves F2, F3, F7, and F9 are opened. (2) The fountain functions both as a water feature and a cooling device. Part of the cooling water enters the machine room for cooling, while the remainder bypasses the machine room, returning directly to the fountain for circulation. Pump No. 1 is activated, and valves F1, F2, F3, F4, and F9 are opened. (3) The fountain is turned off, and cooling demand is met exclusively by the cooling tower. Pump No. 1 is activated, and valves F1, F4, F5, F6, and F8 are opened. The flowchart of the fountain system is illustrated in Figure 2.

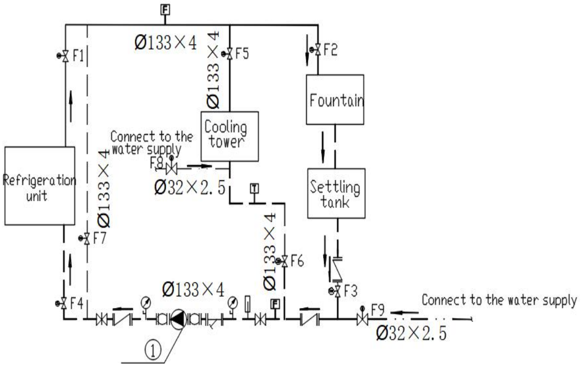

Figure 2. Flowchart of the Fountain System

Note: ① is the supply pump shared by the fountain and the cooling tower.

2.2.3 Experimental apparatus

(1) Platinum resistance temperature sensors (PT100) with a range from -50°C to 200°C and an accuracy of class A (±0.15°C) were used as temperature measurement devices and these were installed at the main supply and return pipes of both the condenser and evaporator. The control cabinet [2] was used to collect the outdoor air dry-bulb temperature data. Temperature sensors were all connected to the control cabinet data acquisition system. (2) Flow Measurement Devices: An electromagnetic flowmeter was placed on the cooling water supply main pipe in the system to measure the instantaneous water flow rate. The flowmeter

possesses an accuracy of ±0.5%, a measurement range of 0-100m³/h and the signals are integrated in the data acquisition system of the control cabinet. (3) Environmental Parameter Measurement Devices: Temperature and Humidity: Sensors were set up indoors in the control cabinet to take automatic readings of the temperature and humidity of the outdoor air. The temperature range measured was -40°C to 60°C with an accuracy of ±0.3°C and the range of measurements for the relative humidity was 0-100%RH with an accuracy of ±3%RH. Wind Speed: Wind speed data were taken from Sunshine Meteorological Observation Station on the south side of the logistics building. The mean wind speed during the experimental days was 2 m/s and the wind direction was mostly from the southeast. The observation station is located about 10 m away from the test area, the data of which can reliably represent the wind conditions around the test area.

(4)Data Acquisition System

Figure 3. Control Cabinet Data Acquisition System

The data acquisition system (see Figure 3) is built into the control cabinet of the fountain, allowing real-time monitoring and display of the fountain system supply and return water temperature, system water pressure and outdoor temperature. Historical data can be stored and data exported for further analysis.

The data acquisition system has been integrated into the controller of the air-conditioning unit, which allows the operating parameters of the unit, such as the inlet and outlet water temperatures of condenser and evaporator and the power consumption of the unit to be monitored and displayed in real-time. This system also has data storage with export of operational data. The unit's data acquisition interface is shown in Figure 4.

Figure 4. Air Conditioning Unit Data Acquisition System

2.3 Experimental Principles and Methods

2.3.1 Experimental principles

During the fountain cooling process, the water columns engage in direct contact with the surrounding air, facilitating both sensible and latent heat exchanges [5]. These two mechanisms conjointly contribute to the reduction of the cooling water temperature [3]. Under steady-state operation, by measuring the inlet and outlet water temperatures of the fountain as well as the cooling water flow rate, the actual heat dissipation of the fountain can be calculated as follows [6]:

$$Q_F=\frac{G_F \triangle T}{0.86} \tag{1}$$

Where,

Q_F— heat dissipation of the fountain, kW;

G_F— flow rate of the fountain water, m³/h;

$\triangle T$— temperature drop, °C.

