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Surface Air Movement: An Important Contributor to Ventilation of Isolated Subsurface Structures?

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Abstract: This study reports on near-surface airspeed measured using a fast-responding thermoanemometer during an investigation of ventilation of an isolated subsurface structure induced by natural forces. Air speed changes continuously, rapidly, and unpredictably when assessed on the time base of one or two seconds. Zero, the most common air speed, occurred in almost all tests throughout the year but especially during cool and cold months. The most probable non-zero air speed, 10.7 m/min (35 ft/min), occurred in all tests. This air speed is below the level of detection by the senses. The number of zero values and the height of the peak at 10.7 m/min follow a repetitive annual cycle. Isolated subsurface structures containing manhole covers share the characteristics of Helmholtz resonators. Grazing air flow across the opening to the exterior induces rotational air flow in the airspace of a Helmholtz resonator. Rotational flow in the airspace potentially influences the exchange of the confined atmosphere with the external one. Ventilation of the airspace occurs continuously and without cost and is potentially enhanced by the unique characteristics of the Helmholtz resonator excited by surface air movement. These results have immense importance and immediate applicability to worker safety.

Keywords: repetitive annual pattern; confined space; isolated subsurface structure; near-surface airflow; fast-response thermoanemometer; velocity distribution

1. Introduction

Opening(s) in manhole covers and access hatches is/are the point of air exchange between the external atmosphere and the atmosphere in subsurface structures [1–3]. Open networks such as sewers contain interlinked structures and a common shared airspace. Some of the structures in the subsurface infrastructure are isolated from each other by design. In structures which are isolated from each other, the internal atmosphere is potentially unique compared to other similar structures. Isolation of the atmosphere in these structures can occur both in space and in time. Isolation in time can occur for long periods. Isolation in time subjects the atmosphere and environmental conditions in these structures to internal and external influences. These influences can create hazardous conditions for workers involved in periodic entry and work as demonstrated in historic and current references [4–11].

Reviews of some of the recent fatal incidents indicated that actions needed to minimize the risk posed by hazardous atmospheric conditions in the airspace are often not taken. Oxygen deficiency can result when chemical or biochemical processes occur on surfaces in the structure. The migration of gases and vapors can occur through soils [12–16]. Entry from the surface of volatile chemical substances accidentally spilled in the vicinity or deliberately poured into access opening(s) in the cover of the structure for disposal is another possible route of entry. Evaporation can lead to the development of a contaminated atmosphere in the airspace. Consistent, optimized ventilation of isolated subsurface structures not entered for a long period induced by natural forces minimizes the development and persistence of hazardous atmospheres. A logical venue through which to pursue these actions is the Prevention through Design (PtD) initiative of the National Institute for Occupational Safety and Health (NIOSH) [5].

Manhole covers and access hatches often contain one or more openings to the atmosphere. These provide the only pathway through which the exchange of the confined atmosphere with the external atmosphere can occur. This exchange depends on the physical movement of gas through the opening(s). This exchange is not intuitive. Casual interviews with practitioners in occupational health and safety individually and in groups consistently demonstrate the belief that the exchange is not occurring.

One of the possible influences on the exchange of the atmosphere in an isolated subsurface airspace and the external atmosphere is air movement along the ground. This study reports on an investigation of this phenomenon. The published technical literature contains little material directly applicable to the subject of airflow along the surface of the ground. Airspeeds less than 15 to 24 m/min (50 to 80 ft/min) do not inform the senses that air movement is occurring [17]. This is likely part of the reason for the absence of knowledge of occupational health and safety practitioners about the occurrence of air exchange in isolated subsurface structures.

In 1936 and in subsequent years, investigators at the US Bureau of Mines published a series of reports concerning ventilation induced by natural forces of the airspace in isolated cast-in-place manholes similar to those belonging to utilities in the Boston area [1,18–20]. Air speed was measured using a three-cup anemometer mounted on a frame in the initial test approximately 1.5 m (60 inches) above the manhole cover and later at 0.75 m (30 inches) above the manhole cover. The height at which air speed was measured was considerably above the height of potential influence of near-surface wind flow on the exchange of contaminated air between the airspace of the structure and the external atmosphere.

In the first report, investigators at the US Bureau of Mines demonstrated that two-way ventilation occurs through a single opening located in the manhole cover [1]. The means by which the exchange occurs is not intuitive and requires further elucidation. What is apparent is that inflow and outflow must occur through the same opening. Where more than one opening is available, the path of inflow and outflow is no less apparent.

The investigators commented in the first two reports [1,18] about the influence of the wind on ventilation rate without providing measurements obtained during this work. The third investigation specifically examined the role of air velocity across the openings in the manhole cover [19]. In the latter, the investigators embedded the bottom surface of a wind tunnel around the manhole cover. A wind tunnel provides precise control over air velocity above the openings in the manhole cover. Results indicated that increasing the air velocity across the manhole cover from 0 to 4.5 m/s (10 mi/h), irrespective of the area of the openings, increased the ventilation rate by 50%. The investigators found no definite relationship between percent increase in ventilation rate due to air velocity across the manhole cover and area of the openings.

