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FUNDAMENTAL AND PARAMETRIC CONSIDERATIONS FOR NUMERICAL RAIN SIMULATION IN A WIND TUNNEL

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Abstract**—**A climatic wind tunnel (CWT) is an important testing facility to study the effect of different environmental conditions on test objects of interest. CWTs are equipped with wind blowing nozzles and water supply systems that are capable to simulate precipitations. Natural rainfall appears as a simple phenomenon, consisting of distinct droplets of water falling from an elevated height. However, simulating rainfall in a wind tunnel is a complex process due to confined space and different droplet formation mechanism as compared to nature. This paper presents the parameters that should be considered when simulating rainfall inside a CWT, including the size of droplets produced from a rain simulation device, falling height for the droplets, and wind speed; which can affect the resulting simulated rainfall characteristics of droplet kinetic energy, impact angle, and size distribution. A computational method is used to perform these parametric considerations. The derived inter-relationships of the parameters serve as a guideline for simulating realistic rainfall characteristics in a CWT, which is believed to be beneficial for numerous research fields. The usage of this guideline is demonstrated with an example of an arbitrary rain test condition.

Keywords-rain simulation; natural rainfall characteristics; multiphase modeling; climatic wind tunnel

I. INTRODUCTION

Rainfall is a common precipitation condition that we face in our everyday lives. It can be beneficial for different fields when the amount of rain is moderate, for example: hydrating soil for agriculture, cleaning debris for solar panels, and providing drinking water to living organisms. However, excessive rainfall can be hazardous, such as causing leakage in buildings, accidents in moving vehicles, and flooding in overloaded drainage systems.

Natural climates are extremely diverse and random, the major obstacles for studying rainfall effects in nature include down-time while waiting for the desired weather condition and the results are often non-repeatable because there are numerous uncontrollable parameters.

On the other hand, many have conducted rainfall testing in a controlled lab and wind tunnel environment to eliminate the previously mentioned issues [1, 2, 3]. In order to study rainfall effects indoor, a rainfall simulation system is required. To best represent realistic conditions, the rainfall simulation system should be able to replicate most if not all the natural rainfall characteristics [4], such as intensity, kinetic energy, impact angle, liquid water content, and droplet size distribution. Currently there is no standardized method in simulating rainfall indoor, as a result, rain test results are often rather qualitative.

This paper synthesizes information from various fundamental studies of individual natural rain characteristics and put together a guideline for numerically replicating these characteristics in a wind tunnel environment. One can refer to this guideline to select the appropriate parameters when designing for a rainfall simulator for quantitative analysis.

II. LITERATURE REVIEW

A. Natural Rainfall Characteristics

This section discusses the definitions of various natural rainfall characteristics, the classifications, and the techniques of measurements intended for quantifying rainfall events. Fig. 1 provides a detailed visual demonstration of rainfall quantification discussed in the subsequent lists of characteristics.

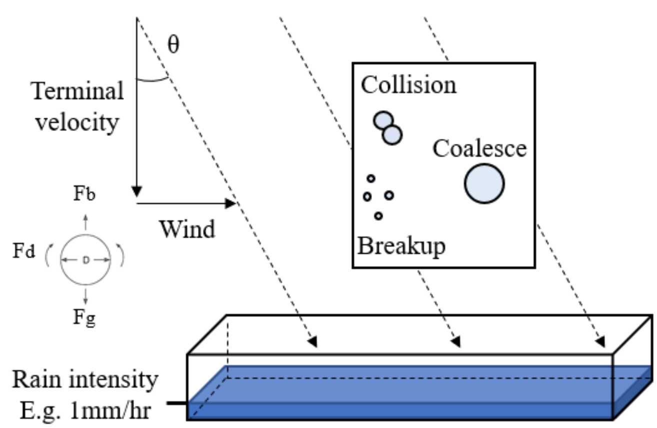

Figure 1. Natural rainfall characteristics.

1) Rain intensity: During rainfall events, the rainfall rate is described as intensity with a unit of mm/hr. According to the United States Geological Survey (USGS) classifications, the upper intensity limits of drizzle, light, moderate, heavy, and cloudburst are 0.25, 1, 4, 15, and 100 mm/hr, respectively [5]. Rain intensity is defined as the volume of rain collected in a specific area over a certain time span ($mm^3/mm^2 \cdot hr$). Rain intensity is typically measured by conventional volume bucket with manual reading or a tipping bucket with electronic data logging [6].

