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Perlite Has Similar Diffusion Properties for Oxygen and Carbon Dioxide to Snow: Implications for Avalanche Safety Equipment Testing and Breathing Studies

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Abstract: On average, one hundred people die each year under avalanche snow. Despite extensive global research on gas exchange in buried avalanche victims, it remains unclear how the diffusion of respiratory gases affects survival under avalanche snow. This study aims to determine how oxygen and carbon dioxide diffuse through snow, as well as through wet and dry perlite, which may serve as a surrogate for avalanche snow. A custom-made apparatus to study the diffusion of respiratory gases consisted of a plastic cylinder (1200 mm long, ID 300 mm) with 13 gas sampling needles evenly spaced along the axis of the cylinder filled with the tested material. Following 60 min of free diffusion, gas samples were analyzed using a vital signs monitor with a module for respiratory gas analysis (E-CAiOVX, Datex-Ohmeda, GE Healthcare, Chicago, IL, USA). A combination of 16% oxygen, 5% carbon dioxide, and 79% nitrogen was used. The rates of diffusion for both respiratory gases were comparable in snow and both forms of perlite. Oxygen propagated faster than carbon dioxide. Due to similar diffusion characteristics to snow, perlite possesses the potential to stand in as an effective substitute for soft snow for the study of respiratory dynamics, for conducting breathing experiments, and for testing avalanche safety equipment.

Keywords: diffusion; diffusion coefficient; oxygen; carbon dioxide; snow; avalanche; safety equipment; perlite

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1. Introduction

As the popularity of winter activities rises, so does the incidence of avalanche fatalities. According to European and American statistics, an average of one hundred people die annually in avalanches [1,2]. The majority of avalanche victims succumb to airway obstruction or critical hypoxia and hypercapnia [3]. Oxygen (O_2) concentration decreases while carbon dioxide (CO_2) concentration increases when the same air is rebreathed in a closed environment. The rate of this process is affected mainly by the properties of the snow [4].

Numerous studies have explored the diffusion of gases through snow cover and its effects on the emission of gases from snow-covered soil [5–10]. The diffusion coefficients (DCs) in all these studies were evaluated as so-called "effective diffusion coefficients" based on the correction of the DCs of gases in the air. Snow was considered to be a uniform, homogeneous, porous layer with constant porosity and tortuosity, and steady diffusion was assumed. Massman et al. [10] published an equation for calculating the theoretical DC of a gas through the studied material, based on the knowledge of the material's parameters and the actual environmental conditions:

$$D_x = \phi \cdot \tau \cdot D_{xair} \cdot \frac{P_0}{P} \cdot \left(\frac{T}{T_0}\right)^{\alpha}, \quad (1)$$

where D_x is the theoreticall y calculated DC of the gas in the material, ϕ is porosity, τ is tortuosity, and D_{xair} is the DC of the gas in air at standard temperature T_0 and standard pressure P_0. P is the actual pressure, T is the temperature of the material, and α = 1.81 is the temperature correction coefficient [11]. The DC of O_2 at standard pressure and temperature in air is D_{O_2} =17.6 $mm^2 \cdot s^{-1}$ [11]. The DC of CO_2 at standard pressure and temperature in air is D_{CO_2} = 13.8 $mm^2 \cdot s^{-1}$ [12].

Since tortuosity is very difficult to measure, it is usually expressed using the relationship from the Mast et al. study [9]:

$$\tau = \phi^{\frac{1}{3}}. \quad (2)$$

By solving the differential equation of Fick's second law, it is possible to compare the theoretical value of the DC (D_x) and the measured DC (D) obtained from the experimental data [13]:

$$\frac{c(x,t) - c_0}{c_s - c_0} = 1 - \text{erf}\left(\frac{x}{2 \cdot \sqrt{D \cdot t}}\right), \quad (3)$$

where $c(x,t)$ is the concentration at a given time t and the distance x from the constant gas source, c_0 is the ambient concentration, c_s is the concentration of the constant gas source, erf is the error function, and D is the measured DC.

