Airflow Patterns and Droplet Spread in Natural Ventilated Classrooms

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Abstract Some infectious diseases, such as COVID-19, are verified by transferring droplets and aerosols through the air or direct contact, which is especially dangerous in enclosed environments like classrooms. This paper aims to investigate airflow patterns in a classroom in Manado, Indonesia, and examine the number and density of droplets that could eventually wind up on students' hands and faces in a naturally ventilated classroom. Visualizations using smoke machines and measurements of airflow speed, air temperature, and humidity have been performed in a naturally ventilated classroom. Modeling the initial velocity of droplet spraying and its spread using electric and manual nozzles with colored liquids is equivalent to the speed of talking, coughing, and sneezing. The number and density of droplets are proportional to their distance from the source, with the initial velocity of their spray exerting greater significance. Compared to what is received on the students' faces, the position of the armchair table or the students' hands receive more droplets in terms of number and density. In this condition, gravitational forces play an essential role in the spreading of droplets. More research is still needed on droplet spread with different classroom conditions, such as air conditioning or other methods.

Keywords Droplet Spread, Natural Ventilation, Classroom, Airflow Pattern

pandemic, which is ongoing and taking lives and has a vast impact on the economy and socio-culture of the community, has triggered and raised awareness of environmental hygiene, significantly cleaner and more comfortable air quality. As a result, the traditional classroom teaching and learning process had to be discontinued and replaced with virtual learning.

These pandemics, especially the spread of viral infections, cannot be predicted when they will end. There are still isolated locations in many parts of Indonesia, which consist of many islands. Moreover, online learning cannot be done effectively and efficiently due to the limitations of the internet network, the lack of gadgets or computers, and, of course, inappropriate and ineffective learning methods. As a result, learning must ultimately be done face-to-face in the classroom, as mandated by the Indonesian government, while following strict prevention methods such as limiting class capacity to 50 or even 25 percent, wearing masks, keeping a distance of 1-2 meters, and washing hands frequently. However, classroom learning activities during pandemic conditions require more intensive prevention efforts and strategies.

Classrooms in Indonesia are typically naturally ventilated with sizable openings on the left and right sides. It is essential to understand airflow patterns in a naturally ventilated classroom, especially the way of spreading droplets flowing in the air from the speaker, professor, or lecturer in front of the room to the student. The condition is necessary as health, safety, and prevention effort in pandemic conditions, such as at what distance the front student's desk should be placed or how the droplets risk spreading in naturally ventilated classrooms. This measure

1. Introduction

The Corona Virus Diseases 2019 (COVID-19)

is one of the prevention strategies when students are in class and provides certainty and confidence in controlled conditions.

The study of airflow patterns is important in efforts to achieve thermal comfort in rooms. Comfortable conditions will increase the concentration and productivity of learning performance. As a result, students will be more focused, more concentrated, able to focus on lessons that have an essential effect on the transfer of science, the formation of young generation character, and their productivity [1,2].

The SARS-CoV-2 virus, which has caused millions of transmissions and hundreds of thousands of fatalities, is the cause of COVID-19. Each person has a different evolution due to the significant variability of the human body's reactions. As a result, there can be mild infections showing no symptoms, or there can also be extreme complications that are very severe and cause death. SARS-CoV-2 is spread from one infected person to another through infectious agents and airborne transmission via droplets released by coughing, sneezing, speaking, and close contact.

ASHRAE, an American association of engineers for heating, refrigeration, and air conditioning in buildings, through the Position Document on Infectious Aerosols [3] and REHVA in Europe through the COVID-19 guidance document [4], provide recommendations for preventing the transmission of these infections. In addition, understanding the significance of ventilation systems and air conditions in limiting the information of COVID-19 is indicated in the guidelines produced by the Indoor Environmental Quality – Global Alliance (IEQ-GA) on indoor environmental comfort [5].

Enclosed environments are much more dangerous and at risk of transmission than open spaces due to inadequate distances between people. Enclosed rooms also necessitate careful ventilation and airflow, which effectively prevents indoor air pollution. Droplets mediate short-range transmission, but smaller aerosol droplets can infect people without direct touch. WHO considers the central spread of virus transmission from aerosol droplets and direct contact [6].