Gribble [21] speculated about the incorporation of engineered features by the builders of the largest of the Egyptian tombs (KV5) in the Valley of the Kings to induce ventilation by natural forces. KV5 is horizontally oriented and several chambers and many sub-chambers are located at different levels [22]. The other tombs in the Valley of the Kings are vertically oriented. Tombs in the Valley of the Kings have only a single entrance. Flow-through ventilation was not technically possible by this choice of design. Yet, ventilation was essential for thermal comfort and for removal of airborne dust and other contaminants during the mining activity involved in construction. Gribble [21] speculated that specific differences in the elevation of floors during construction induced natural airflow into and out of the airspace of the structure through the single opening. Ventilation induced by natural forces was possible because of the thermal conditions imposed by the desert climate. Air cools rapidly at night and induces flow based on difference in temperature outside the tomb compared to the airspace inside. The efficiency and effectiveness of the process depended on the absence of turbulent mixing between the two flows.

Beyond these reports, wind flow close to ground level has received little attention in the technical literature. The current focus in the literature is the movement of the wind at heights for ventilation of buildings and power generation. For structures that experience isolation in time, the exchange between the external atmosphere and the atmosphere in the airspace is critically important [3,5]. McManus [3] and McManus and Haddad [manuscripts submitted for review, not yet cited] confirmed the work of investigators at the Bureau of Mines [1] that ventilation induced by natural forces occurs continuously and showed through videos how the process involving surface airflow occurs and through instrumental monitoring that the process produces an instantaneously well-mixed atmosphere in the airspace. McManus and Haddad (manuscripts submitted for review, not yet cited) showed that air quality in the airspace (represented by decrease in concentration of CO introduced from a small gasoline engine just prior to the start of monitoring) improves in a predictable manner dependent on the number of openings in the manhole cover as well as other factors under investigation. Optimizing a reduction in the concentration of contaminants in these structures considerably decreases risk to passersby as well as to workers who must enter and work in them.

Weather forecasters typically report wind velocity at a height of 10 m above the ground using the three-cup or multi-cup anemometer [23,24]. Wind velocity decreases from that height in open air to considerably lower levels near the ground. This decrease, known as the wind gradient (shear), is due to the roughness of the surface of the earth [25]. This roughness depends on topography, natural features such as forests, and structures that form towns and cities.

The decrease in velocity with decreasing height above ground level is modeled as a logarithmic or power curve. Chen et al. [23] evaluated five mathematical models using statistical indices to determine the most appropriate one. The logarithmic model did not adequately describe the variation of wind speed with height between 0 and 10 m above the ground. These authors found power law models to be more applicable. The exponential term ranged from 0.3 to 0.6 for the two-parameter model and 0.4 to 0.6 for the three-parameter model. The three-parameter exponential function can favorably fit data for wind speed versus height.

Mini- and micro-fluctuations in wind velocity near the surface of the ground were not a consideration of the investigators at the US Bureau of Mines [1,18–20]. Mini- and micro-fluctuations in air velocity normally are not a consideration in measurements used in weather-forecasting, design of buildings to resist wind loads, and design of structures such as windmills and wind turbines to optimize the capture of wind [23]. Macro-fluctuations outweigh any impact and resulting consideration of mini- and micro-fluctuations at the heights of equipment and structures normally under consideration. Micro-fluctuations in velocity are not a concern in forums that discuss design and are not discussed in published literature and on-line resources discoverable on the Internet. At heights just above the ground where air velocity is considerably less due to surface roughness, mini- and micro-fluctuations have the potential to influence ventilation of the airspace in isolated subsurface structures. Information about the characteristics of airflow at these heights is currently unavailable.

Casual experience gained by industrial users of modern fast-responding air velocity meters equipped with dataloggers and operating on short time constant (1 sample/1 s) indicated that air speed near the ground changes rapidly. The challenge for operators of this equipment is to determine the 'correct' value for air speed when the display shows a wide range of values during half a minute of observation. While determining the 'true' value is functionally as simple as storing values over a period of time and determining the average, these rapid changes indicate that airflow near the surface in the absence of the influence of moving vehicles and other sources of turbulence is considerably more complex than first appears. The literature is silent on this type of study and its significance.

2. Materials and Methods

This work was performed in the yard of a construction company in Burnaby, BC, a suburb of Vancouver. Trucks and equipment left the yard prior to the start-up of measuring equipment and returned late in the afternoon after the completion of measurements. Measurements were obtained using a thermoanemometer (Kanomax Climomaster and 6541-2G probe, Kanomax USA, Andover, NJ). During a test, the body of the instrument was positioned into a short section of plastic pipe held horizontally approximately 20 cm above the ground (Figure 1). The pipe provided firm positioning as well as camouflage to minimize interest in passers-by concerning this activity. The probe was horizontally oriented in the north–south direction and the opening in the probe, vertically. The manual for the instrument indicates that the probe receives flow from an arc at least 45° in size on each side of the center line though the opening [26]. This orientation maximizes capture effectiveness but cannot indicate direction. The probe has a response time of 1 s to reach 90% of the reading at 1 m/s and an accuracy of ±2% of the reading or ±0.015 m/s, whichever is greater. This response is almost instantaneous and a considerable improvement over the averaging capability of the three- or four-cup anemometer. The instrument was new at time of first use and was calibrated by the manufacturer.