Winston et al. [8] reported calculated values (corrected for porosity and tortuosity) of the DC of CO_2 in snow in the range of 8.1–9.9 $mm^2 \cdot s^{-1}$. In another study, the authors attempted to estimate DCs from measured fluxes and concentration profiles measured during winter using the first Fick's law and obtained values in the range of 2–50 $mm^2 \cdot s^{-1}$, with values exceeding the DC of CO_2 in air attributed to the effect of convection [8]. Schwander et al. [14] conducted a study on the diffusion of respiratory gases, O_2 and CO_2, to determine the age differences between ice and gases in their air pockets. The cylindrical firn samples used in the study were placed between two stainless steel adapters, sealed in a rubber tube, and then analyzed for their DCs of CO_2 and O_2 using a thermal conductivity detector. The firn had a porosity ranging from 0.13 to 0.5. The DC was discovered to have a near-linear dependence on the porosity, with DCs ranging from 0 to 10 $mm^2 \cdot s^{-1}$.

In an effort to investigate the gas exchange of an individual buried in avalanche snow, Roubik et al. [15] conducted a study to identify materials that could simulate snow. Three porous materials, including perlite, wood shavings, and polystyrene, were tested in both dry and wet forms. The time courses of the volunteers' recorded inhaled and exhaled concentrations of oxygen and carbon dioxide were very similar between the materials. Perlite was identified as the most suitable material for simulating avalanche snow due to its uniformity, reproducibility, and ease of manipulation. Furthermore, perlite is an inexpensive, non-toxic, amorphous mineral used commercially for its low density and ability to hold large amounts of water [16]. The subsequent study conducted by Roubik et al. [17] aimed to compare dry and wet perlite with snow in terms of ventilation and gas exchange parameters. Thirteen male subjects underwent three breathing phases—in snow, wet perlite, and dry perlite. The resulting values of the gas-exchange parameters for the snow used in the study ranged between those for dry and wet perlite.

According to a study conducted by Brugger et al. [18], the solubility of respiratory gases in snow or in the water contained in snow could affect the spread of gases when avalanche victims breathe under the snow. The solubility values of oxygen and carbon dioxide in water at 0 °C and standard atmospheric pressure are 1.46×10^{-2} $g \cdot L^{-1}$ and 3.3 $g \cdot L^{-1}$, respectively [19,20]. The solubility of CO_2 in ice is significantly lower [21]. In dry snow, the absorption of CO_2 at the ice surface is insignificant [22], but the flux in snow containing liquid water could be affected by the absorption processes.

Previous studies have investigated the diffusion of various gases through snow [5–10] or the properties of snow that affect gas exchange [4,18,23]; other studies have compared snow with other materials based on ventilation parameters [15,17]. However, no experimental study of the diffusion of respiratory gases in the snow layer and perlite in relation to avalanche survival has been conducted to our knowledge.

The aim of the study was to experimentally determine the diffusion rate of oxygen and carbon dioxide in snow, wet perlite, and dry perlite simulating avalanche snow and to compare the materials in terms of diffusion.

2. Methods

The experimental study of the diffusion of respiratory gases was conducted in Přední Labská, located in the Krkonoše mountains, at an altitude of 700 m above sea level. The study was conducted at ambient temperatures ranging from −1 °C to 1 °C and atmospheric pressure between 930 hPa and 937 hPa.

2.1. Apparatus

A special apparatus made of a polyvinyl chloride cylinder, 1200 mm long, with an inner diameter of 300 mm, was designed to study the diffusion properties of respiratory gases. The apparatus and its components are depicted in Figure 1. The cylinder was hermetically closed from the bottom with a cover using buckles (1). A plastic mesh (2) was mounted inside the cylinder, dividing the cylinder into two parts, the inlet chamber serving as a constant concentration gas mixture source and the chamber for the diffusion through the tested material. The inlet chamber volume was minimized to 3 L. Twelve airtight O-rings (3) were evenly spaced and secured along the cylinder wall to prevent the gases from propagating along it. Thirteen metal needles (4) connected to three-way valves (5), each 50 mm apart in the vertical direction, were used for gas sampling from defined points of the cylinder, of which twelve were located in the chamber with the tested material and one in the inlet chamber (6). Gas sampling lines connected to the needles led to the vital signs monitor containing a module for respiratory gas analysis (E-CAiOVX, Datex-Ohmeda, GE Healthcare, Chicago, IL, USA). Two ports were created in the inlet chamber: the gas inlet port (7) with an inner diameter of 3 mm supplying the gas mixture to the inlet chamber and the gas outlet port (8) with an inner diameter of 11 mm. The mixture of O_2, CO_2, and N_2 was created using pressure-reducing valves (9) and throttle valves (10).