Droplets with a diameter of more than 10 microns released through coughing and sneezing fall to the floor and on the surface within 1-2 m, according to Correia et al. [7]. According to Chen et al. [8], close contact should be avoided to limit the modality of respiratory infections. According to Morawska et al. [9], droplets drip and evaporate into aerosols in the air and can float for several meters to tens of meters. The transmission size by air or aerosol is generally smaller than 10 microns so that the transmission can be from a longer distance. When sneezing, the largest droplet size is 2000 microns, 95% between 2 – 100 microns in length, and 76% between 80-180 microns as described by Buckland et al. [10] and Fabian et al. [11].

Yao et al. [12] conducted a statistical study of the

confirmed negative relationship between COVID-19 and nearby ozone levels and positive relationships with relatively average humidity. The same investigation evaluates those droplets in a closed environment that evaporate rapidly into fine aerosols, which necessitate particular attention, notably the crucial part of ventilation systems.

Variations in indoor pressure that can protect the room from other spaces around it have been studied in terms of ventilation control in buildings to deal with the transmission and spread of COVID-19 [13]. Quian et al. [14] emphasized the importance of natural and mechanical ventilation in diluting pollutants. By enlarging the window size, natural ventilation can improve indoor air quality, dilute toxins, and allow pathogen-free air to enter the room.

In conducting studies on ventilation and thermal comfort in the room, they often use several instruments and software. For measurement and visualization of airflow in space, tracer techniques are used. This gas tracer technique has been widely used in several studies that have shown satisfactory results. Some articles describe the use of this technique, such as Kalliomäki et al. [15], which researches isolation rooms in hospitals primarily to maintain appropriate airflow. The same protocol was also used by Kokkonen et al. [16] and Barber et al. [17] in testing the technical control performance of airborne infection isolation chambers, where the results showed similar potential. Buggenhout et al. [18] suggest that gas tracer techniques in ventilated rooms should pay attention to the precise placement of research objects; otherwise, the results are biased.

The ability of gas tracers and measurement techniques, wildly when space configuration varies, and the layout of different window and door openings is minimal. However, the pattern of airflow in space on a scale of 1:1 is very suitable for tracer techniques. Thus, if research aims to see the movement of smoke due to airflow patterns in space, this technique is considered helpful.

2. Materials and Methods

A classroom located in the Faculty of Engineering of Sam Ratulangi University in Manado, Indonesia, was chosen as the object of research. This classroom has natural ventilation using cross-ventilation and is located on the ground floor of a three-story building block. This classroom measures 8 x 12 m, with a height of 3.10 m or a room volume of 297.6 m³. On the left and right of the room located windows and ventilation; at the time of the study, the door was opened, thus providing permanently open ventilation, but the shutters in the form of glass frames were in a closed state. The location and position of the classroom are indicated in Figure 1.

The use of permanent ventilation models on both sides of the classroom walls allows for continuous air exchange.

The bottom vent, which is 80 cm above the floor, is made up of 45-degree board blades that obstruct the student's view out of the classroom, allowing them to maintain their concentration and focus on the lecturer in front of the class. In addition, the incoming wind is probably influenced by this position, which increases airflow. In

contrast, the upper ventilation consists of board blades arranged horizontally to flow air permanently easily. As illustrated in Figure 2, these lower and upper vents, coupled with standard glass windows, offer a suitable amount of light illumination into the classroom.

Figure 1. The block plan of the building where the classroom is located (a). The classroom is located on the ground floor of the second door (b)

Figure 2. The floor plan and details of the classroom

The upper and lower vents' opening area on the right-left of the class is 16.13 m^2 while the door area is 3.85 m^2 , making the total area of opening ventilation and doors 19.98 m^2 .

There is a 1.5 m wide corridor on the porch that is protected from rain and heat. The classroom is close to other classrooms on the East and West sides, while the Northside is flanked by other buildings, with a reasonably big grass area to the south.

The smoke machine (600W) produces theater smoke (liquid for the smoke machine), visualizing airflow patterns. Two smoke machines, one on either side of the room, emit smoke into the space. Floating smoke can detect and follow the flow of air caused by natural ventilation.