By substituting the experimentally obtained environmental parameters (air temperature, relative humidity, wind speed) and fountain design parameters (nozzle diameters, spray height) into the mathematical model of heat and mass transfer for the water columns [1], the theoretical temperature drop T_{T} of the fountain system under corresponding operating conditions is computed. Comparing the theoretical calculation with the experimentally measured temperature drop T_{T}, the relative error is determined to validate the accuracy of the mathematical model, as defined by:

$$\delta=\frac{|T_{\mathrm{T}}-T_{\mathrm{A}}|}{T_{\mathrm{A}}}\times 100\% \tag{2}$$

Where,

δ— relative error;

T_{T} — theoretical temperature drop of the fountain, °C;

T_{A} — experimentally measured actual temperature drop of the fountain, °C.

2.3.2 Experimental Procedure

(1) Prior to the experiment, it is essential to confirm that all instruments are functioning correctly and that the system valves are set appropriately, ensuring the correct switching for each operational mode. (2) The experiment was conducted during clear weather with relatively steady wind direction. Valves were opened according to Mode One, and supply pump ① was activated to enable the independent operation of the fountain system. After the system had been stabilized, cooling water inlet and outlet temperatures, outdoor air temperature and humidity were measured and recorded continuously during the entire process. When complete, valves were set back to their original positions and supply pump ① was stopped. (3) Under the same outdoor environmental conditions, the cooling tower experiment was performed. Valves were adjusted according to Mode Three, and supply pump ① was started. After the system stabilized, continuous observation and recording of the cooling tower's inlet and outlet temperatures and ambient parameters proceeded during the entire operation. Following the experiment, supply pump ① was turned off, and the valves were restored to their original configuration.

2.4 Results Analysis

2.4.1 Experimental data compilation

The test was performed on a normal summer day in Zhangjiakou, the outdoor temperature kept stable at 31°C-32°C, the relative humidity kept stable at about 50%, and the average wind speed was 2.0 m/s, which were favorable weather conditions. Once the system was in steady operation, the operational data were collected from both the cooling tower and the fountain as presented in Tables 1 and 2.

Table 1. Operational Parameters of the Cooling Tower

No.	Condenser Outlet Water Temperature (°C)	Condenser Inlet Water Temperature (°C)	Outdoor Temperature (°C)	Temperature Difference (°C)
1	38.7	34.3	31.72	4.4
2	38.6	34.3	31.71	4.3
3	38.5	34.2	31.70	4.3
4	38.4	34.2	31.74	4.2
5	38.4	34.2	31.73	4.2
6	38.3	34.2	31.71	4.1
7	38.2	34.2	31.74	4.0
8	38.1	34.2	31.70	3.9
9	37.9	34.1	31.70	3.8
10	37.7	34.1	31.69	3.6
11	37.6	33.9	31.68	3.7
12	37.4	33.9	31.71	3.5
13	37.3	33.8	31.74	3.5
14	37.0	33.5	31.73	3.5
15	36.9	33.5	31.75	3.4

The condenser outlet water temperature was between 36.9°C and 38.7°C and the inlet water temperature was between 33.5°C and 34.3°C, the variation in water temperature was between 3.4°C and 4.4°C with an average temperature drop of 3.89°C. These data show that the condenser outlet water temperature (cooling tower inlet water temperature) was consistently lowered by about 4°C by the cooling tower.

With the flow of water in the cooling tower being 24 m³/h, the heat dissipation capacity of the cooling tower was calculated by using Equation (1):

$$Q_C=\frac{G_C\triangle T}{0.86}=\frac{24\times3.89}{0.86}=108.56\text{kW} \qquad (3)$$

Where,

Q_C — total heat dissipation of the cooling tower (kW),

G_C —total flow rate (m³/h);

$\triangle T$ — temperature drop (°C).

This heat removal ability meets the cooling requirement of the logistics building's air-conditioning system, so the normal operation of the system can be guaranteed.

The average reduction in temperature was 3.95°C for the fountain (with condenser outlet temperature ranging from 33.2 to 36.5°C, inlet from 29.9 to 31.8°C, and a temperature difference range of 3.3 to 4.7°C), while the cooling tower had a slightly lower average reduction, with the fountain having a larger range of temperature fluctuation.