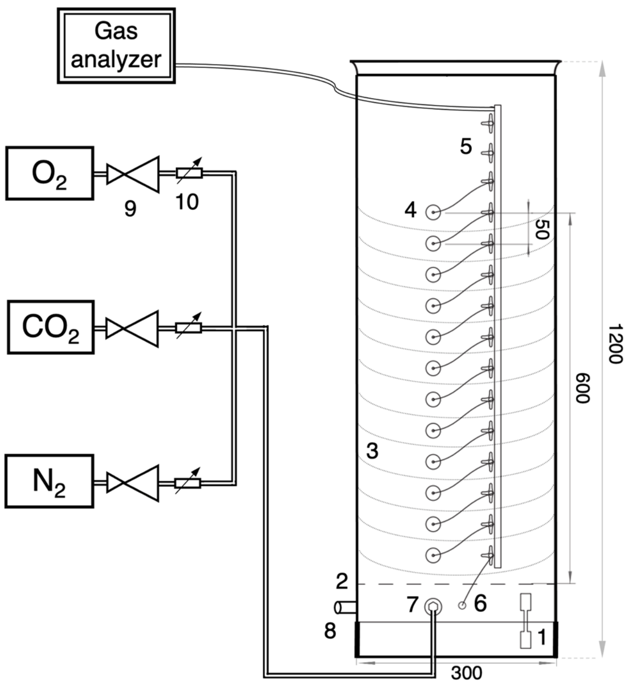

Figure 1. A scheme of the apparatus with the gas analyzer and gas cylinders. 1—buckle fixing the cover to the cylinder; 2—plastic mesh separating the cylinder into two parts; 3—airtight O-rings; 4—rubber plug with a metal needle; 5—three-way valve; 6—sampling point of the gas mixture in the inlet chamber; 7—gas inlet port; 8—gas outlet port; 9—pressure-reducing valve; 10—throttle valve. Dimensions are in millimeters.

2.2. Protocol

Snow (S), wet perlite (PW), and dry perlite (PD) were tested in this study. The basic physical properties of the materials, including density, porosity, and grain size, were measured before each measurement using a calibrated container (1.6 L) and a standardized raster for snow grain size measurement. Liquid water content and snow hardness were determined according to the international classification for seasonal snow on the ground [24]. The cylinder was then filled with 60 L of the tested material. The cylinder was filled gradually to prevent the formation of large cavities in the tested materials. After each measurement, the density of the tested material was measured at three vertical positions (bottom, middle, and top).

The gas mixture that entered the cylinder through the inlet port was composed of 16% oxygen, 5% carbon dioxide, and 79% nitrogen. The inlet chamber was supplied with a constant flow of 2 L/min. To prevent overpressure and any potential convection of respiratory gases through the tested materials, an open gas outlet port with a considerably larger cross-section (13 times the area of the gas inlet port) was used.

The O_2 and CO_2 concentrations were measured after 60 min of diffusion to cover the entire span of the chamber at all twelve sampling points situated within the chamber containing the tested material. Additionally, the concentrations were measured in the inlet chamber to ensure the stability of O_2 and CO_2 concentrations in the supplied gas mixture. The temperature of the gas mixture was continually monitored during the experiment.

2.3. Data Processing and Analysis

Gas samples from each sampling point were recorded by S/5 collect software (version 4.0, Madison, WI, USA) with an extension program for data analyses [25].

The recorded data for oxygen from each sampling point were normalized by recalculation:

$$N_{O_2} = \frac{20.9 - c_t}{20.9 - c_0} \ , \tag{4}$$

where N_{O_2} is the resulting normalized oxygen concentration, c_t is the gas concentration at a given location and time, c_0 is the gas concentration in the inlet chamber, and the number 20.9% represents the oxygen concentration in the air. The recorded data for carbon dioxide from each sampling point were normalized by recalculation:

$$N_{CO_2} = \frac{c_t}{c_0} \ , \tag{5}$$

where N_{CO_2} is the resulting normalized concentration of carbon dioxide.