A speaker or teacher is represented in front of the class using an electric and manual gun sprayer to imitate droplet beams shooting out of the speakers using a colored liquid, red cake coloring. The electric and manual sprayers are located in the front of the classroom, with the sprayer nozzle height set to 146 cm, which is the height of an adult's mouth. The smoke flow is illuminated with theatrical highlights, as the expected visualization of the smoke and droplet beam can leave a clear trail. An anemometer data-logger measured and recorded airflow speed for a moment and over a more extended period.

Three scenarios are applied: The first scenario is to visualize the airflow pattern using smoke from a smoke machine. The second scenario is to measure the number and density of droplets from electric and manual sprayers emitted from a distance of 1 m, 2 m, and 3 m when they fall on an A4 white paper located on the armchair, in the student's hand position. The initial speed of the electric sprayer model represents when someone sneezes and coughs, while the speed of the manual sprayer represents the rate of droplets coming out of someone who is talking. While the third scenario aims to check the number and density of droplet spread exposed to a student's face, the white paper is placed in the same position on the seated student's head position (Figure 3 and Figure 4).

Figure 3. Setting up experiments in classrooms that have cross-ventilation

The suitability and validity of the initial speed value of

the electric sprayer and manual sprayer gun and the range of the dispersal droplets are attentive and based on what some researchers have done in terms of closely related.

An article from American Lung Association [19] said that droplets containing germs are widespread in the air when coughing and sneezing. The average droplet spreads to about 2 meters. There are about 3,000 droplets out in a single cough, and their speed can reach 50 mph. As for one sneeze, the number of droplets released is about 100,000 droplets. Therefore, the droplet speed released when sneezing is relatively large and can reach 100 mph. When teaching or discussing, a teacher must speak louder to be heard by students or others. According to Asadi et al. [20], people who talk loudly emit more droplets or droplets than those who speak slowly.

Figure 4. The chair's position against the sprayer: a piece of white paper is placed on the table from the armchair (a), a part of white paper is placed on the student's face when sitting (b)

While Kwon et al. [21] studied the first speed and angle of airflow exhaled after coughing and speaking using Particle Image Velocimetry and an indoor acrylic chamber, men coughed at an average of 15.3 m/s and women coughed at an average of 10.6 m/s. In contrast, men and women spoke at an average of 4.07 m/s and 2.31 m/s, respectively. They also identified a linear relationship between the height of the test subjects and the speed with which they coughed and spoke.

Figure 5(a) shows an electric or manual sprayer gun in place right in front of the class is 1.5 m from the front wall or the whiteboard, right in the middle of the course. The student seats are set as usual, with the first row being one meter away from the sprayer, the second row being two meters away, and the third row being three meters away.

Figure 5. Two types of sprayers are used: an electric sprayer gun and a manual sprayer gun, using coloring liquid (a) and a Hot Wire Anemometer (b)

The GM8903 hot wire anemometer measures indoor airflow speed. It can measure in the range of 0 - 45 m/s, has a resolution of 0.001, and accuracy of 0.1. In addition,

it can be operated at a temperature of 0-60 °C with an accuracy rate of 1.0 °C, as shown in Figure 5(b).

3. Results and Discussion

3.1. Airflow Patterns in a Classroom

Two smoke machines are positioned in front of the class to visualize airflow patterns. The speed of airflow entering the classroom due to the outside wind was insignificant in some circumstances. The situation is because, on the north side of the school or the right side, there are other buildings adjacent to each other at a distance of only 4 meters. This position at least affects the direction and speed of airflow in and out of the classroom. However, the wind flowing through the door and the open vents significantly impacted this situation. The airflow speed measured at the open door varied from 0.01 to 0.4 m/s even more. In some cases, very weak winds were not enough to induce airflow movement in the class.

Visualization of smoke flow has shown that there is the movement of air as a result of the wind entering the class passing through the openings. Under certain conditions, it is reasonable to suppose that the speed of indoor airflow caused by wind, which blows from one side to the other, does not considerably affect airflow in the classroom. In those circumstances, smoke visualization shows that scattered smoke drifts up and out to the right and left sides through ventilation openings and windows, as seen in Figure 6(a)-(d). The intervention of wind flow at speeds of 0.00 - 0.004 m/s does not directly affect the spread of droplets produced in this scenario. Intervensi aliran angin pada kecepatan 0,00 - 0,004 m / s tidak secara langsung mempengaruhi penyebaran tetesan yang dihasilkan dalam skenario ini.