2) Droplet kinetic energy: Droplets fall and accelerate vertically from the sky and reach terminal velocities when drag, boyancy, and gravity forces are in equilibrium; the droplet falling velocity will not increase further beyond that point [7]. Typically, disdrometers are used to measure droplet speed and kinetic energy [6]. The terminal velocities of droplets have a square-root dependence on the droplet diameters [7] as shown in (1) and the droplet kinetic energy can be calculated using its falling speed. This may raise the question of how high inside a wind tunnel droplets need to be released to achieve their terminal velocities? Reference [8] has studied the falling time of a water droplet (0.083 mL) with respect to falling heights up to 6.3 m, and derived a mathematical expression for the velocity at ground level. In this paper, the falling speeds of a full range of droplet sizes are simulated and are compared to the measured values in [8].

$$V_t = \sqrt{\frac{4gD}{3C_D}\left(\frac{\rho_{water}}{\rho_{air}} - 1\right)} \qquad (1)$$

3) Droplet impact angle: The rain angle of a vertically falling droplet is influenced by the horizontal interference of air flow [9]. In other words, the droplets do not strike normal to the ground surface in the presence of wind. From a simplified perspective, the angle can be estimated with (2), where the rain angle arises from the resultant vector of vertical falling velocity and horizontal wind velocity. Reference [10] has measured in nature for the droplet angles with respect to wind speeds up to 70 km/hr for a range of droplet sizes up to 2.5 mm. They found that the droplet size has an effect on the droplet impact angle at the same wind speed [10]. In this paper, the droplet impact angles of larger droplets are also investigated under the influence of different wind speeds and falling heights.

$$\theta = \tan^{-1} (v_{wind} / v_{fall}) \qquad (2)$$

4) Droplet breakup and size distribution: Cloud droplets are extremely tiny at a scale of 0.02 mm and can be suspended inside the clouds, the droplets begin to fall towards the ground when they reach 0.2 mm to form raindrops [11]. Events of collision, breakup, and coalescence during their falling journey towards the ground are likely to occur [12]. The chance of occurrence increases with rain intensity. Thus, according to the USGS classifications, the mean droplet sizes vary for different rain intensity conditions, ranging from 0.96 mm for drizzle to 2.85 mm for cloudburst [5]. There are several techniques to measure droplet size distribution, for example, the conventional flour stain method where each stained area size is corresponded to a specific droplet size; infrared sensor that uses bounced beam signals, the signal strength is varied based on the size of droplet detected; and video disdrometer which can map out the shape of the droplets detected [6].

5) Liquid water content: The liquid water content is defined as the amount of water within a given volume of dry air space, which can also be thought of as an analogy for absolute humidity [13]. Humidity has an effect on droplet size distribution as it controls the lifetime and evaporation of droplets [14]. Generally, smaller droplets are found in more humid environments, whereas larger droplets can survive with lower humidity. Ambient conditions are modeled in this study, thus, humidity is not considered.

B. Rain Simulations

Rainfall simulation is a common practice in wind tunnels. The methods recorded in the literature is classified into two groups: pressurized spray and drop former [15]. As the names suggest, pressurized spray method utilizes atomization nozzles, the intensity and droplet size are varied through changing pressure and number or type of nozzles; whereas drop former method uses small openings such as needles from a reservoir of water to drip droplets of water.

Pressurized spray method can easily cover a larger area at lower cost with simpler control mechanisms and fewer components. Despite the advantages, this rain simulation method is not the ideal candidate for rain test studies as there are a number of limitations associated with this method. The major shortcoming is its inability to replicate natural rainfall characteristics, i.e. increasing pressure will increase intensity, but will also produce smaller droplets, which is the reverse expectation of natural rainfall.

Drop former resembles natural rainfall where droplets are falling vertically due to gravity without being pressurized [15]. Therefore, the computational studies presented in this paper are based on the drop former method. The extent to which this rain simulation method can replicate natural rainfall characteristics depends on the available space in the wind tunnel, and the capacity of the drop forming device to produce a range of droplet sizes. These limitations are discussed further in the results and discussions section, the selection of simulation parameters and trade-off rationales are also suggested.

This paper aims to point out the important parameters to consider for rain simulation in a CWT in order to best replicate the natural rainfall characteristics. The guideline presented can be used to support quantitative analyses of rainfall effects on test subjects of interest for various research fields. It can also be implemented when designing for a rainfall simulation system.