Table 2. Operational Parameters of the Fountain

No.	Condenser Outlet Water Temperature (°C)	Condenser Inlet Water Temperature (°C)	Outdoor Temperature (°C)	Temperature Difference (°C)
1	36.5	31.8	31.87	4.7
2	36.3	31.7	31.86	4.6
3	36.1	31.7	31.87	4.4
4	35.9	31.6	31.89	4.3
5	35.7	31.5	31.92	4.2
6	35.5	31.4	31.95	4.1
7	35.3	31.3	31.93	4.0
8	35.0	31.2	31.94	3.8
9	34.9	31.0	31.92	3.9
10	34.4	30.8	31.95	3.6
11	34.2	30.6	31.92	3.6
12	34.1	30.5	31.94	3.6
13	33.9	30.4	31.95	3.5
14	33.6	30.0	31.92	3.6
15	33.2	29.9	31.93	3.3

The heat dissipation capacity during the operating time of the fountain was determined by Equation (1), according to the flow rate of the fountain of 54.42 m³/h:

$$Q_{\mathrm{F}}=\frac{G_{\mathrm{F}}\triangle T}{0.86}=\frac{54.42\times 3.95}{0.86}=249.95\mathrm{kW} \tag{4}$$

This heat dissipation is enough to satisfy the cooling demand of the air-conditioning unit of the logistics building, and thus, to let the building operate normally.

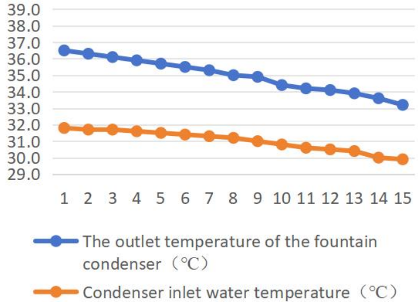

Figure 5. Fountain Operational Parameters

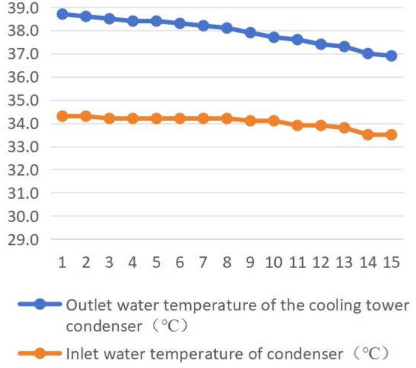

Figure 6. Cooling Tower Operational Parameters

Comparative study of figures 5 and 6 shows: (1) Both cooling tower and fountain condenser show a decreasing trend in condenser inlet/outlet water temperatures during run time and the difference in these water temperatures is on the range of 4°C to 5°C. The cooling tower had a relatively low rate of change as the outlet water had decreased from about 38.7°C to 36.9°C and the inlet water had decreased from 34.3°C to 33.5°C, showing minimum variation in the operation of the cooling tower. On the other hand, the outlet water temperature of the fountain system decreased from 36.5°C to 33.2°C and the inlet water temperature decreased from 31.8°C to 29.9°C showing a higher rate and higher degree of cooling than the cooling tower, which is an evidence of better cooling efficiency. The average difference in temperature of the fountain system is 3.95°C which is similar to that of the cooling tower which is 3.89°C, indicating that the fountain system can cool as much as the cooling tower and a little bit more. Interestingly, the fountain was able to achieve a maximum temperature drop of 4.7°C during its operation compared to a maximum temperature drop of 4.4°C recorded by the cooling tower, suggesting that the fountain could be used for better cooling performance under certain operating conditions or initial start-up.

The experimental results have proved that the fountain condenser is close to the cooling tower in capacity, and has advantages in reducing the cooling water temperature. Hence, it is concluded that in this experiment the feasibility and efficacy of the fountain as a viable cooling device has been confirmed.

2.4.2 Comparison between fountain and cooling tower under equal load

With this cooling tower load of 108.56 kW, the cooling water flow rates are compared for both the fountain operating at the same load and the cooling tower operating at the same load. The flow rate of the cooling tower is known to be 24 m³/h and the flow rate of cooling water in the fountain can be calculated as follows:

$$G_F=\frac{0.86Q_F}{\triangle T}=\frac{0.86\times108.56}{3.95}=23.63\text{m}^3/\text{h} \quad (5)$$

Given the same cooling load, the required water flow rate for the fountain is 23.63 m³/h, which is slightly lower than the water flow rate for the cooling tower (24 m³/h), which means that the fountain system, in comparison with the traditional cooling tower, has a small but significant water-saving benefit.