Some experiments show the same thing where the spread of droplets is dominated by the sprayer nozzle's speed, both from electric and manual sprayer pistols. It is pronounced because the volume and wind speed from the outside that goes into the class is minimal and slow, even showing values approaching 0 m/s.

The ventilation rate is commonly used to determine whether a room meets the air change per hour criterion. A minimum of 8 times air change per hour is recommended by Indonesian National Standard No. 03-6572-2001 on the procedures for planning ventilation and air conditioning systems in buildings [22]. The WHO publication/guidelines [23] propose the following formula for estimating wind-driven ventilation rates in a room with two opposed openings (e.g., a window and a door):

$$ACH = 0.65vA3600/V \quad (1)$$

Where: ACH : air change per hour, v : wind speed (m/s), A : smallest opening area (m^2), V : room volume (m^3).

(a)

(b)

(c)

(d)

Figure 6. Smoke visualization in a naturally ventilated classroom

When utilizing equation (1) to compute the ACH of the classroom understudy, a wind speed of 0.051 m/s is required to meet the criteria set forth by [22], which is eight times the ACH. The condition of the spacious classroom openings opposite each other of 19.98m^2 , which is the area of ventilation apertures and open doors, may be used to determine the wind speed. The opening area while the door is closed is 16.13m^2 , requiring an airflow speed of 0.064 m/s. A proper airtightness is not difficult to attain with an opening area of that magnitude,

around 20% of the floor area.

Figure 7 depicts the air temperature and relative humidity inside for one month (May 23 to June 23), with an average air temperature of 28.16°C and relative humidity of 79.30%. While the average air temperature in the room from 12:00 to 16:00 indicates a hotter than average daily temperature. The maximum air temperature was 31.7°C with RH as much as 72%, it occurring at 14:30, while the lowest was 25.4°C with RH 82%, and it happened between 04:00 and 06:30.

Figure 7. The profile of air temperature and humidity in the classroom within one month

Figure 8. The air temperature and airflow speed in the classroom when measuring the spray towards the hands of the sitting student

3.2. Position on Students' Hand

The speed of airflow measured when spraying droplets falling over a table from an armchair or in the student's hand position does not exceed 0.4 m/s. The first minute on the curve indicating airspeed shows a very small, flat, and even near-zero value; this is the moment before the spraying is done. At the spraying time, the airflow speed increases, which is affected by the initial spraying speed, as shown in Figure 8. Spraying is carried out in the first two stages using a strong spraying gun, while the second is done with a manual sprayer gun (weak spraying). An electric sprayer gun's initial spraying speed is 16.2 m/s, similar to when a teacher coughs or sneezes in front of a class. Although the initial rate used is not the same as the reel condition but can be used as a reference according to what was reported in experimental data by Chao et al. [24]. The speed of respiratory airflow and saliva micro-droplets injected from the mouth varies between 6.3 m/s and 22.3 m/s, and it is typical of a statistically representative variety of coughing and sneezing. Likewise, what was studied by Kwon et al. [21] reported speed as an average value only.

Spraying is carried out with three treatments, namely 1x sprayed, 2x sprayed, and 3x sprayed. The number and density of droplets that fall on the white paper surface are

presented in Figure 9, where they are placed from the source of the sprayer within 1 m, 2 m, and 3 m. The number and density of droplets that fall on the white paper size A4 with a surface area of 623.7 cm² are proportional to the distance, where the further the number and density occur. For 1x sprayed, the number of droplets that fall on the paper for distances of 1m, 2m, and 3m amounted to 258, 240, and 37 droplets with densities of 0.41, 0.38, and 0.06 droplets/cm² respectively. The more spraying is done, the greater the number and density of droplets that fall on the paper. Three times sprayed results support it at 1m, 2m, and 3m the number of droplets that fall on paper as many as 885, 826, and 191 droplets with densities of 1.42, 1.32, and 0.31 droplets/cm², respectively. It implies that droplets can reach distances greater than 2 meters, possibly even 3 meters or more.

On the next occasion, spraying was carried out using a manual sprayer gun, with the initial speed of the spray being 1.3 m/s. Therefore, it can be assumed to be similar to the initial velocity of speaking. Consequently, it is reasoned still following the range produced by the Asadi et al. study [20], and also because all of these studies at the initial speed did not use fixed values but all reported in maximum values [20], averages [21], or interval values [24] alone.