(**a**) (**b**)

Figure 1. Near surface air velocity and temperature. (**a**) The general area of the study. (**b**) The probe of the thermoanemometer is visible in the picture. The probe is approximately 20 cm above the ground and oriented approximately north–south in the horizontal plane. This height and the canopy above provided protection to the probe from dust and rain.

The instrument was programmed to sample once per second (1 sample/1 s) or once per two seconds (1 sample/2 s). The datalogger can accumulate 9999 records of both velocity and temperature. The datalogger was downloaded following every test using software sold for the instrument (Anemometer Measuring Software for Windows, Version 5.45, Kanomax Japan, Inc., Kanomax USA, Andover NJ). This software captures individual readings and calculates the arithmetic mean, standard deviation and maximum and minimum value during the period of operation. This scheme limited the sample time to a maximum of 167 min using the sampling regime of 1 sample/1 s and 334 min for 1 sample/2 min. Under these regimes, the completion time for a start time around 07:00 were 09:47 and 12:35, respectively.

Thermoanemometers are normally contraindicated for use outdoors because of sensitivity to condensing levels of moisture and dusty environments. Protection of the probe against wetting by rain and contact with airborne particulates is essential. Protection against wetting occurred through use of a canopy shelter positioned above the area in which measurement occurred. The frame positioned the center of the canopy approximately 2 m above the ground. The sides of the structure were completely open to the flow of air. In protecting the probe of the anemometer against wetting, the canopy was positioned so as not to interfere with normal surface wind flow. The canopy appeared not to influence readings provided by the instrument. Protection against contact with airborne particulates is a function of the choice of location, regular cleaning of the probe (as needed) and comparison against a source having known velocity. The site under study was free from airborne dust, a benefit from a climate that experiences frequent rain.

Software functions in Microsoft Excel (Microsoft Office, Microsoft Corporation, Redmond, WA) were used to visualize the frequency distribution of air speed values. Statistical tests were performed using SOFA, Version 1.4.6 [27].

3. Results

This work occurred during most months of the calendar. During the winter months, there was no snow or ice in the work area. The surface across which air flowed near the cover of the manhole remained unaltered during the period in which measurement occurred. Hence, the effects observed reflected surface air flow. Results reported here form part of a larger study of ventilation of isolated subsurface structures induced by natural forces [3]. Videos obtained during this study indicated that air movement occurred along the surface of the ground. The videos also showed the manner of entry of air into the opening(s) in a manhole cover and across and downward through the airspace of the structure. Air entered a single opening infrequently and unpredictably. Entry into two openings was considerably enhanced and occurred regularly compared to what occurred when a single opening was present.

Table 1 contains the summary data provided by the Kanomax software. Several trends are observable. Mean velocity was consistently higher during the summer months compared to autumn, winter and spring. Considerable variability expressed through the mean value, standard deviation, range and maximum value exists throughout the year. Zero was a value during all but seven of the 83 days of measurement. At the same time, the minimum value was 2 ft/min for 4 days, 6 ft/min for 2 days, and 16 ft/min for 1 day. Six of the non-zero days occurred during June, July and early August.

Table 1. Summary of Data Provided by the Thermoanemometer.

Date	Rate	Mean ft/min	Std Dev	Min ft/min	Max ft/min
2015					
Jan-30	1/1 s	53	57.6	0	344
Feb-11	1/2 s	91	78.7	0	583
Feb-17	1/2 s	62	58.3	0	417
Feb-18	1/2 s	197	134	0	841
Feb-19	1/2 s	115	76	0	490
Feb-20	1/2 s	69	64.4	0	490
Feb-23	1/2 s	65	49.9	0	425
Feb-24	1/2 s	94	74.1	0	474
Feb-25	1/2 s	132	91.1	0	555
Feb-26	1/2 s	147	110	0	650
Feb-27	1/2 s	56	41.4	0	343
Mar-02	1/2 s	87	57.4	16	447
Mar-03	1/2 s	82	71.9	0	545
Mar-05	1/2 s	110	85.3	0	581
Mar-06	1/2 s	72	60.5	0	455
Mar-09	1/2 s	144	97.5	0	630
Mar-10	1/2 s	56	41.8	0	317
Jun-08	1/2 s	156	92.8	2	618
Jun-10	1/2 s	111	74.3	0	583
Jun-12	1/2 s	157	106	6	880
Jun-22	1/2 s	157	106	6	880
Jun-24	1/2 s	200	125	0	768
Jun-26	1/2 s	181	110	0	711
Jun-30	1/2 s	198	126	0	844

