Research on Evaporative Cooling of Liquid in Container

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Abstract. Cooling is a common phenomenon in daily life. Among different means of cooling, evaporative cooling through the evaporation of liquids is a prominent method, for it removes large quantities of heat. Our prompt is aimed at evaluating the impacts of different parameters on the speed of evaporative cooling. We evaluate the degree of impact by the means of experiment and simulation of experiments with finite element simulation software COMSOL, using containers of different shapes, different wind speeds, and controlling the existence of evaporation. Research shows that the speed of evaporative cooling is mainly determined by the difference in the amount of evaporation, followed by the geometric shape category of the upper surface of the container. Simply changing the proportion of the upper surface of the container does not pose a large impact on the speed of evaporative cooling due to the impact from turbulence around the container and the conductive heat transfer of the container itself. In the process of the research, the experiment and simulation results achieve a high degree of agreement, confirming the accuracy of the simulation.

1. Introduction

Evaporative cooling has many real-life applications, including the natural drying of clothes and cooling of food. Be it cooling of hot food, cooling of residence during summer, or cooling steam or chemicals in industrial applications, the speed of cooling is placed at a high priority. In VEX and FIRST Robotics Competitions, motor overheating often occurs, forcing the electric motor into protective mode and depriving its power. Solutions include natural cooling or applying alcohol on the outer shell, as wind cooling has suboptimal effects. This in turn means the robot cannot operate for prolonged periods, decreasing efficiency while practicing and posing unnecessary safety risks for maintenance groups. The perplexity is that ordinary cups and complicated car engines are both highly effective at radiating heat, but why the robot motor is not?

Figure 1. Motor on a FIRST Robotics Competition robot.
The Mercedes-AMG PETRONAS Formula One team has also been troubled by cooling issues. Their car’s aerodynamic shape contributes greatly to the speed, but the narrow tail limit heat radiation, thus making hot weather the Achilles’ heel for Mercedes.

Fig. 2 displays the aerodynamic profile of the 2019 Mercedes Formula One car. The profile determines its sluggish cooling performance. The aviation industry also emphasizes aerodynamics and heat radiation.

Evaporative cooling has been extensively researched throughout the world. Northwestern China is one particular region that requires suppression on evaporative cooling due to the dry climate; [3][4] sometimes, for example in electric motors, evaporative cooling needs to be exploited. [5] These common phenomena have profound physical principles behind them. In the article, a wind tunnel is employed to judge the impacts on cooling speed from different container shapes and wind speeds; a finite element model is constructed to simulate the cooling process for fitting. Results show that the fit results and the experiment results are highly matched, showing the effectiveness and potential of finite element simulation for fitting. In future researches, simulation results can be utilized to better assist experiments.

2. Material & Method

2.1. Wind Tunnel
The experiment is conducted with a container holding water placed within a wind tunnel, with a wind source at one end to enable the natural evaporation of the water. Temperature is constantly measured throughout the experiment.

The experiment device shown in Fig. 3 includes a rectangular wind tunnel made from foam board measuring 85*19*18cm; at one end of the wind tunnel an electric fan (SIYU SY01-160, dual-channel, rated power 20W) is installed; the container is placed 15cm from the fan; a digital thermometer (range
20-300°C, precision up to 0.1°C) is inserted from the top of the wind tunnel and makes contact with the water (but not with the side or the bottom of the container) for measuring and recording real-time temperature.

![Figure 4. Actual experiment device](image1)

Fig. 4 and Fig. 5 displays the actual experiment device. The wind tunnel is made of smooth hard foam board; the thermometer is inserted into the water through the hole on the top of the water.

Inside the wind tunnel is a container holding water. 4 different containers are used in the experiment, numbered from 1 to 4. Each container is made of ABS plastic with a density of 0.976g/cm³ and a thermal conductivity coefficient of 0.1. Each container has a upper surface area of 49cm², a height of 8cm, and a wall thickness of 5mm. Container 1 has an upper surface of a circle; Container 4 has an upper surface of a square; Container 3 has an upper surface of a rectangle with a length/width ratio of 2; Container 4 has an upper surface of a rectangle with length/width ratio of 3. Each trial has a duration of 20 minutes; temperature data is recorded every minute; the initial water temperature (at equilibrium with the container) is approximately 60.8°C.