Plots depicting the normalized concentrations of both respiratory gases in the tested materials at varying distances from the inlet chamber were created. After the Shapiro–Wilk test for data normality, the statistical significance of the differences between the respiratory gases for each material was tested using the *t*-test. ANOVA for repeated measures with LSD post hoc tests (STATISTICA 7.1, StatSoft, Tulsa, OK, USA) was used to compare materials in terms of diffusion rate. $p < 0.05$ was considered statistically significant.

Theoretically calculated DCs were determined based on the physical properties of S, PW, and PD using Equation (1). Measured DCs for S, PW, and PD were calculated according to Equation (3) using concentrations of O_2 and CO_2 measured at twelve sampling points in the cylinder, 60 min after commencing the experiment.

3. Results

The snow used during the experiment was classified as dry and moist snow of low density (150 ± 5 kg·m^{-3}). The snow grain size was determined to be 1 mm (medium to coarse), and the snow hardness corresponded to soft snow (4F). The density of PD was 157 kg·m^{-3} with a porosity of 0.78 and a tortuosity of 0.92, and the density of the PW, prepared as a mixture of dry perlite and water in a defined weight ratio of 80:20, was 250–255 kg·m^{-3}.

Figure 2 illustrates the findings of the analysis of normalized concentrations of O_2 and CO_2 in S, PW, and PD materials after a diffusion time of 60 min. O_2 propagated faster than CO_2 in all materials. For S and PW, the concentrations of O_2 and CO_2 differed significantly throughout the cylinder, except for the first sampling point. For PD, there was a significant difference in concentrations of O_2 and CO_2 beginning 250 mm from the inlet chamber.