Table 1. *Cont.*

Date	Rate	Mean ft/min	Std Dev	Min ft/min	Max ft/min
Jul-03	1/2 s	178	96.9	0	677
Jul-07	1/2 s	201	128	2	791
Jul-09	1/2 s	177	104	0	687
Jul-13	1/2 s	157	109	0	699
Jul-15	1/2 s	202	128	0	880
Jul-17	1/2 s	152	99.9	2	656
Jul-21	1/2 s	135	96.5	0	722
Jul-23	1/2 s	168	119	0	732
Jul-30	1/2 s	134	94	0	724
Aug-04	1/2 s	163	110	2	793
Aug-06	1/2 s	111	81.1	0	573
Aug-10	1/2 s	106	92.7	0	656
Aug-12	1/2 s	110	77.2	0	573
Oct-22	1/2 s	83	64	0	441
Oct-26	1/2 s	128	96.5	0	904
Nov-03	1/2 s	87	79.8	0	526
Nov-05	1/2 s	54	40.2	0	1199
Nov-09	1/2 s	57	52.2	0	411
Nov-12	1/2 s	231	168	0	1553
Nov-16	1/2 s	92	76.8	0	720
Nov-19	1/2 s	52	49.2	0	543
Nov-23	1/2 s	48	47.4	0	435
Nov-25	1/2 s	32	27.9	0	278
Nov-27	1/2 s	43	36.1	0	236
Dec-01	1/2 s	114	93.4	0	703
Dec-03	1/2 s	163	112	0	1246
Dec-07	1/2 s	64	58.6	0	457
Dec-09	1/1 s	57	46.7	0	476
Dec-14	1/1 s	226	158	0	994
Dec-16	1/1 s	40	30.8	0	331
Dec-18	1/1 s	55	43.3	0	280
Dec-22	1/1 s	43	44.5	0	321
2016					
Jan-05	1/1 s	35	40.5	0	325
Jan-11	1/1 s	63	69.6	0	545
Jan-15	1/1 s	36	44	0	360
Jan-19	1/1 s	80	85.7	0	563
Jan-21	1/1 s	209	146	0	994
Feb-22	1/1 s	78	81.3	0	551
Feb-24	1/1 s	67	80	0	425
Feb-26	1/1 s	33	39.5	0	396
Jun-14	1/1 s	129	137	0	1144
Jun-16	1/1 s	198	115	0	750
Jun-20	1/1 s	135	109	0	750
Jun-23	1/1 s	110	98.6	0	931
Jun-27	1/1 s	67	40.7	0	305
Jun-29	1/1 s	175	143	0	906
Jul-04	1/1 s	116	102	0	630
Jul-06	1/1 s	111	85.9	0	518
Jul-08	1/1 s	137	110	0	959
Jul-12	1/1 s	53	43.3	0	343
Jul-18	1/1 s	114	89.4	0	719
Jul-20	1/1 s	139	106	0	724
Jul-22	1/1 s	67	56.2	0	591
Jul-26	1/1 s	105	92.9	0	602

Table 1. *Cont.*

Date	Rate	Mean ft/min	Std Dev	Min ft/min	Max ft/min
Jul-28	1/1 s	60	54.5	0	476
Aug-02	1/1 s	55	46.7	0	656
Aug-04	1/1 s	45	41.7	0	344
Aug-08	1/1 s	134	113	0	744
Aug-10	1/1 s	35	31.5	0	376

Air speed data for March, 2015 and June, 2015 and June, 2015 and July, 2015 contained in Table 1 were compared by the independent t-test using SOFA, Version 1.4.6 [27]. The independent t-test comparing mean air speed obtained during March, 2015 versus June, 2015 indicated that the difference between the mean of the groups was statistically significant (p = 0.001) and that there was little difference in the variance between the groups (O'Brien's test for homogeneity of variance = 1.0). Mean standard deviations obtained during tests in March, 2015 were statistically different (p = 0.005) from mean standard deviations obtained in June, 2015. There was little difference in the variance between the groups (O'Brien's test for homogeneity of variance = 0.76). Mean maximum values obtained in March, 2015 were statistically different (p = 0.002) from mean maximum values obtained in June, 2015. There was little difference in the variance between the groups (O'Brien's test for homogeneity of variance = 0.79). By contrast, average air speed in tests performed in June and July, 2015 was not statistically different (p = 0.61).

Figures 2–5 contain the temporal distribution of air speed obtained from the thermoanemometer for representative days during winter, spring, summer and autumn. Figures 2–5 show that zero values occur singly and in clusters. Readings shown in Figures 2–5 indicate that near-surface air speed is considerably more variable than suggested in the summary data provided in Table 1. Air speed showed considerable variability when sampled in this manner (1 sample/1 s or 1 sample/2 s). Considerable variability occurred during the entire period of the test. As a result, near-surface air speed for every period in time is a statistical decision based on individual measurements within the period. The occurrence of a particular value at a particular moment is not predictable. On many days there was a baseline of almost constant speed around 10.7 m/min (35 ft/min). Highly variable air speeds superimposed onto and completely obliterated this baseline.