2.2. Room Temperature & humidity

Over the course of the experiment, room temperature is kept constant at 26°C. The relative humidity is kept constant at 55%.
2.3. Container Shape
Over the course of the experiment, the water temperature decreases from equilibrium. Temperature is recorded every minute. Each trial has a duration of 20 minutes. To evaluate the impact on cooling speed from the shape of the container, ceteris paribus, we repeat the experiment with different containers. (Fig. 6) To evaluate the impact of whether evaporation exists, we repeat the experiment by placing plastic films on the water surface to hold off evaporation. Different plastic films are made for different containers.

![Figure 6. Actual experiment device (seen from inside)](image)

2.4. Symmetrical Finite Element Model
To better comprehend the impact of evaporative cooling, we use the commercial finite element software COMSOL to build a model of the experiment device. To decrease computation amount, the model is built with symmetric boundaries. Only half of the model needs computation for inference of the entire system.

![Figure 7. Symmetric Finite Element Model](image)

Fig. 7 displays the finite element model. The wind tunnel is at the same size as the one used in the experiment (85*9.5*18cm), and the container is located within the wind tunnel at the same position.

The main control equation when evaporation is present is:

\[ q_{evap} = L_v g_{evap} \]  

(1)

Here, \( q_{evap} \) represents heat lost due to evaporation; \( L_v \) represents heat conductivity coefficient with a unit of J/kg; \( g_{evap} \) represents evaporation flow with a unit of kg. This equation serves to calculate the heat transfer amount. \( g_{evap} \), the evaporation flow, is calculated using the following equation:
Here, $g_{\text{evap}}$ represents evaporation flow with a unit of kg; $K$ represents rate of evaporation; $M_v$ represents the molar mass of water vapor (18 g/mol); $c_v$ represents vapor concentration; $c_{\text{sat}}$ represents saturation vapor concentration.

When evaporation does not exist, a simple heat conduction equation can represent the entire process:

$$\frac{\partial u}{\partial t} = \text{div}(Uu) = k \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) = k(u_{xx} + u_{yy} + u_{zz})$$

Here, $u = u(t, x, y, z)$ represents temperature, a function of time variable $t$ and space variable $(x, y, z)$. $\frac{\partial u}{\partial t}$ is the rate of change in temperature of a single point in space to time. $u_{xx}, u_{yy}, u_{zz}$ are the second derivatives of temperature along the three space axes. $k$ is the thermal conductivity rate.

2.5. Wind Speed Measurement

Through measurements by a hand-held anemometer, we observe that the electric fan emits wind at the speed of 0.7 m/s at the first channel, and 0.8 m/s at the second channel. Through comparison with experiment and simulation results, we conclude that the observed wind speed is accurate.

2.6. Error Analysis

In the experiment, a plastic film is employed to block water evaporation, as it absorbs minimal heat and has little impact on the equilibrium temperature. The experiment at first used a slick of cooking oil to block water evaporation, which absorbed a large amount of heat from the water, resulting in severe errors. Oleic acid cannot form an oil film thin enough to block evaporation. As a result, we finally decide to use plastic film.

Figure 8. Container No.2 with plastic film on the water surface

Also, the model is set in a low Reynolds number configuration, thus reducing the impact from viscosity.

3. Results

In this research, we mainly focus on the impacts on evaporative cooling speed from different container shapes, different wind speeds, and whether latent heat source on surface exists.