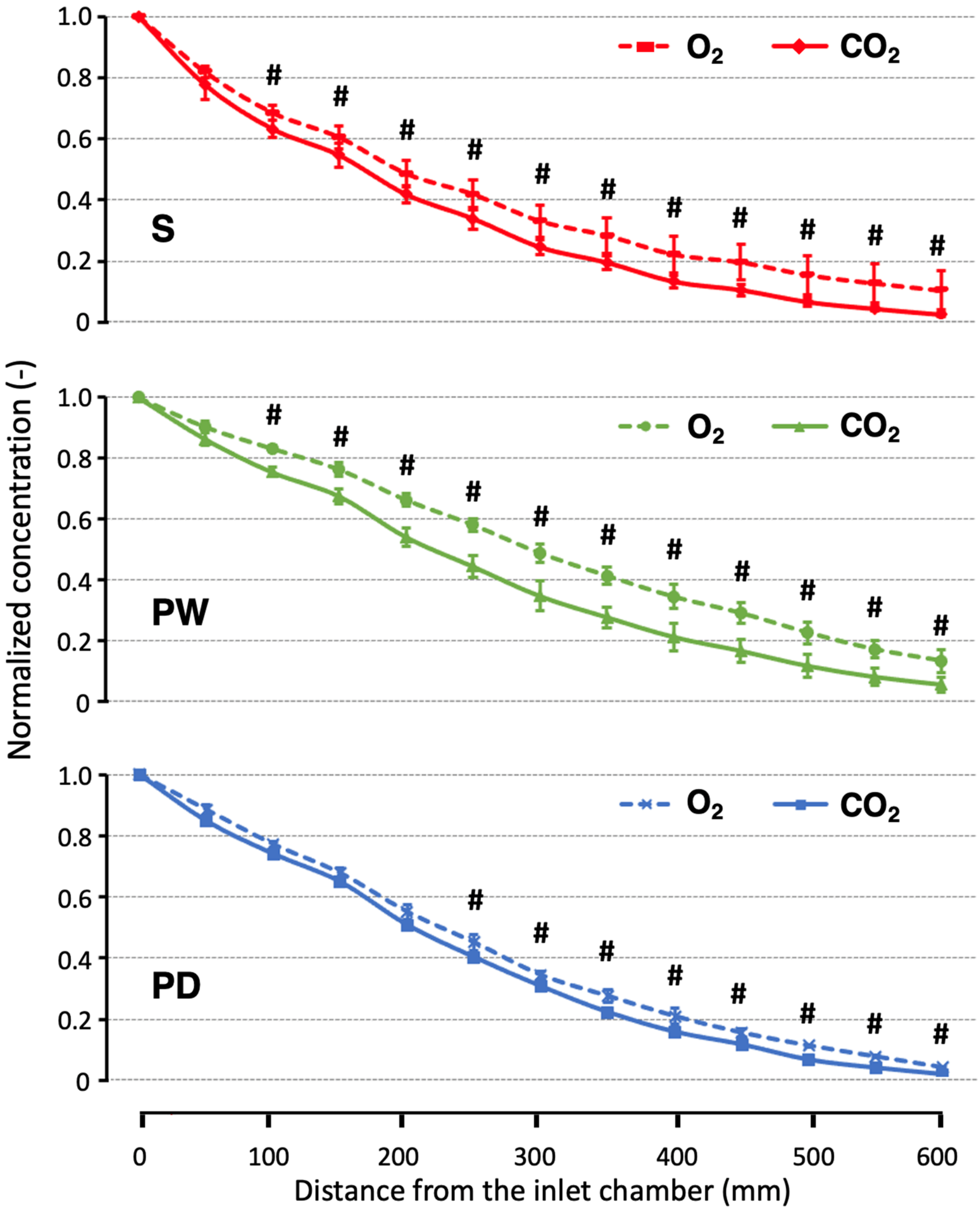

Figure 2. Normalized measured concentrations of O_2 and CO_2 related to the concentrations in the inlet chamber depending on the distance from the inlet chamber in S, PW, and PD. Symbol # indicates a statistically significant difference between O_2 and CO_2.

When comparing the tested materials, O_2 propagated the fastest in PW, as shown in Figure 3. The rate of O_2 propagation in the snow was bordered by the rate of propagation in PW and PD from a distance of 300 mm from the inlet chamber. For CO_2, the differences were less pronounced between PW and PD than for O_2. The rate of CO_2 propagation in S was slower than in PW or PD.