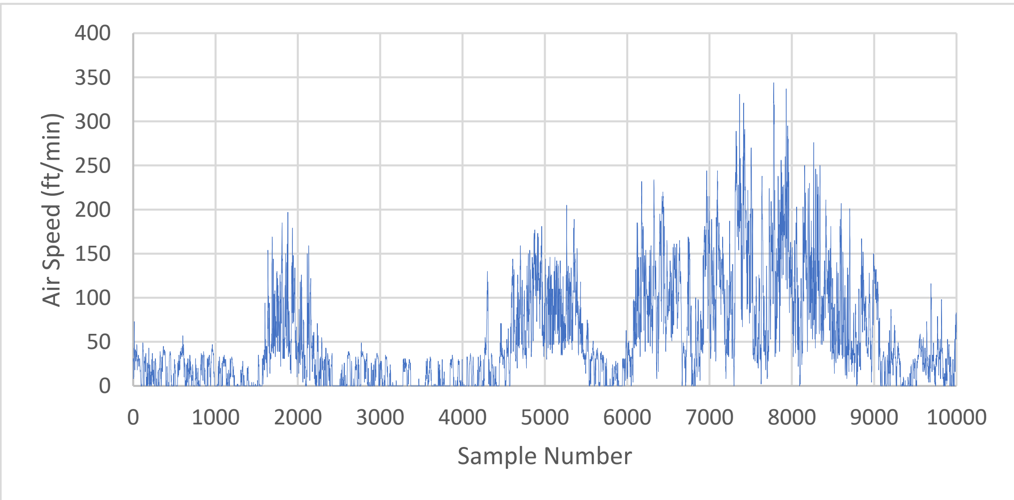

Figure 2. Air speed (ft/min) versus sample number for 30 January, 2015.

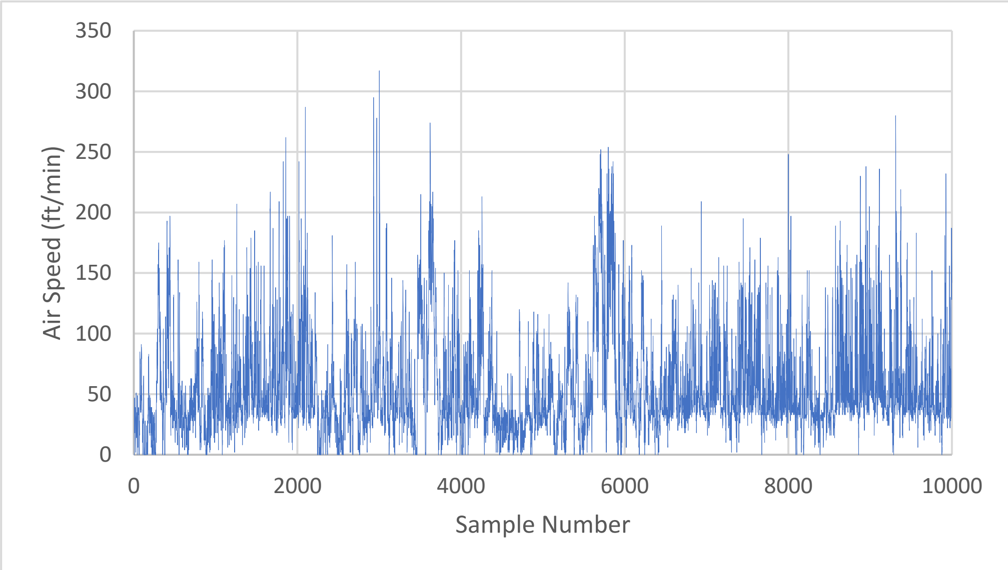

Figure 3. Air speed (ft/min) versus sample number for 10 March, 2015.