2.4.3 Theoretical calculation of the fountain

Based on the theoretical calculation shown in reference [1], the flow rate for the fountain is 54.42 m³/h and the total heat dissipation capacity is 269.41 kW. The heat dissipated from the continuous jet segment is 48.68 kW, which is about 18% of total heat dissipated, and the fragmented droplet cluster after jet breakup dissipates 220.73 kW, which is about 82% of the total. This collection of droplets after breakup is the major factor responsible for the fountain's heat dissipation [7]. Calculations of the heat dissipation of the fountain are sufficient for the cooling needs of the air conditioning system in the logistics building. During typical summer operating conditions, the cooling tower typically will produce a temperature drop of 4-5°C, cooling the water from the air-conditioning unit from around 37°C to 32-33°C as required by the heat rejection requirement of the air-conditioning unit. The fountain system theoretical prediction is a temperature drop of 4.2°C, which takes the temperature of the cooling water from 37°C to 32.8°C. This cooling temperature decrease is also within the engineering-acceptable range of 4-5°C, which shows the stable and effective cooling performance. Furthermore, the biomimetic nozzle design of the fountain promotes the uniform distribution of water columns in space, thereby avoiding concentrated hot spots and heat and moisture accumulation, and thus improving heat dissipation efficiency.

2.4.4 Comparison between theoretical and experimental results

The relative error between calculated data and measured data is:

$$\delta=\frac{|T_T-T_A|}{T_A}\times100\%$$
$$=\frac{|4.2-3.95|}{3.95}\times100\%=6.3\% \quad (6)$$

The relative error was 6.3%, which is within the engineering tolerances. This result shows that the mathematical model [1] built is able to predict the actual cooling performance of the fountain, proving the validity of the mathematical model. The theoretical temperature drop obtained (4.2°C) is similar to the actual average temperature drop obtained by the cooling tower (3.89°C) and both are within the range of temperature drop achieved by cooling tower (4-5°C), further confirming that fountains can be considered as air-conditioning cooling devices.

The discrepancy is caused by a number of factors: firstly, the deviations caused by the major assumptions in the model, for example linear changes of diameter and temperature along the jet trajectory; secondly, the uncertainties of the measurement instruments; thirdly, the empirical uncertainty associated with the criteria for jet breakup and the droplet size distribution model; and fourthly, the transient change of the environmental conditions during the experiment compared to those that are fixed in the model. This error margin is considered acceptable when taken together as a whole in an engineering environment and therefore validates the accuracy and usefulness of the model used here.

2.4.5 Comparison of theoretical fountain calculations and cooling tower at the same flow rate

This project has site restrictions, so the entire fountain flow rate is quite large compared to the cooling tower's flow rate. Nineteen nozzles were chosen outward from the fountain's central nozzle (nozzle parameters are given for each nozzle in the reference [1]) to simulate the flow rate of the fountain to be as close to the flow rate of the cooling tower as possible, disregarding the practical limits of the fountain's footprint. These nineteen nozzles have a combined flow rate of 25.43 m³/h which is similar to the cooling tower's flow rate of 24 m³/h, allowing a direct comparison. The total heat dissipation of this nozzle subset is 148.95 kW, of which the heat dissipated in the continuous jet segment is 10.72 kW, which represents 7% of the total heat dissipation, and of which the heat dissipated in the jet breakup segment is 138.23 kW, which represents 93% of the total heat dissipation. This distribution of heat dissipation strongly shows the improvement in heat exchange efficiency due to the greater area of contact with the air, which is created by the droplet formation after the jet breakup.

The temperature difference ΔT of the fountain is given by:

$$\triangle T = 0.86\frac{Q}{G} = 0.86 \times \frac{148.95}{25.43} = 5.0^{\circ}\mathrm{C} \quad (7)$$

The temperature drop in the fountain is 5 °C, which is higher than that of the logistics building's cooling tower which is 3.89°C under the same cooling water flow rate. This difference is due to the fact that the nozzles selected are mostly located along the center line of the fountain where smaller nozzle diameters result in lower breakup heights and consequently more heat is dissipated than the water columns located in the periphery of the fountain where there is no breakup. However, this theoretical outcome is still in the range of the temperature drop that is possible in a cooling tower, which verifies that fountains have the same cooling efficiency as cooling towers when dealing with the same amount of cooling water [8].

2.5 Actual Operational Performance of the Fountain

The system has significantly improved the thermal conditions within the logistics building since it was commissioned. The top floor – the fourth floor – is the hottest in the summer with full sun. Following activation, the stable indoor temperatures of 26-27°C have been obtained on the fourth floor which has significantly enhanced the comfort level of the office space. At the same time, the aesthetic value of the fountain has been fully realized as the water columns during the fountain's operation have a harmonious and graceful arrangement, and a large number of faculty and students stay near the fountain to enjoy and take time off. Because of the multiple operational modes in the design, the system has been given the ability to be flexibly scheduled: the fountain serves in the day time to provide both cooling and landscape purposes, and then the conventional cooling tower provides night time cooling. The engineering implementation has shown that the model was strong and stable and the engineering implementation results have met the engineering design goals and further proved the applicability of the model in engineering applications. The fountain installation on the west side of the logistics building is shown in Figure 7.