III. Experimental

A. Computational Model Setup and Details

Multiphase computational fluid dynamics (CFD) analysis is performed with discrete phase modeling using ANSYS Fluent. The geometry of the model follows the dimensions of the test chamber at Ontario Tech University's Climatic Wind Tunnel (7.5 m high × 14.3 m long) in Oshawa, Canada. The wind inlet has a height of 2.9 m, and the drop forming nozzle (0.1 m × 0.1 m) is placed at 0.25 m horizontally from the wind inlet.

The CFD model is simplified to 2D studies as a 3D object is absent. Advantages of employing 2D simulation include reduced computational cost and time especially for a wide range of parametric cases and tracking of large amount of discrete phase particles like raindrops. However, if a 3D object is present in the study, then 3D simulation is preferred to capture the shape effect on the aerodynamics, which also cause raindrops to follow different pathways.

The boundary conditions for the CFD model are as follows: wind with constant velocity normal to the inlet; pressure outlet; non-slip walls for the wall above the inlet, wind tunnel floor, and ceiling; injections of liquid water droplets at a rate of 0.25 mL/s from the drop forming nozzle; and droplets are trapped at the walls upon impact.

There are four mesh models for different drop forming nozzle heights, elements are refined for rain area using the body of influence (BOI) method. The four mesh models have an average number of elements of 845,000. Mesh independence study is also performed for the BOI at the air space below the drop forming nozzle for selected cases. Rainfall is simulated for 10 s with a time step of 0.005 s.

B. Parametric Study Cases

The parameters studied are chosen based on the available space of the CWT, and the assumption that the drop forming nozzle is able to produce a range of droplet diameters between 0.5 mm to 6.0 mm. Since the wind inlet has a height of 2.9 m, in order to avoid interference of the aerodynamics, the drop forming nozzle is placed outside of the wind stream starting at 3.0 m high, and up to an accessible height of 6.0 m.

This paper contains three major groups of studies: effect of falling height, effect of droplet size, and effect of wind speed at 25 km/hr increments on (i) droplet falling speed, (ii) droplet impact angle, and (iii) droplet size distribution. (i) is modeled with 50 km/hr wind speed and the vertical y-velocity of droplets at the bottom wall is extracted. (ii) and (iii) are studied with 4 m falling height, which represents at least 70% of terminal velocity and is a safe height to work with during physical experiments. ImageJ is used to post-process for (ii). Stochastic Secondary Droplet (SSD) model is enabled in (iii) for droplet collision, coalescence, and breakup. Critical Weber number of 8 is used as the breakup criteria and D_{30} volume mean diameter is selected to represent the droplet size distribution as it is the most indicative averaging value for hydrology applications.

IV. Results And Discussions

A. Droplet Falling Speed vs. Droplet Size and Falling Height

Fig. 2 shows the falling speeds of droplets of various sizes falling from a height range of 3 to 6 m in a wind tunnel. Velocity is extracted at the bottom wall from the CFD model. The results are found to be within 12% of discrepancy for 5 mm droplets when comparing the falling speeds derived in [8]. Reference [8] measured the time needed for a droplet with approximately 5 mm diameter to fall through a certain height, the velocity was calculated with the derived mathematical expression instead of direct measurements. Therefore, it is conclusive to state that the simulations performed in this study agree well with the physical experiments performed by [8].

From Fig. 2, no effects are observed for smaller droplets, i.e. 0.5 and 1 mm, their falling speeds remain constant when the falling height is raised. There is gradual increase in falling speed with height for 2 mm droplets. In general, between the falling height range of 3 to 6 m, the falling speeds increase linearly with falling height, and the slopes become steeper for larger droplet sizes, due to higher acceleration with larger mass.

B. Droplet Impact Angle vs. Droplet Size and Wind Speed

Rain angle arises from the raindrop having both vertical and horizontal velocities, the angle is measured between the vertical axis and the resultant rain direction. Reference [10] has measured and normalized rain angles for different wind speeds and droplet sizes up to 70 km/hr and 2.5 mm, respectively. The trends and values obtained in this study agree well with [10].