3.1. Evaporative Cooling Results for the Round Container under Different Wind Speeds

In the experiment, a plastic film is employed to block water evaporation, as it absorbs minimal heat and has little impact on the equilibrium temperature. The experiment at first used a slick of cooking oil to block water evaporation, which absorbed a large amount of heat from the water, resulting in severe errors. Oleic acid cannot form an oil film thin enough to block evaporation. As a result, we finally decide to use plastic film.
Fig. 9 describes evaporative cooling results for the round container at different wind speeds. The horizontal axis represents time (min), and the vertical axis represents temperature (℃). Different coloured curves and scatterplots represent simulation and experiment results under different wind speeds; Yellow represents a wind speed of 0.8m/s, while blue represents 0.7m/s. The curves represent simulation results, and the scatterplots represent experiment results. Initial temperatures, final temperatures, and temperature variations for each trial are shown in Table 1.

| Wind speed 0.8m/s | Initial temperature (℃) | Final temperature (℃) | Temperature variation (℃) |
|-------------------|--------------------------|------------------------|---------------------------|
| simulation        | 60.815                   | 39.528                 | 21.287                    |
| experiment        | 60.9                     | 39.7                   | 21.2                      |

| Wind speed 0.7m/s | Initial temperature (℃) | Final temperature (℃) | Temperature variation (℃) |
|-------------------|--------------------------|------------------------|---------------------------|
| simulation        | 60.815                   | 40.854                 | 19.961                    |
| experiment        | 60.4                     | 40.9                   | 19.5                      |

As for the round container, the margins of error of the initial temperature are respectively 0.13% and 0.69%; the margins of error of the initial temperature are respectively 0.4% and 2.3%. Within the scope of the project, the error is acceptable. The errors might come from the viscosity of the wind tunnel surface in the experiment, the complexity and of turbulence in liquid flow, the initial temperature of container, container absorbing heat, change in room temperature, etc. A±0.05 variation is enough to offset the impact from the error.

Kept wind speed constant, the temperature decreases faster at higher temperatures is caused by the larger difference between the temperatures of the liquid and the environment. That temperature decreases faster when wind speed increases is because a faster flow of air carries away more heat.

The results show that for the same container, the greater the wind speed is, the more the liquid cools.
3.2. Impacts of Evaporation on Cooling speed

Fig. 10. Evaporative cooling results for the round container (without plastic film)

The experiment shows that the existence of latent heat source on surface greatly accelerates cooling. This is because matters absorb extra vaporization heat (latent heat) when a phase change from liquid to gas occurs. As a result, more heat is absorbed even when the temperature does not change.

|                      | Initial temperature (°C) | Final temperature (°C) | Temperature variation (°C) |
|----------------------|---------------------------|------------------------|----------------------------|
| **Simulation (no plastic film)** | 60.815                    | 39.528                 | 21.287                     |
| **Experiment (no plastic film)** | 60.9                      | 39.7                   | 21.2                       |
| **Simulation (plastic film)**   | 60.815                    | 45.363                 | 15.452                     |
| **Experiment (plastic film)**  | 60.9                      | 45.9                   | 15                         |
3.3. Comparison of Evaporative Cooling Results for Four Containers

![Evaporative cooling results for four containers](image)

Fig. 11 displays evaporative cooling results for the four containers without plastic films under a wind speed of 0.8m/s. Different coloured curves and scatterplots represent simulation and experiment results for the four containers; blue represents container 1; magenta represents container 2; green represents container 3; azure represents container 4. The curves represent simulation results, and the scatterplots represent experiment results. Initial temperatures, final temperatures, and temperature variations for each trial are shown in Table 3.

|                  | Initial temperature (°C) | Final temperature (°C) | Temperature variation (°C) |
|------------------|--------------------------|------------------------|---------------------------|
| Simulation for container 1 | 60.815                  | 39.528                 | 21.287                    |
| Experiment for container 1   | 60.9                   | 39.7                   | 21.2                      |
| Simulation for container 2   | 60.948                 | 39.369                 | 21.579                    |
| Experiment for container 2   | 60.7                   | 39.1                   | 21.6                      |
| Simulation for container 3   | 60.754                 | 39.313                 | 21.441                    |
| Experiment for container 3   | 60.3                   | 39.5                   | 20.8                      |
| Simulation for container 4   | 60.555                 | 39.03                  | 21.525                    |
| Experiment for container 4   | 60.2                   | 39.1                   | 21.1                      |

The experiment shows that container 1 has the fastest rate of decrease in temperature, while container 3 has the slowest.
Fig. 12 displays evaporative cooling results for the four containers with plastic films under a wind speed of 0.8m/s. Different coloured curves and scatterplots represent simulation and experiment results for the four containers; azure represents container 1; yellow represents container 2; green represents container 3; magenta represents container 4. The curves represent simulation results, and the scatterplots represent experiment results. Initial temperatures, final temperatures, and temperature variations for each trial are shown in Table 4.