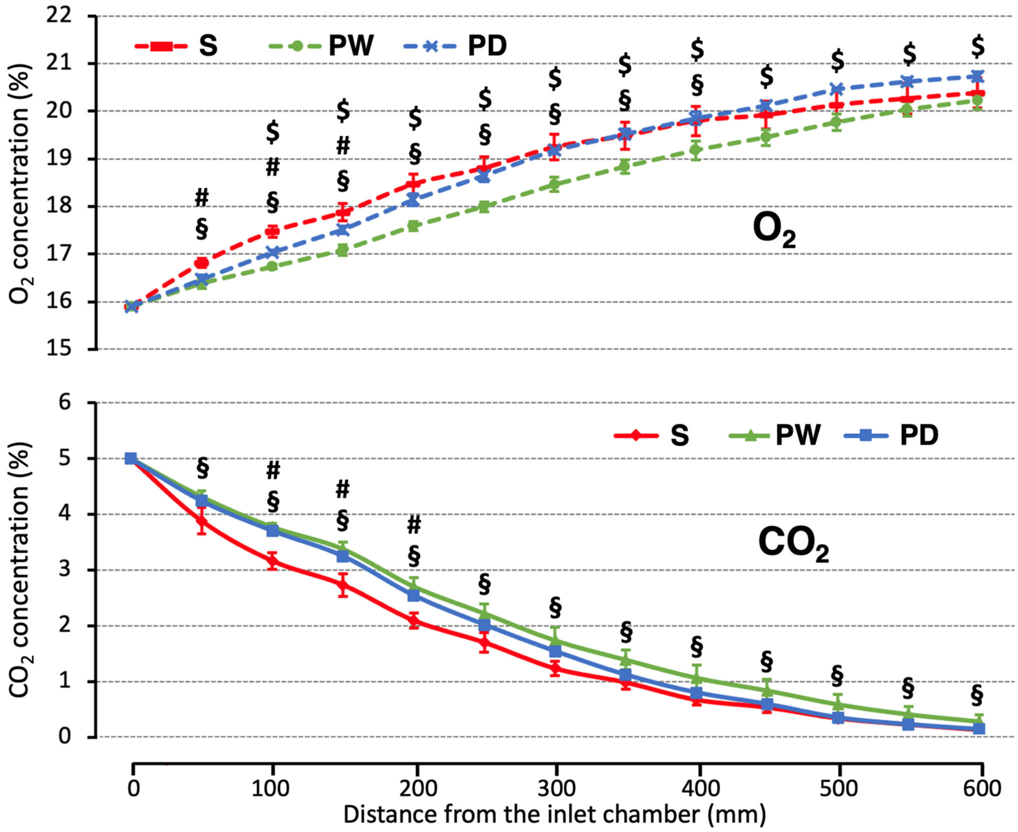

Figure 3. Measured concentrations of O_2 and CO_2 related to the concentrations in the inlet chamber depending on the distance from the inlet chamber in S, PW, and PD. Symbol # indicates a statistically significant difference between S and PD, symbol $ indicates a statistically significant difference between PW and PD, and symbol § indicates a statistically significant difference between S and PW.

The density of the snow, measured after the experiment, varied from 304 $kg \cdot m^{-3}$ (porosity of 0.66 and tortuosity of 0.87) at greater depths to 145 $kg \cdot m^{-3}$ (porosity of 0.84 and tortuosity of 0.94) at shallower depths. With the decrease in snow depth and density, the average DCs for O_2 and CO_2 increased on average up to 19 $mm^2 \cdot s^{-1}$ and 11 $mm^2 \cdot s^{-1}$, respectively, as shown in Figure 4.

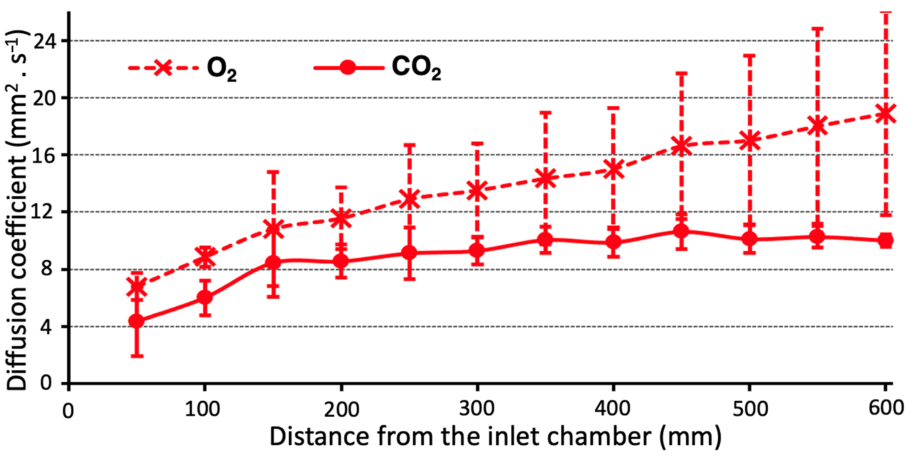

Figure 4. The measured DCs for O_2 and CO_2 in snow depending on the distance from the inlet chamber.

A comparison between the theoretically calculated and measured DCs of O_2 and CO_2 in S, PW, and PD is shown in Table 1. For S, the theoretically calculated DCs were

11.1–15.1 $mm^2 \cdot s^{-1}$ for O_2 and 8.7–11.9 $mm^2 \cdot s^{-1}$ for CO_2 depending on the snow density and environmental conditions. The decrease in snow density resulted in measured DCs for O_2 exceeding theoretical DCs. The measured DCs for CO_2 were in good agreement with the theoretically calculated DCs, except for the first two sampling points. The average ratio of DCs between O_2 and CO_2 was between 1.2 and 1.9.

Table 1. Theoretical and measured DCs of O_2 and CO_2 in S, PW, and PD.

Material		**O_2 DC ($mm^2 \cdot s^{-1}$)**	**CO_2 DC ($mm^2 \cdot s^{-1}$)**	**O_2/CO_2 DC Ratio (-)**
S	Theoretical	11.1–15.1 *	8.7–11.9 *	1.27
	Measured	13.2 ± 3.7	8.8 ± 1.9	1.50 ± 0.17
PW	Theoretical	10.9	8.5	1.27
	Measured	25.8 ± 2.5	14.0 ± 1.0	1.85 ± 0.14
PD	Theoretical	13.8	10.8	1.27
	Measured	13.0 ± 1.1	11.2 ± 1.2	1.16 ± 0.06

* Depending on the density.