Position on the arm of the chair (student's hand)			
Type's sprayer	Strong (electric)		
Distance	1m	2m	3m
1x sprayed
	No. of droplets: 258 Density: 0.41 drop./cm ²	No. of droplets: 240 Density: 0.38 drop./cm ²	No. of droplets: 37 Density: 0.06 drop./cm ²
2x sprayed
	No. of droplets: 787 Density: 1.26 drop./cm ²	No. of droplets: 694 Density: 1.11 drop./cm ²	No. of droplets: 63 Density: 0.10 drop./cm ²
3x sprayed
	No. of droplets: 885 Density: 1.42 drop./cm ²	No. of droplets: 826 Density: 1.32 drop./cm ²	No. of droplets: 191 Density: 0.31 drop./cm ²

Figure 9. Droplet traces from the strong sprayer on white paper were placed on the table of an armchair for 1x, 2x, and 3x sprayed at distances of 1m, 2m, and 3m. All images have been modified with 100% sharpness

The same treatment as intense spraying, in weak spraying, the number and density of droplets that fall on paper is less compared to what happens to spray using an electric sprayer, whose initial speed is much greater. The number and density of droplets that land on paper largely depend on how many times the spray is done and the distance from the mist's source.

The number and density of droplets that fall on paper at

distances of 1m, 2m, and 3 m for 1x sprayed are 457, 34, 19 droplets and 0.73, 0.05, and 0.03 droplets/cm², respectively. The farther away, the fewer droplets that land on paper. However, with this weak spraying, droplets can still reach more than 2 m, even up to 3 m in small amounts, as described in Figure 10. The results of research supported this by Merghani et al. [25] and Renzi et al. [26], which found that the largest droplets

consistently traveled more than two meters due to a phenomenon known as a buoyant vortex - the turbulent motion of hot air masses that are ejected along with

droplets when sneezing or coughing. In addition, they claim that buoyant vortices push droplets more than 3.5 meters in some cases.

Position on the arm of the chair (student's hand)			
Type's sprayer	Weak (manual)		
Distance	1m	2m	3m
1x sprayed
	No. of droplets: 457 Density: 0.73 drop./cm ²	No. of droplets: 34 Density: 0.05 drop./cm ²	No. of droplets: 19 Density: 0.03 drop./cm ²
2x sprayed
	No. of droplets: 530 Density: 0.85 drop./cm ²	No. of droplets: 23 Density: 0.04 drop./cm ²	No. of droplets: 23 Density: 0.04 drop./cm ²
3x sprayed
	No. of droplets: 652 Density: 1.05 drop./cm ²	No. of droplets: 15 Density: 0.02 drop./cm ²	No. of droplets: 14 Density: 0.02 drop./cm ²

Figure 10. Droplet traces from a weak sprayer spraying on white paper put on an armchair's table for 1x, 2x, and 3x scattered at 1m, 2m, and 3m distances

Figure 11. The air temperature and airflow speed in the classroom when measuring the spray towards the position of the sitting student's face

3.3. Position on Students' Face

The third scenario checks the range of sprays to students' faces 1 m, 2 m, and 3 m from the spray source, in the number and density of droplets. For this purpose, a piece of white paper is placed in the student's faces when they sit at a distance of 1m, 2m, and 3m (cf. Figure 4 (b)). Airflow speed and air temperature in classrooms were measured, where the initial rate did not exceed 0.1 m/s before spraying and fluctuated when spraying with a maximum value of no more than one m/s. This airflow speed is more dominantly affected by the initial velocity of spraying. While the recorded air temperature ranges from 26.2 °C to 27.2 °C, as shown in Figure 11.

With the same protocol as what is completed on spraying on the student's hand, the same is achieved for spraying that hits the part of the student's face.

In spraying using an electric sprayer or intense spraying, producing traces of droplet on paper varies in the number and density of droplets, depending on the distance from the spraying source. The farther away, the lower the number and density of droplets. The number and density of droplets that fall on paper at the student's face position with distances of 1m, 2m, and 3m to 1x sprayed using intense spraying of 569, 73, 13 droplets 0.91, 0.12, and 0.02 droplets/cm², respectively.