Fig. 3 presents the effect of wind speed on rain angle for different droplet sizes falling from 4 m high. It is assumed that collision, breakup, and coalescence do not occur, such that the larger droplets exist and survive the wind flow that can sometimes be found during natural rainfall events. Also, Fig. 3 suggests that the higher the wind speed, the larger the rain angle. Smaller droplets are observed to be more sensitive to environmental influences at lower wind speed of 25 km/hr. The curves for 0.5 mm and 1 mm rise quickly to 72º and 56º,

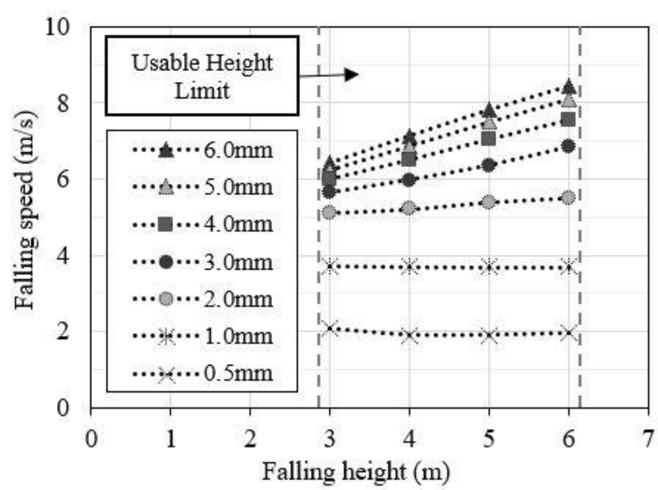

Figure 2. Effects of droplet size and falling height on droplet falling speed.

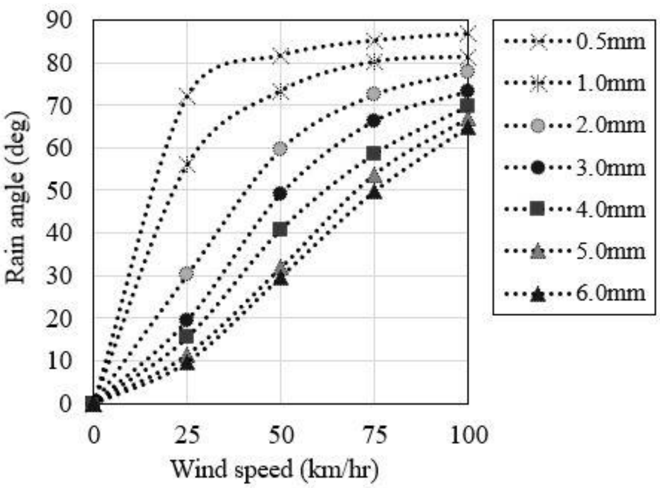

Figure 3. Effects of droplet size and wind speed on droplet impact angle.

respectively at 25 km/hr wind, and approach horizontal impact at 100 km/hr. Larger droplets are heavier and are less affected by wind. The behavior changes from logarithmic growth for smaller droplets to S-curve for larger droplets.

The differences in the curves imply that the growth rates of rain angles are opposite for smaller and larger droplets at both lower (25 km/hr) and moderate (50 – 75 km/hr) wind speeds, and all the curves saturate at higher wind speed of 100 km/hr.

C. Droplet Size Distribution (DSD) vs. Wind Speed

Sections A and B provide guideline for replicating natural rainfall characteristics that assume for no droplet interactions and breakup events. Those conditions hold true for individual droplets provided that the droplets exist in the wind stream and is not produced from the drop forming nozzle.

This section discusses the details that are relevant to an experimental set up at the CWT as shown in Fig. 4. This is also a realistic representation of rainfall simulation combining all the factors presented in sections A and B, in addition, droplets are allowed for collision, breakup, and coalescence in the CFD model. The critical Weber number is obtained experimentally for selected cases.

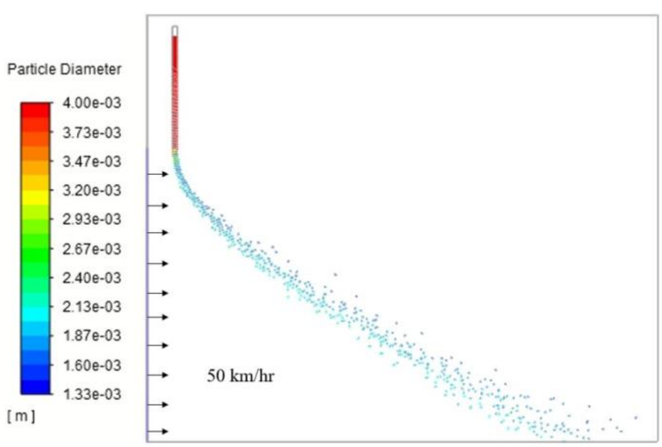

Figure 4. Droplet size distribution for 4 mm droplets falling from 4 m.