The measured DCs in PW, ranging from 22.2 to 29.5 $mm^2 \cdot s^{-1}$ for O_2 and from 11.5 to 15.3 $mm^2 \cdot s^{-1}$ for CO_2, largely exceeded the theoretically calculated DCs. On average, the ratio of DCs between O_2 and CO_2 was between 1.7 and 2.1.

In PD, the theoretically calculated DC was calculated to be 13.8 $mm^2 \cdot s^{-1}$ for O_2 and 10.8 $mm^2 \cdot s^{-1}$ for CO_2. The measured DCs for O_2 were found to be 1 $mm^2 \cdot s^{-1}$ lower than the theoretically calculated DCs, whereas those for CO_2 were in agreement with the theoretically calculated DCs. Thus, the measured ratio of DC between O_2 and CO_2 was 1.16 ± 0.06, which was lower than the theoretical value.

4. Discussion

The main finding of this study is that perlite in both forms (wet and dry) has similar diffusion properties for oxygen and carbon dioxide as the low-density snow used in this study. Oxygen diffused faster than carbon dioxide in all tested materials, consistent with the diffusion coefficients for both respiratory gases.

S and PW exhibit similarly in terms of diffusion, with a marked difference between oxygen and carbon dioxide in both materials. In contrast, for PD the difference between O_2 and CO_2 is minimal but still statistically significant, as presented in Figure 2.

We speculate that the greater difference between O_2 and CO_2 in PW and S compared to PD may be attributed to the absorption of CO_2 in the water present in these two materials. This is because the experiment was conducted at temperatures around 0 °C. The small difference in diffusion between O_2 and CO_2 in PD could potentially be attributed to the physical and chemical distinctions among the molecules. The effect of CO_2 solubility in water was also considered in the breathing experiments conducted by Brugger et al. [18], where the authors speculated that the snow surrounding the air pocket might act as a CO_2 buffer, owing to its 24-fold higher solubility of CO_2 in water compared to O_2 [26]. It is important to note, however, that the findings may have been different at lower ambient temperatures, as the absorption of CO_2 in ice is very low and almost unmeasurable, according to a study by Ahn et al. [21].

The equation published in the study by Massman et al. [10] for estimating the theoretically calculated DC in snow was applied to PW and PD in this study. The measured DCs for both respiratory gases were twice as high as the theoretically calculated DCs when utilizing Equation (1) for PW. It can be speculated that this is due to water or ice in the PW causing clogging of the pores in the individual grains, resulting in the faster propagation of respiratory gas molecules around the individual grains. In PD, the measured DC for O_2 was about 1 $mm^2 \cdot s^{-1}$ lower (relative deviation up to 8%) than the theoretically calculated values, but the measured DC for CO_2 was in good agreement with the theoretically calculated value. The measured ratio of DC between O_2 and CO_2 was found to be 1.16 ± 0.06, which is lower than the theoretical value of 1.27.

The measured DCs for both PD and PW remained unchanged throughout the entire cylinder, probably due to the compactness and incompressibility of the perlite. The DCs were notably highest in PW, with measured values up to 29.5 $mm^2 \cdot s^{-1}$ for O_2 and 15.3 $mm^2 \cdot s^{-1}$ for CO_2. The slight difference observed between PW and PD for CO_2 may have arisen from the potential absorption of CO_2 in the water present in PW.

The density of the snow varied throughout the cylinder, possibly due to gravitational forces. At the deepest sampling points of the apparatus, where the snow density reached 304 $kg \cdot m^{-2}$, the measured DC for O_2 was approximately 5.7–9.5 $mm^2 \cdot s^{-1}$. At shallower depths, the measured O_2 DCs were up to 10 $mm^2 \cdot s^{-1}$ (1.6 times) higher than they should theoretically be. The measured DCs for CO_2 were consistent with the theoretical calculations. However, there is a possibility that the CO_2 absorption in water has compensated for the decreasing snow density and any potential faster diffusion.