Student's face position			
Type's sprayer	Strong (electric)		
Distance	1m	2m	3m
1x sprayed
	No. of droplets: 569 Density: 0.91 drop./cm²	No. of droplets: 73 Density: 0.12 drop./cm²	No. of droplets: 13 Density: 0.02 drop./cm²
2x sprayed
	No. of droplets: 643 Density: 1.03 drop./cm²	No. of droplets: 122 Density: 0.20 drop./cm²	No. of droplets: 2 Density: 0.00 drop./cm²
3x sprayed
	No. of droplets: 708 Density: 1.14 drop./cm²	No. of droplets: 123 Density: 0.20 drop./cm²	No. of droplets: 21 Density: 0.03 drop./cm²

Figure 12. Droplet traces from the strong sprayer on white paper were placed on the position of the student's face for 1x, 2x, and 3x sprayed at distances of 1m, 2m, and 3 m

The number and density of droplets that hit the paper depending on how many times the spray is performed. The more mist, the denser the droplets on the form, as shown in Figure 12.

Furthermore, using a manual sprayer, an investigation was carried out whether the flow of droplets could reach a distance of 2 m and 3 m. Figure 13 explains that droplets can reach the position of a student's face up to a distance of 2 m with a less significant amount and density, but at a distance of 3 m, it is difficult to reach.

Droplets can reach a student's face if the teacher

repeatedly speaks, as is done with 2x and 3x sprayed. In the case of 2x sprayed, the number and density of droplets landing on paper differ significantly compared to 3x spread, let alone at a close distance of 1 m from the source.

It explains that the droplets before reaching the student's face are pulled by gravity first and fall to the floor. Conversely, in the position of the student's hand, although at a distance of 3 m and using a manual sprayer, the number and density of trace droplets in the paper are still relatively large and dense.

Figure 13. Droplet traces from a weak sprayer on white paper were placed on the student's face position for 1x, 2x, and 3x spray times at distances of 1m, 2m, and 3 m

Type's sprayer	Weak (manual)		
Distance	1m	2m	3m
3x sprayed, with droplets landing on the student's hand position.
	No. of droplets: 652 Density: 1.05 drop./cm²	No. of droplets: 15 Density: 0.02 drop./cm²	No. of droplets: 14 Density: 0.02 drop./cm²
3x sprayed, with droplets landing on the student's face.
	No. of droplets: 29 Density: 0.05 drop./cm²	No. of droplets: 7 Density: 0.01 drop./cm²	No. of droplets: 0 Density: 0.00 drop./cm²

Figure 14. Comparison of the number and density of droplets that hit the hands and faces of students for 3x sprayed with a manual sprayer at distances of 1 m, 2 m, and 3 m

Figure 14 compares the number and density of droplets between arriving at the hands and on students' faces at the same distance using a manual sprayer with 3x sprayed.

For distances of 1 m, 2 m, and 3 m, the number and density of droplets that reached the hands of students were more than those exposed on their faces. It suggests that in stagnant airflow in the classroom, the effect of gravitational force plays a vital role in the droplets that reach the position of the student's face.

4. Conclusions

Visualization of flow patterns in naturally ventilated classrooms has been done using smoke machines. The flow of smoke rises upwards and drifts out through ventilation holes and open doors, indicating that the airflow that occurs is not caused by the wind entering the classroom. It is also due to the unfavorable position of the school for cross ventilation.

The spread of droplets sourced from spraying an electric sprayer using a dyeing liquid similar to the initial speed at which coughing and sneezing can reach more than 3 m, including those that land on students' hands and faces while sitting. While what resulted from using a manual sprayer was likened to the initial speed when the person was speaking, the amount and density were even insignificant, which reached a distance of 3 m from the

sprayer, both hitting the student's hands and face.

The number and density of droplets that hit the hands and face largely depend on the distance from the spraying's source and how often the spraying occurs. The closer and more frequently sprayed, the greater the amount and density. In the hands and face's position, determined by the initial speed of the spray droplets, the faster, the more the number and density of droplets reached the hands and faces of the students.

The number and density of droplets that reach the position of the hand are more numerous and denser than those getting the face position, caused by the influence of the gravitational force that pulls the falling droplets before reaching a higher and farther plane on the vertical profile, between the part of the student's face and hand. This condition occurs when the airflow is stagnant, or the airflow speed is close to 0 m/s.

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