Table 4. Evaporative cooling results for the four containers under a wind speed of 0.8m/s with plastic film

|                      | Initial temperature (°C) | Final temperature (°C) | Temperature variation (°C) |
|----------------------|--------------------------|------------------------|---------------------------|
| Simulation for container 1 | 60.815                   | 45.363                 | 15.452                    |
| Experiment for container 1 | 60.9                    | 45.9                   | 15                        |
| Simulation for container 2 | 60.948                  | 45.007                 | 15.941                    |
| Experiment for container 2 | 60.6                    | 46.3                   | 14.3                      |
| Simulation for container 3 | 60.754                  | 44.699                 | 16.055                    |
| Experiment for container 3 | 60.4                    | 43.4                   | 17                        |
| Simulation for container 4 | 60.555                  | 44.095                 | 16.46                     |
| Experiment for container 4 | 60.4                    | 43.7                   | 16.7                      |

The experiment shows that container 1 has the fastest rate of decrease in temperature, while container 4 has the slowest.
3.4. Isobar Distribution Results

Fig. 13 displays the isobar distributions for the four containers. It can be observed that the isobaric lines around container 1 are relatively concentrated, showing that container 1 has higher pressure around. Higher pressure restrains water evaporation and heat loss, explaining why container 1 has a slow rate of cooling.

3.5. Isotherm Contours

Fig. 14 displays the isotherm contours for the four containers. Due to the existence of the turbulence zone behind the container, heat transfer will bypass the rear of the container. It can be observed that the three cuboid containers have a larger turbulence zone at the rear. While the oriented flow of matter is an important heat transferring method in fluids, the flow of gas in turbulence zones is irregular. As a result, turbulence zones block the transfer of heat, which in turn slows down cooling. This suggests
that the three cuboid containers have a slower rate of cooling than the cylindrical one. In the process, container 4 has a turbulent zone larger than container 3 but has a faster rate of cooling. This is because container 4 has a large surface area on the side, inducing substantial heat loss on the sides, thus producing a result inconsistent with prediction.

3.6. Distribution of Airflow Direction

![Figure 15. Distribution of airflow direction of the four containers.](image)

Fig. 15 displays the direction of airflow around the four containers. The red lines represent the airflow. It can be observed that containers 1, 2, and 3 have violent turbulences behind, while container 4 has relatively stable turbulence because of its narrow, long shape, contributing to worse heat insulation than containers 1, 2, and 3 and faster cooling.

3.7. Distribution of Air Humidity

![Figure 16. Distribution of air humidity above the four containers.](image)

Fig. 16 displays the distribution of air humidity above the four containers. It can be observed that container 1, which has a circular upper surface, causes substantially higher humidity than containers 2, 3, and 4. Humid air restrains the evaporation of water, which in turn slows down heat loss. As a result, container 1 has a substantially slower cooling rate.
4. Discussions
The relationship between vortex and cooling has been thoroughly studied by predecessors [6-11]. We assume that the rate of cooling might be related to the moisture flux magnitude. To verify this hypothesis, we construct 8 cuboid containers with different length/width ratios, and employ them in evaporative cooling simulations with a duration of 120 minutes, both with and without latent heat source on surface. We record the respective times for the water temperature to decrease to 25°C and average moisture flux magnitudes. The data obtained are listed in Table 5.