In Fig. 4, droplets with 4 mm diameter are dispensed from 4 m of height and are blown by 50 km/hr wind when they reach 2.9 m of height. It is observed that upon wind influence, the droplets reduce in size to about 3 mm. The droplets further reduce in size to less than 2 mm as they experience longer time span of wind influence.

Tables I – IV present the droplet size distributions induced by wind for 2 – 5 mm droplets that are dispensed from the drop forming nozzle placed at 4 m in height. Since there is only one drop forming nozzle in the CFD model, collision events seem to be negligible, droplets tend to primarily undergo breakup. The onset of wind induced breakup is found to be 75 km/hr for 2 mm dispensed droplets, and 50 km/hr for dispensed droplets larger than 3 mm.

TABLE I. WIND INDUCED DSD FOR 2 MM DROPLETS

Dispensed Droplet Size (mm)	**Wind Speed (km/hr)**	**D_{30} (mm)**	**Min. Droplet Size (mm)**
2.00	25	2.00	2.00
	50	2.00	2.00
	75	1.41	0.93
	100	1.06	0.54

TABLE II. WIND INDUCED DSD FOR 3 MM DROPLETS

Dispensed Droplet Size (mm)	**Wind Speed (km/hr)**	**D_{30} (mm)**	**Min. Droplet Size (mm)**
3.00	25	3.00	3.00
	50	2.16	1.40
	75	1.21	0.77
	100	0.83	0.47

TABLE III. WIND INDUCED DSD FOR 4 MM DROPLETS

Dispensed Droplet Size (mm)	**Wind Speed (km/hr)**	**D_{30} (mm)**	**Min. Droplet Size (mm)**
4.00	25	4.00	4.00
	50	2.24	1.33
	75	1.21	0.65
	100	0.84	0.46

TABLE IV. WIND INDUCED DSD FOR 5 MM DROPLETS

Dispensed Droplet Size (mm)	**Wind Speed (km/hr)**	**D_{30} (mm)**	**Min. Droplet Size (mm)**
5.00	25	4.97	4.37
	50	2.31	1.20
	75	1.12	0.65
	100	0.85	0.38

Smaller droplets tend to be more stable inside the wind stream, this is evident by the fact that the 2 mm dispensed droplets retain a larger final droplet size of 1.06 mm even at 100 km/hr wind. The larger droplets are less stable and prefer to breakup demonstrated by the smaller D_{30} sizes as compared to the 2 mm dispensed droplet case. In general, Tables I – IV suggest that if a larger dispensed droplet size is used, the DSD range will also be wider.

D. Using The Presented Guidelines

This section shows the procedures that are recommended to be taken when designing for rain simulation test at a climatic wind tunnel. An example case is explained in detail to demonstrate how the presented guidelines can be employed.

1) Step 1: It is importatnt to first know the capacity of the drop forming device, as the droplet sizes it can produce will dictate the decisions on the subsequent steps.

2) Step 2: The big picture of the test conditions should be defined. The test condition should outline the desired testing wind speed range according to applications and DSD based on the rain intensity classifications. Readers may refer to Tables I – IV to identify the relevant outcome.

3) Step 3: This step involves selection of component parameters. In order to decide on the positioning of the test object, the droplet impact angle should be calculated. Rain angle can be determined using (2) after selecting for the suitable falling height. Refer to Fig. 2 for the falling speeds of the droplets with D_{30} diameter and not the size that is first dispensed, since D_{30} is the size that survives in the wind stream.

4) Step 4: Lastly, multiple drop former devices may be required to cover for a larger area depending on the test object size. To vary for rain intensity, the number and density of drop forming nozzles can be planned based on the device capacity.

Take example of a test case for a stationary target of 0.1 m^2 that is placed close to ground level at the wind tunnel test section floor. It is desired to test for heavy rain with 50 km/hr wind gusts. It is assumed that the drop forming device can produce 5 mm droplets. With these conditions, D_{30} is 2.31 mm based on Table IV, which is approximately the same DSD reported in [5]. According to [5], the droplets should fall with a speed of 6.7 m/s, however, when referring to Fig. 2, the highest speed that can be achieved with 2 mm is 5.5 m/s falling from 6 m of height. Using this falling height and (2), the rain angle is calculated to be 68.4^{o}, and the target should be placed at 7.3 m from the wind inlet. Finally, assuming for a rain intensity of 9 mm/hr, one drop forming nozzle with the same dripping rate of 0.25 mL/s (0.0009 m^3/hr) studied with the CFD models in this paper can be used. The intensity falling onto a 0.1 m^2 will therefore be 9 mm/hr.