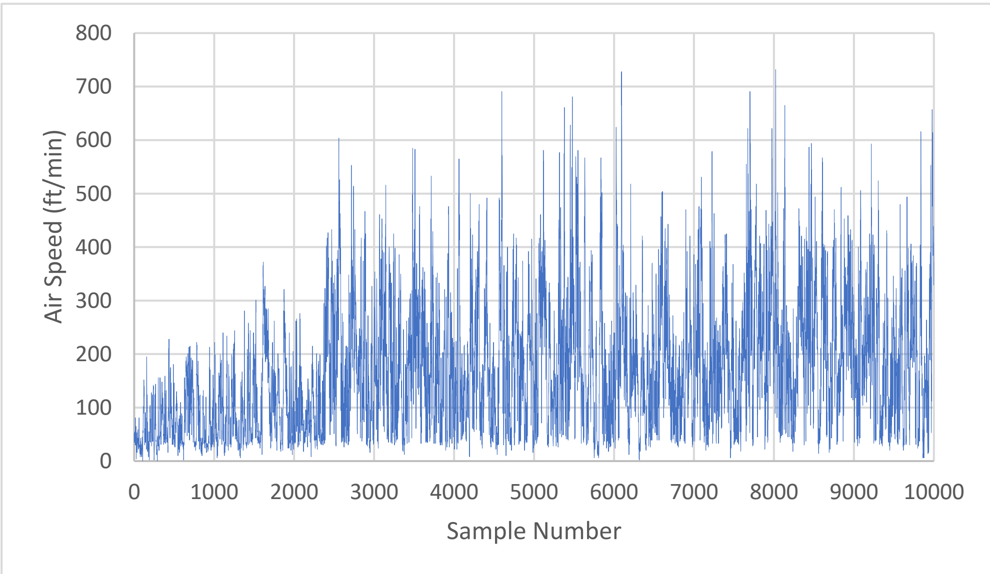

Figure 4. Air speed (ft/min) versus sample number for 23 July, 2017.

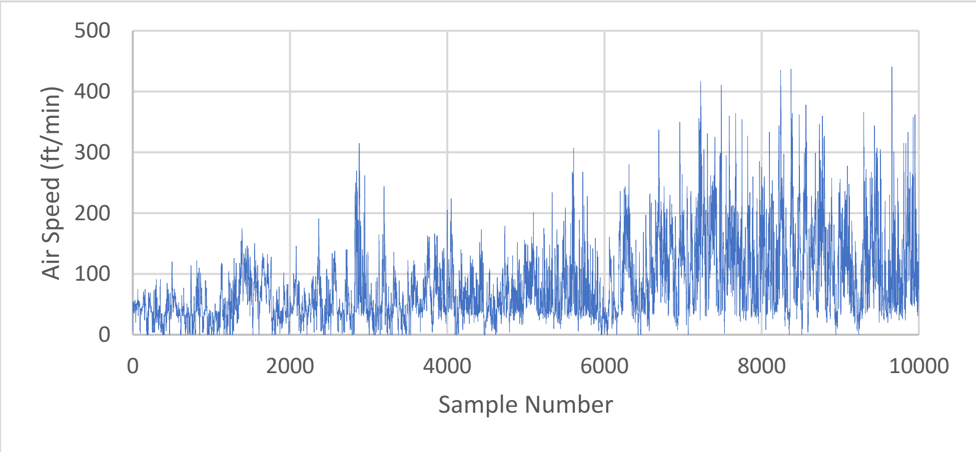

Figure 5. Air speed (ft/min) versus sample number for 22 October, 2015.

Figures 6–9 contain the frequency distribution of the same readings ranging from zero to the highest value obtained during a particular day. Figures 6–9 provide additional information about the occurrence of zero values and the visually apparent non-zero baseline mentioned above. Zero readings increased and decreased in frequency during the year in an annual pattern. The number of zero readings generally increases during the cooler months and decreases during the warmer months in an apparent annual cycle. The transformation used to create Figures 6–8 removes the ability to compare the relationship between individual readings provided by the instrument.

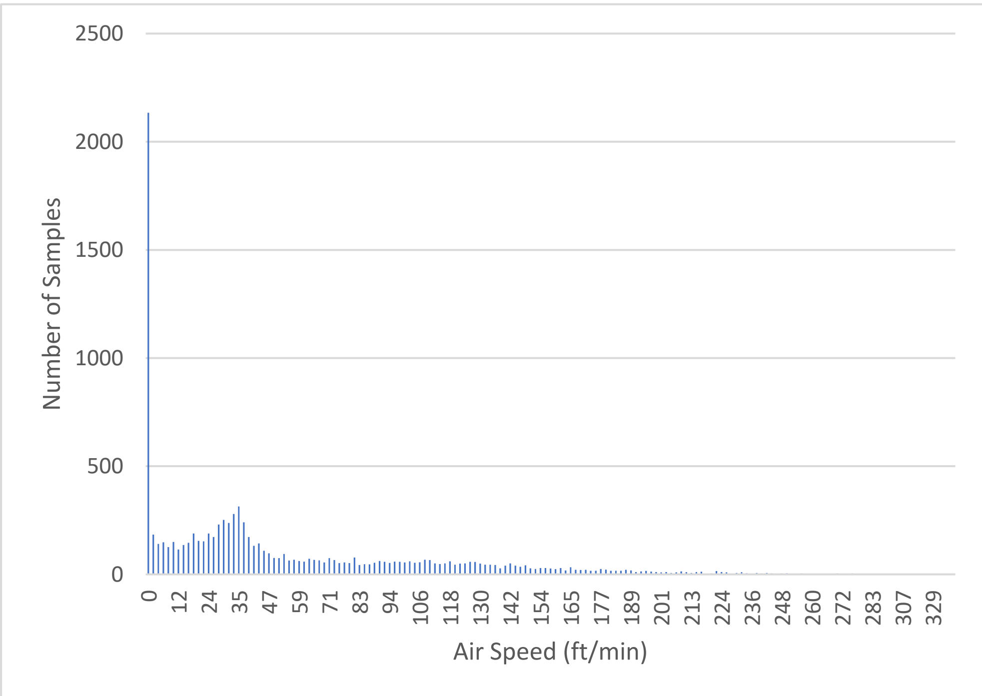

Figure 6. Frequency distribution comparing sample number versus air speed (ft/min) for 30 January, 2015.