Solomon et al. [27] measured the distribution of CO_2 from soil to air through snow and determined that the measured DC of CO_2 in snow ranged from 2.6 to 10 $mm^2 \cdot s^{-1}$. However, it is important to note that the measurement was conducted mainly in snow with a higher density compared to this study. The measurement done by Schwander et al. [14] was performed in firn with a porosity between 0.13 and 0.5. The measured DCs were 0–10 $mm^2 \cdot s^{-1}$ for O_2 and 0–8 $mm^2 \cdot s^{-1}$ for CO_2, respectively. In the present study, the snow porosity ranged from 0.66 to 0.84. The measured DCs for both respiratory gases corresponded to those measured in the study by Schwander et al. [14].

The convective process of respiratory gas exchange in a closed environment between the lungs of a victim buried in avalanche snow and the surrounding avalanche snow, with increasing concentrations of CO_2 and decreasing concentrations of O_2, occurs so rapidly that only 30% of victims survive for 35 min under the snow [28]. The diffusion of respiratory gases during breathing experiments into the simulated avalanche snow has been considered in various experiments [4,18,29]. Grissom et al. [23] conducted an experimental study which indicates a negative correlation between CO_2 diffusion and snow density. The higher the snow density, the slower the diffusion of CO_2 from the subject. Based on research conducted by Strapazzon et al. [4,29], higher snow porosity surrounding the air pocket may facilitate O_2 diffusion. Low and medium snow densities allow enhanced diffusion of O_2 into the air pocket and of CO_2 out of the air pocket, prolonging the duration of the breathing experiments. The results of the present study are consistent with the findings of the above studies that O_2 propagates faster than CO_2 and that the solubility or absorption of CO_2 could affect the rate of diffusion. It should be acknowledged, however, that the diffusion rate in snow is relatively slow compared to the rate of gas exchange (caused by the high cyclic tidal volumes and flows) in a subject breathing under avalanche snow, so the increase in survival time is limited.

The similar diffusion properties of respiratory gases in snow and perlite, as well as the similar trends of gas exchange during breathing in snow and in dry and wet perlite [17], suggest the possibility of perlite being utilized as a suitable material for testing technical and new avalanche safety equipment prior to field experiments in mountain environments or for the preparation of breathing experiments and their protocols [30–32]. Perlite can also be used for studies on different population groups (i.e., with different physical conditions, ages, etc.) and for training subjects in the laboratory environment for outdoor experiments, if this training is a part of the protocol.

The study has several limitations. As the measurements were carried out at temperatures around 0 °C, the snow may have melted along the cylinder wall, thus allowing respiratory gases to pass along the wall. Nonetheless, any gas flow along the cylinder wall was prevented by twelve airtight O-rings. Secondly, the amount of water contained in the snow could have varied throughout the experiment. Measurements at lower temperatures should be conducted to verify the impact of water or ice on gas diffusion within the material.

Furthermore, the findings of this study on the diffusion of respiratory gases are limited to low-density snow.

Obvious limitations of perlite when used as a model material of avalanche snow are that it has different material properties than snow and, unlike snow, there is no interaction between perlite and respiratory gases. In real-life scenarios, snow undergoes changes upon contact with the warm respiratory gases exhaled by the buried subjects. On the other hand, perlite is non-toxic, homogeneous in its structure, does not change its properties over time, and is available for experiments all year round.

Next, the theoretically calculated DCs for PW were calculated based on Equation (1), which was specifically derived for snow. However, the unclear determination of porosity and tortuosity for the mixture of dry perlite and water, coupled with the potential for water or ice to clog pores in individual perlite grains, may impact the resulting values. Finally, the impact of gravity on the diffusion of respiratory gases has not been tested.

5. Conclusions

The findings from this study emphasize that perlite can serve as an effective substitute for soft snow in controlled environments, enabling research in the realms of avalanche safety, respiratory science, and diverse population studies. Perlite, with similar diffusion characteristics to snow, presents opportunities to refine field experiments contributing to the enhancement of safety measures and procedures during avalanche incidents and might facilitate our understanding of respiratory dynamics in snow under various conditions.

Author Contributions: S.W. and K.R. conceptualized the study. All authors prepared the methodology of the study. S.W. and K.R. administered the study. S.W. and K.R. executed the study and acquired the data. S.W. and M.R. performed data analysis, interpretation, and visualization. S.W., M.R., and K.R. drafted the manuscript. All authors revised and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The datasets generated and analyzed during the current study are available in the repository at https://ventilation.fbmi.cvut.cz/data/ (accessed on 19 November 2023).

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Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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