Figure 7. Fountain Installation on the West Side of the Logistics Building

3. Engineering Application of the Fountain

The engineering project is named as "Spray-Type Heating (Cooling) Characteristic Experiment and Cooling Water Heating (Cooling) Project", the fountain is a dry-type rectangular fountain located on the east side of the west gate in a university in Zhangjiakou. The fountain is split into two parts, an eastern and a western part, separated by a square ornamental pool of 16.2 × 16.2 m (in which the cooling water does not flow). The fountain on the east side is 33.4 m long and 12.6 m wide, covering an area of 420.84 m². The fountain on the west side is 34.1 m long, 12.6 m wide, and covers an area of 429.66 m². The main goal of this project is to decrease the central air-conditioning cooling water temperature for four academic buildings on the campus including Mechanical Building, Civil Engineering Building, Electrical Engineering Building, and Information Engineering Building. Water loop of the central air-conditioning system is the cooling water source. These four teaching buildings have a total area of 9, 250 m² and a cooling load index of 80 W/m², which leads to a total cooling demand of 740 kW.

3.1 Operating Modes of the Fountain System

The fountain system can be operated in 4 different modes: (1) The fountain is used only as a decorative water feature and not circulated through the machine room. Pumps numbered 2, 3, 4, 5, and 6 operate concurrently, while valves F1, F2, F3, F5, F6, F7, F12, F14, and F15 are opened. (2) The fountain is used as both a landscape water feature and a cooling device. In this mode, a portion of the cooling water flows into the machine room for refrigeration purposes, while the remainder bypasses the machine room and returns directly to the fountain to participate in the circulation. Pumps 1, 3, 5, and 6 operate simultaneously, with valves F1, F2, F3, F4, F6, F8, F11, F13, F14, and F15 opened. (3) When fountain operation is required solely to meet the refrigeration demands of the machine room, pumps 2, 3, 4, and 5 are turned off, leaving pumps 1 and 6 in operation. Valves F1, F3, F4, F8, F11, F13, F14, and F15 are opened accordingly. (4) When the fountain is not activated, cooling needs are satisfied exclusively by the cooling tower. In this setting, pumps 2, 3, 4, 5, and 6 are deactivated, with only pump 1 running. Valves F4, F9, F10, and F11 remain open.

The schematic flow diagram of the fountain system is depicted in Figure 8:

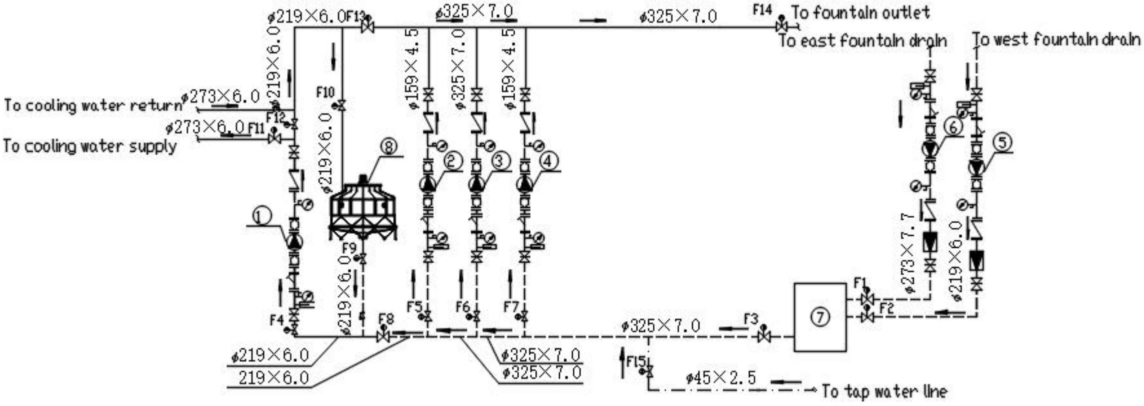

Figure 8. Fountain System Flow Diagram

Legend in the diagram: ① Cooling tower water supply pump;②, ③, ④ Fountain water supply pumps; ⑤, ⑥ Fountain return water pumps; ⑦ Settling water tank; ⑧ Cooling tower.