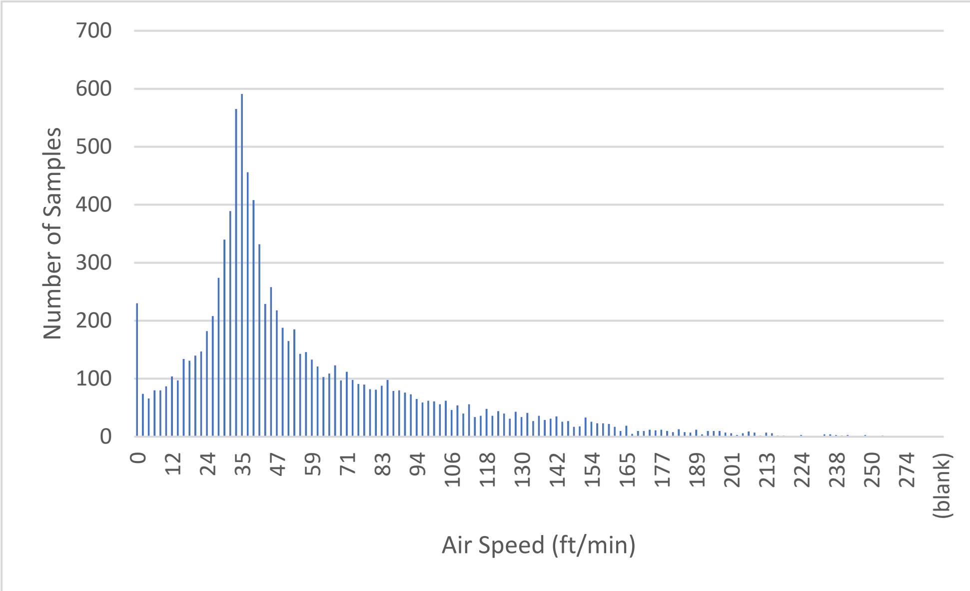

Figure 7. Frequency distribution comparing sample number versus air speed (ft/min) for 10 March, 2015.

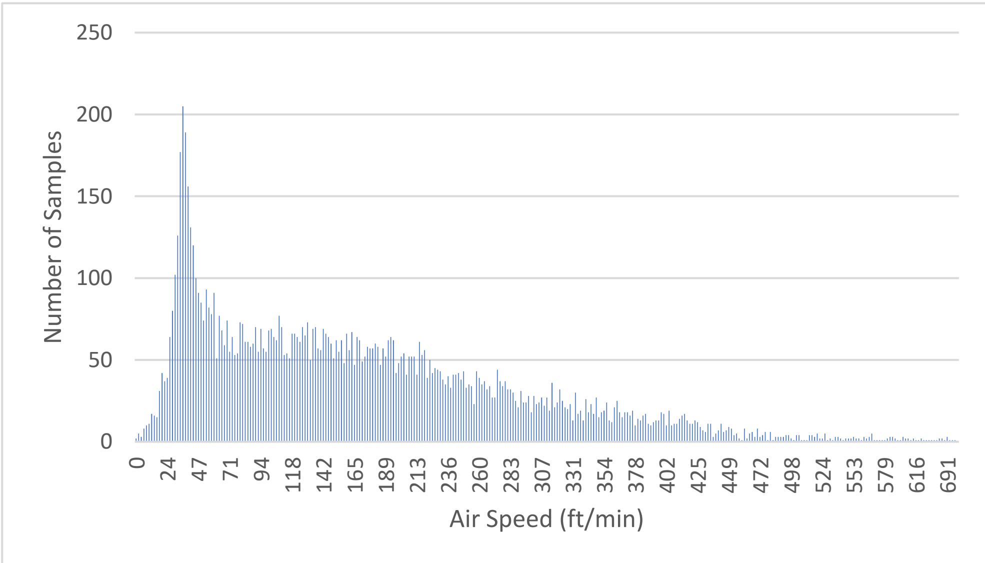

Figure 8. Frequency distribution comparing sample number versus air speed (ft/min) for 23 July, 2015.