| Length/width ratio | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| **With latent heat source on surface** |       |       |       |       |       |       |       |       |
| Time to 25°C (min) | 58.119| 58.17 | 57.586| 59.84 | 58.643| 50.354| 55.576| 57.702|
| Average moisture flux (kg·m⁻²·s⁻¹) | 2.87E⁻⁰³ | 2.86E⁻⁰³ | 2.86E⁻⁰³ | 2.85E⁻⁰³ | 2.86E⁻⁰³ | 2.92E⁻⁰³ | 2.88E⁻⁰³ | 2.86E⁻⁰³ |
| **Without latent heat source on surface** |       |       |       |       |       |       |       |       |
| Time to 25°C (min) | 95.981| 94.326| 90.765| 89.031| 96.304| 79.938| 91.901| 95.972|
| Average moisture flux (kg·m⁻²·s⁻¹) | 2.90E⁻⁰³ | 2.88E⁻⁰³ | 2.87E⁻⁰³ | 2.86E⁻⁰³ | 2.89E⁻⁰³ | 2.96E⁻⁰³ | 2.91E⁻⁰³ | 2.89E⁻⁰³ |

![Figure 17. Moisture flux curve](image17)

![Figure 18. Temperature decrease curve](image18)
We discover that the rate of cooling and the average moisture flux do not completely match. When latent heat source on surface is present, moisture flux is not the only parameter that affects the rate of cooling. There might be complicated impacts resulted from vorticity. To verify whether vorticity plays a part in deciding the rate of cooling, we record the respective times for the water temperature to decrease to 25°C and the vorticities. The data obtained are listed in Table 6.

| Length/width ratio | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      |
|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| With latent heat source on surface | Time to 25°C (min) | 58.119 | 58.17  | 57.586 | 59.84  | 58.643 | 50.354 | 55.576 | 57.702 |
|                   | vorticity (s⁻¹)  | 22.821 | 22.172 | 21.942 | 21.722 | 22.504 | 25.529 | 23.232 | 22.423 |
| Without latent heat source on surface | Time to 25°C (min) | 95.981 | 94.326 | 90.765 | 89.031 | 96.304 | 79.938 | 91.901 | 95.972 |
|                   | vorticity (s⁻¹)  | 22.821 | 22.172 | 21.942 | 21.722 | 22.504 | 25.529 | 23.232 | 22.423 |

Using data from 16 simulations in the table above, we conduct a linear regression for vorticity and the time for the water temperature to decrease to 25°C. The regression line is shown in Fig. 20.
Figure 20. Linear regression result for vorticity (s⁻¹) and time for the water temperature to decrease to 25°C (min) (latent heat source on surface present).

Under a 95% confidence interval, the coefficient for the terms in the linear equation are:

\[ p_1 = -2.341 \ (-3.024, -1.658) \] (4)
\[ p_2 = 110.4 \ (94.78, 125.9) \] (5)

(SSE: 4.748; R-square: 0.9214; Adjusted R-square: 0.9083)
The resulting equation is:

\[ y = -2.341x + 110.4 \] (6)

We use the vorticity and time for the water temperature to decrease to 25°C of a ninth simulations (a container with a surface length/width ratio of 1.25) to verify the equation:

- Vorticity (s⁻¹): 22.377
- time for the water temperature to decrease to 25°C (min): 57.105
- anticipated value for vorticity: 58.015
- residual: 1.000

We observe that because of a large R-square and a small residual, the linear equation can adequately describe the relationship between vorticity and the time for the water temperature to decrease to 25°C, that when evaporation is present, the rate of cooling is positively related to vorticity.

Figure 21. Linear regression result for vorticity (s⁻¹) and time for the water temperature to decrease to 25°C (min) (latent heat source on surface absent).
When latent heat source on surface is absent, a linear regression does not give a convincing result. This suggests that vorticity is not the only factor deciding the cooling rate. There are more complicated parameters affecting the rate of cooling.

5. Conclusion
Through verification with wind tunnel experiments and simultaneous finite element simulations with software COMSOL, as well as analysis of experiment and simulation results, we can conclude:

In the evaporative cooling process for cuboid containers, changing the length-width ratio of the upper surface influences evaporation with the change in the flow field behind the container, thus affecting the rate of cooling. The most effective way to alter the rate of cooling is to change the shape of the container, as when water evaporation is present, changing the length/width ratio alters the vorticity in the flow field, therefore affecting the final rate of cooling. After careful analysis, cooling speed is positively related to vorticity when evaporation is present. The situation when evaporation is absent is complex, that the rate of cooling and vorticity is not linearly related, and may receive influence from other factors.

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