3.2 Equipment and Specifications

(1) Heat Pump Unit: Heating capacity of 975 kW and cooling capacity of 740 kW. (2) Settling Water Tank: Stainless steel tank with dimensions 4 m × 4 m × 3 m. (3) Pumps: Cooling tower supply pump (①): Flow rate of 185 m^3/h, head of 35 m, rated power 24.6 kW; Fountain supply pump (②): Flow rate 106 m^3/h, head 25 m, rated power 10.3 kW; Fountain supply pump (③): Flow rate 475 m^3/h, head 25 m, rated power 40 kW; Fountain supply pump (④): Flow rate 74 m^3/h, Head 25 m, Rated power 7.2 kW; Fountain return pumps (⑤ and ⑥): Flow rate 340 m^3/h, Head 20.4 m, Rated Power 24 kW each. This is because the topographical differences in elevation prevent the water from flowing back into the settling tank, so it must be pumped to circulate. (4) Cooling Tower: Cross flow type cooling tower with 153 m^3/h cooling capacity. (5) Piping: Seamless steel pipes are used for all pipes in the pump room, while the fountain supply and return pipelines are made of PE pipes, which are connected by hot-melt fusion. (6) Nozzles: All nozzles are made of brass and have straight-flow designs.

3.3 Biomimetic Arrangement Design of the Fountain

The fountain layout is conceived based on a biomimetic model inspired by the golden spiral and the morphological structure of arboreal canopies [9,10]. The eastern fountain measures 33.4 m in length and 12.6 m in width, covering an area of 420.84 m^2, while the western fountain spans 34.1 m by 12.6 m, encompassing 429.66 m^2. The spiral parameters are set as clockwise spiral number β=3 and counterclockwise spiral number γ=5. The central jet height is H_0=6 m, with the fountain canopy opening angle chosen as θ_p=60°.

For engineering purposes, each fountain area to the east and west is subdivided into two equal rectangular areas and then a single spiral is located centrally in each rectangle, making four spiral units in all across the entire fountain plane. Centers of the spirals are the geometric centers of their rectangles. The smallest nozzle diameter at the centre is 4 mm and the largest nozzles on the periphery are 15 mm to assure manufacturability, ease of operation and maintenance. There are a total of 45 nozzles per spiral and 180 nozzles in the fountain system. Some of the nozzle coordinates, the jet height *H*, the flow rate *G*, the nozzle diameter *D* and the velocity *U* at each nozzle are summarized in part in Table 3.

Table 3. Nozzle Parameters

No.	ω	i (Counter)	j (Clockwise)	Polar Radius R (m)	Polar Angle ξ (°)	Jet Height H (m)	Flow Rate G (m^3/h)	Nozzle Diameter D(mm)
1	0	0	0	0.5	0	5.5	0.47	4
2	0	1	0	0.41	324	5.6	0.47	4
3	0	2	0	0.34	288	5.6	0.47	4
4	0	3	0	0.28	252	5.6	0.48	4
5	0	3	1	0.2	192	5.7	0.48	4
6	0	4	2	0.12	96	5.7	0.48	4
7	1	0	0	1.31	180	5.0	2.28	9
8	1	0	1	0.95	120	5.3	1.41	7
9	1	1	0	1.08	144	5.2	1.82	8
10	1	1	2	0.57	24	5.5	0.47	4
11	1	2	1	0.65	48	5.4	0.73	5
12	1	3	0	0.73	72	5.4	0.73	5
13	2	0	0	3.43	360	3.8	5.51	15
14	2	0	1	2.49	300	4.4	5.88	15
15	2	0	2	1.8	240	4.8	4.61	13
16	2	1	0	2.83	324	4.2	5.75	15
17	2	1	1	2.05	264	4.6	6.05	15
18	2	1	2	1.49	204	4.9	3.37	11
19	2	2	0	2.33	288	4.5	5.94	15
20	2	2	1	1.69	228	4.8	3.96	12
21	2	2	2	1.23	168	5.1	2.29	9
22	2	3	0	1.92	252	4.7	5.31	14
23	2	3	1	1.4	192	5.0	2.80	10
24	2	3	2	1.01	132	5.2	1.40	7
25	2	4	0	1.59	216	4.9	3.98	12
26	2	4	1	1.15	156	5.1	1.82	8
27	2	4	2	0.84	96	5.3	1.04	6
28	3	0	1	6.51	120	2.0	4.02	15
29	3	0	2	4.72	60	3.1	4.94	15
30	3	1	0	7.4	144	1.5	3.48	15
31	3	1	1	5.37	84	2.7	4.63	15
32	3	1	2	3.9	24	3.6	5.31	15
33	3	2	0	6.1	108	2.3	4.25	15
34	3	2	1	4.43	48	3.2	5.07	15
35	3	2	2	3.21	348	3.9	5.59	15
36	3	3	0	5.04	72	2.9	4.79	15
37	3	3	1	3.65	12	3.7	5.41	15
38	3	3	2	2.65	312	4.3	5.82	15
39	3	4	0	4.15	36	3.4	5.19	15
40	3	4	1	3.01	336	4.1	5.56	15
41	3	4	2	2.19	276	4.5	6.00	15
42	4	2	2	8.41	168	0.9	2.73	15
43	4	3	2	6.94	132	1.8	3.77	15
44	4	4	1	7.89	156	1.2	3.14	15
45	4	4	2	5.73	96	2.5	4.45	15
Total							154.26	