V. CONCLUSIONS

Rain simulation in a climatic wind tunnel (CWT) is a widely accepted rainfall test method in different fields, however, there is no standardized rain simulation method available in the literature. This paper presents a matrix of inter-related parameters when simulating for rainfall at a CWT, in the hope of contributing to the development of a standardized rain simulation technique such that the results obtained from rain tests can be easily quantified.

Parametric study of droplet size, falling height, and wind speed is performed with computational fluid dynamics (CFD) method. A guideline to simulate realistic rainfall characteristics is built upon the computational results. The guideline uses a top-down approach to decide on the simulation parameters which first identify the big picture of the test condition, then determine the component parameters such as falling height and the required droplet size produced from the drop forming device. This guideline provides detailed step-by-step planning for rain simulation test and an example case of how to employ the guideline.

Qualitatively, falling speed increases with falling height for larger droplets; smaller droplets tend to be insensitive to falling heights, but are highly deflected by any wind gusts and result in large rain angle. Wind induced droplet size distributions is modeled for various droplet sizes produced from the drop forming nozzle, larger droplets are observed to be less stable and have higher tendency to undergo breakup.

The limitations to satisfy all the listed natural rainfall characteristics due to the available space at the CWT are considered. Therefore, the example case presented in Section D of results demonstrates the trade-off of droplet kinetic energy for other rainfall characteristics. On the other hand, if the droplet kinetic energy is an important variable, then droplet size or wind speed can be compromised. Besides establishing rain test plans, this guideline can also be used to design for a rainfall simulation system to be integrated into a CWT.

REFERENCES

[1] A. Ghani, S. A. A. Aroussi, and E. Rice, “Simulation of road vehicle natural environment in a climatic wind tunnel,” Simulation Practice and Theory, vol. 8, pp. 359–375, 2001.

[2] R. H. Rasshofer, M. Spies, and H. Spies, “Influences of weather phenomena on automotive laser radar systems,” Advances in Radio Science, vol. 9, pp. 49-60, 2011.

[3] C. T. Hignett, S. Gusli, A. Cass, and W. Besz, “An automated laboratory rainfall simulation system with controlled rainfall intensity, raindrop energy and soil drainage,” Soil Technology, vol. 8, pp. 31-42, 1995.

[4] T. P. Regmi and A. L. Thompson, “Rainfall simulator for laboratory studies,” Applied Engineering in Agriculture, vol. 16, pp. 641-647, 2000.

[5] H. W. Lull, Soil Compaction on Forest and Range Lands. Washington, DC: Forest Service, U.S. Department of Agriculture, 1959.

[6] G. Kathiravelu, T. Lucke, and P. Nichols, “Rain drop measurement techniques: a review,” Water, vol. 8, no. 29, 2016.

[7] K. Subramanya, 1000 Solved Problems in Fluid Mechanics. New Delhi, India: Tata McGraw-Hill Publishing Company Limited, 2005.

[8] M. Ng, “A mathematical model of the velocity of a falling water drop in air,” University of British Columbia Science One Program Report, 2010.

[9] F. Bocci, “Whether or not to run in the rain,” European Journal of Physics, vol. 33, 1321-1332, 2012.

[10] L. C. Sieck, S. J. Burges, and M. Steiner, “Challenges in obtaining reliable measurements of point rainfall,” Water Resources Research, vol. 43, W01420, 2007.

[11] A. Nugent, D. DeCou, S. Russell, and C. Karamperidou, "Precipitation processes," in Atmospheric Science, Atmospheric Processes and Phenomenon, Honolulu, HI: University of Hawai'I at Mānoa.

[12] T. B. Low and R. List, "Collision, coalescence and breakup of raindrops. Part 1: experimentally established coalescence efficiencies and fragment size distributions in breakup," Journal of the Atmospheric Sciences, vol. 39, pp. 1591-1606, 1982.

[13] R. Stull, "Water vapor," in Practical Meteorology: An Algebra-based Survey of Atmospheric Science, Vancouver, BC: University of British Columbia, 2017, pp. 87-118.

[14] L. Chen, "Effects of ambient temperature and humidity on droplet lifetime – a perspective exhalation sneeze droplets with COVID-19 virus transmission," International Journal of Hygiene and Environmental Health, vol. 229, 113568, 2020.

[15] M. L. Yakubu and Z. Yusop, "Adaptability of rainfall simulators as a research tool on urban sealed surfaces – a review," Hydrological Sciences Journal, vol. 62, 996-1012, 2017.