According to calculations, each individual spiral achieves a flow rate of 154.26 m^3/h, resulting in a total flow rate of 617.04 m^3/h for the complete fountain—comprising all four spirals. The schematic layout of the fountain's nozzle plane is illustrated in Figure 9.

3.4 Heat Dissipation Calculation and Result Analysis

Ambient parameters were selected based on typical summer conditions in Zhangjiakou: air temperature T_a =32.1℃, relative humidity 50%, and average wind speed U_w=2.1 m/s. The outlet temperature of the air conditioning cooling water is 37 ℃. These environmental conditions along with the biomimetic arrangement parameters were then put into the heat and mass transfer model of the free falling water jet [1] to calculate the heat dissipation of a single water column. The total heat dissipation of one spiral was then calculated by adding all the heat dissipations of jets in one spiral given in Table 4.

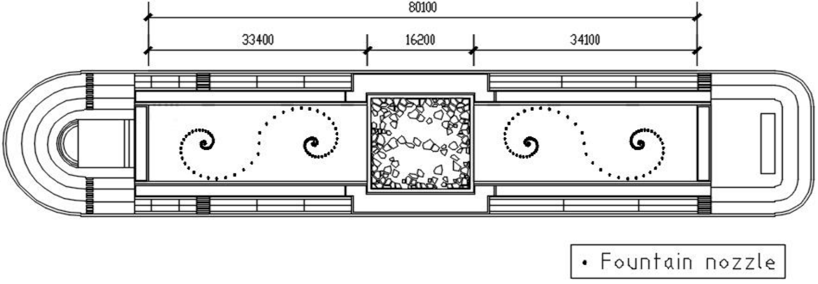

Figure 9. Schematic Diagram of the Fountain Nozzle Layout

Table 4. Heat Dissipation of a Single Spiral

No.	Breakup Height *h*(m)	Heat Dissipation in Continuous Jet Segment (kW)	Heat Dissipation in Jet Breakup Segment (kW)	Total Heat Dissipation (kW)
1	0.1	0.08	3.90	3.98
2	0.1	0.08	3.96	4.04
3	0.09	0.07	4.01	4.08
4	0.09	0.07	4.04	4.11
5	0.09	0.07	4.09	4.16
6	0.09	0.07	4.14	4.21
7	0.86	0.90	15.97	16.87
8	0.42	0.31	10.77	11.08
9	0.53	0.44	13.61	14.05
10	0.1	0.08	3.86	3.94
11	0.2	0.12	5.90	6.02
12	0.21	0.13	5.81	5.94
13	1.83	0.33	24.32	24.65
14	1.94	3.87	30.36	34.23
15	1.68	2.95	27.48	30.43
16	1.92	3.89	28.04	31.93
17	1.98	4.05	33.35	37.40
18	1.2	1.62	22.21	23.83
19	1.95	3.95	31.43	35.38
20	1.46	2.30	24.63	26.93
21	0.85	0.87	16.23	17.10
22	1.91	3.54	30.16	33.70
23	1.06	1.22	18.98	20.20
24	0.43	0.32	10.65	10.97
25	1.39	2.02	25.36	27.38
26	0.54	0.47	13.43	13.90
27	0.32	0.21	8.15	8.36
28	1.34	2.36	8.39	10.75
29	1.62	2.94	16.98	19.92
30	1.21	1.66	4.88	6.54
31	1.52	2.70	13.65	16.35
32	1.76	3.27	21.54	24.81
33	1.41	2.46	10.14	12.60
34	1.69	3.03	18.48	21.51
35	1.87	3.54	25.59	29.13
36	1.56	2.81	15.38	18.19
37	1.81	3.38	22.91	26.29
38	1.93	3.84	29.23	33.07
39	1.75	3.17	19.95	23.12
40	1.89	3.45	26.87	30.32
41	1.96	3.97	32.44	36.41
42	-	9.13	0.00	9.13
43	1.28	2.03	6.61	8.64
44	1.14	1.36	3.22	4.58
45	1.47	2.57	11.90	14.47
Total		91.7	712.99	804.69

Under typical summer conditions, the fountain system—comprising four spirals—operates with a total flow rate of 617.04 m³/h. A single spiral dissipates 804.69 kW of heat and the total heat dissipation of the whole fountain system is 3,218.76 kW. The dissipation of the continuous jet portion is 91.7kW or about 11% of the total dissipated heat, and the atomized droplets (spray) dissipate 712.99kW or about 89% of the total dissipated heat. The droplet cloud formed after breakup plays an important role in increasing the gas-liquid interface area, which is the major factor in the cooling performance of the fountain.

The temperature decrease $\triangle T$ of the cooling water in the fountain is:

$$\triangle T = 0.86\frac{Q_F}{G_F} = 0.86\times\frac{3218.76}{617.04} = 4.5^{\circ}\mathrm{C} \qquad (8)$$

A 4.5°C drop will cause the actual cooling water temperature to drop from 37°C to 32.5°C by 4 to 5°C which is well within the acceptable engineering parameters. This outcome implies that the fountain system can be used for cooling with a similar effect as the conventional cooling towers. Furthermore, the obtained heat dissipated data is able to satisfy the cooling requirement for four academic buildings, and also validates the mathematical model used in this study.

3.5 Comparative Analysis of Cooling Performance between Fountain and Cooling Tower

The flow rate of a single spiral fountain is 154.26 m³/h and the flow rate of the cooling tower is 153 m³/h, which are comparable for both systems. During the summer, the actual temperature drop of the cooling tower is 4-5°C, reducing the cooling water temperature from 37°C to about 32-33°C. The calculated temperature drop of the fountain at the same flow rate is 4.5°C, well within this range. The cooling effectiveness of the fountain and the cooling tower at the same flow rate, with the same order of magnitude, certifies the accuracy of the model and guarantees its applicability in the engineering projects of large-scale fountain.

3.6 Engineering Implementation Outcomes

The system has been quite stable since commissioning. It is consistently found that the fountain system has lowered the central air-conditioning cooling water temperature from 37℃ to less than 33℃ under typical summer day operating conditions, which is very close to the theoretical prediction. The total heat dissipation capacity of fountain system is 3,218.76 kW, which is enough to meet the thermal load requirement of four academic buildings. There has been a significant improvement in the indoor thermal environment of these buildings, where the room temperature has been reduced from 32°C to 26°C, which has resulted in a significant improvement in the occupants' thermal comfort. The incorporation of four operational modes into the design ensures flexible scheduling in different scenarios, further enhancing the system's adaptability and reliability. In addition to its impressive cooling effect, the fountain system has created an attractive visual effect; the water flow is evenly distributed and the fountain is very well presented making it a very striking landmark on campus. The fountain system is shown in the engineering project in Figure 10.

Figure 10. Engineering Application Image

4. Conclusions

(1) The result of the fountain cooling performance experiment showed the average measured temperature drop of 3.95℃, and the difference between the measured value and the value predicted by the model was only 6.3% (i.e., 4.2℃), demonstrating the accuracy of the heat and mass transfer model and the biomimetic arrangement strategy.

(2) The biomimetically designed system was applied to a large scale dry fountain project of 850.5 m² with 180 nozzles, the heat dissipation capacity of the system is 3,218.76 kW and the temperature drop is 4.5°C. The system was operated in the indoor environment, and the indoor temperature was reduced from 32°C to 26°C, which meets the cooling needs of a 9,250 m² building. This validates the applicability of the model in large scale engineering context.

(3) Comparative analysis with conventional cooling towers shows that fountains can provide

lower flow rates under the same thermal loads and, at the same flow rates, can provide the same amount of temperature reduction as conventional cooling towers. This highlights the potential for fountain condensers to be used to replace or supplement cooling towers in buildings to provide a new and inventive approach to designing energy-efficient cooling systems in public buildings.

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