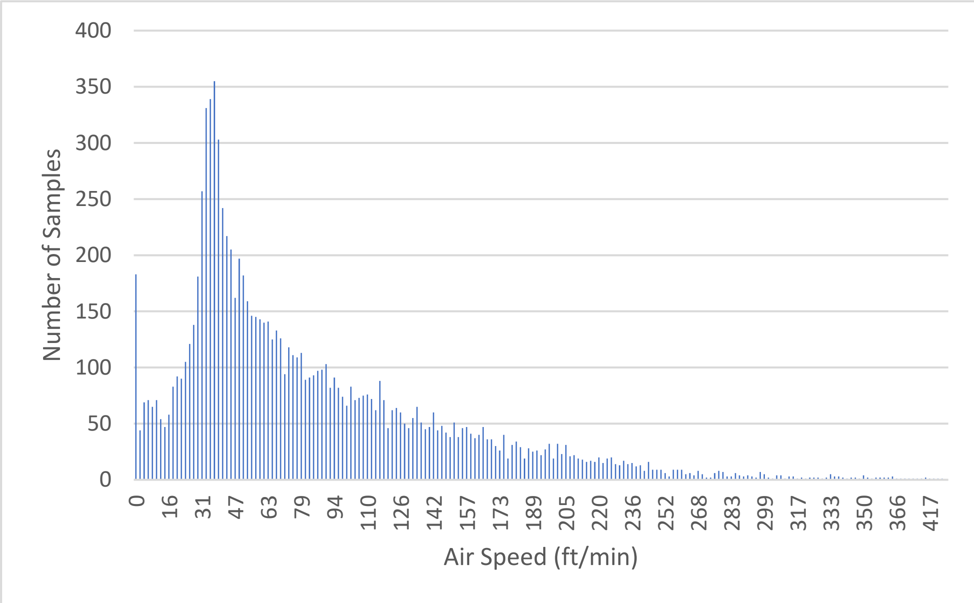

Figure 9. Frequency distribution comparing sample number versus air speed (ft/min) for 22 October, 2015.

Another trend occurring in all of the samples in Figures 6–9 is the recurrent peak located at 10.7 m/min (35 ft/min), indicating the most probable air speed. This value occurs in Figures 2–5 as the non-zero baseline onto which much larger highly variable values are often superimposed.

Figures 10–13 contain data from the same days converted to acceleration, having the units m/min/sec (ft/min/sec). The transformation used to create Figures 9–12 provides some ability to compare the relationship between individual readings provided by the instrument in Figures 2–5. The calculation of acceleration creates positive and negative values depending on whether the difference in air speed in successive readings reflects an increase (+ve difference) or decrease (-ve difference). Figures 10–13 show that these values cluster around zero. The caption for each figure contains the sum of the differences in successive readings. The sums are positive (>0) and increase and decrease in an annual cycle. Considered over 9999 readings provided by the datalogger, the average acceleration compared to average airspeed (Table 1) is very small. The increase and decrease in the value of the sums parallels the instability in the velocity during the same period, Figures 2–5.

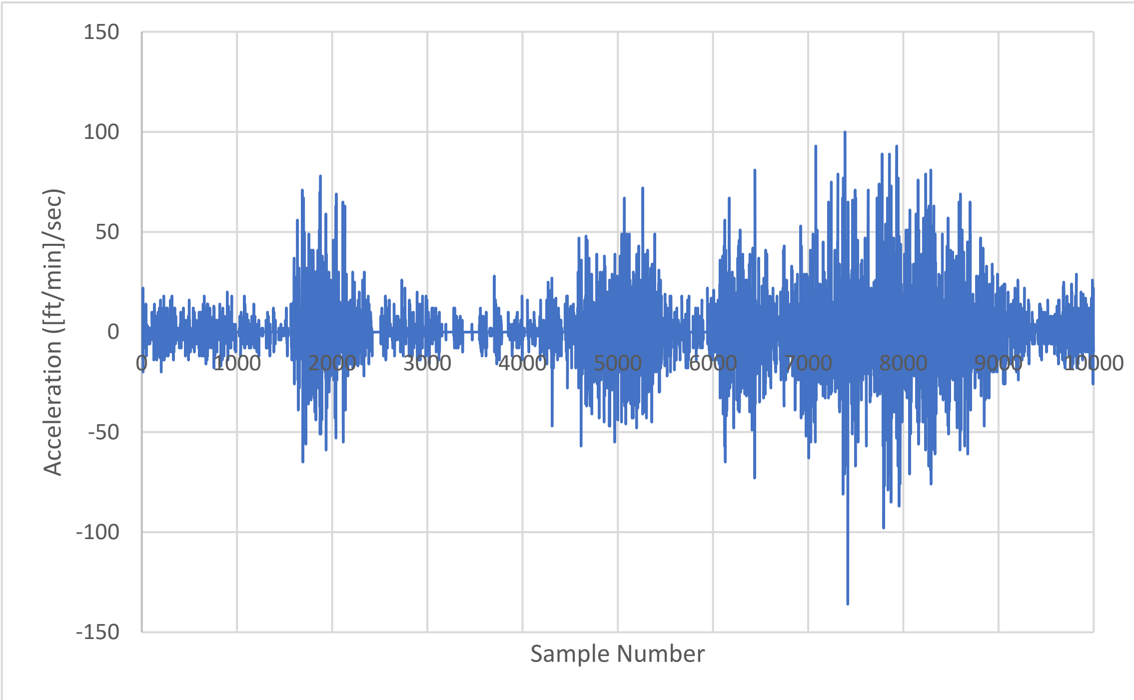

Figure 10. Plot of acceleration ([ft/min]/sec) versus sample number on 30 January, 2015. The sum of the acceleration over 9999 readings was 31 (ft/min)/sec.

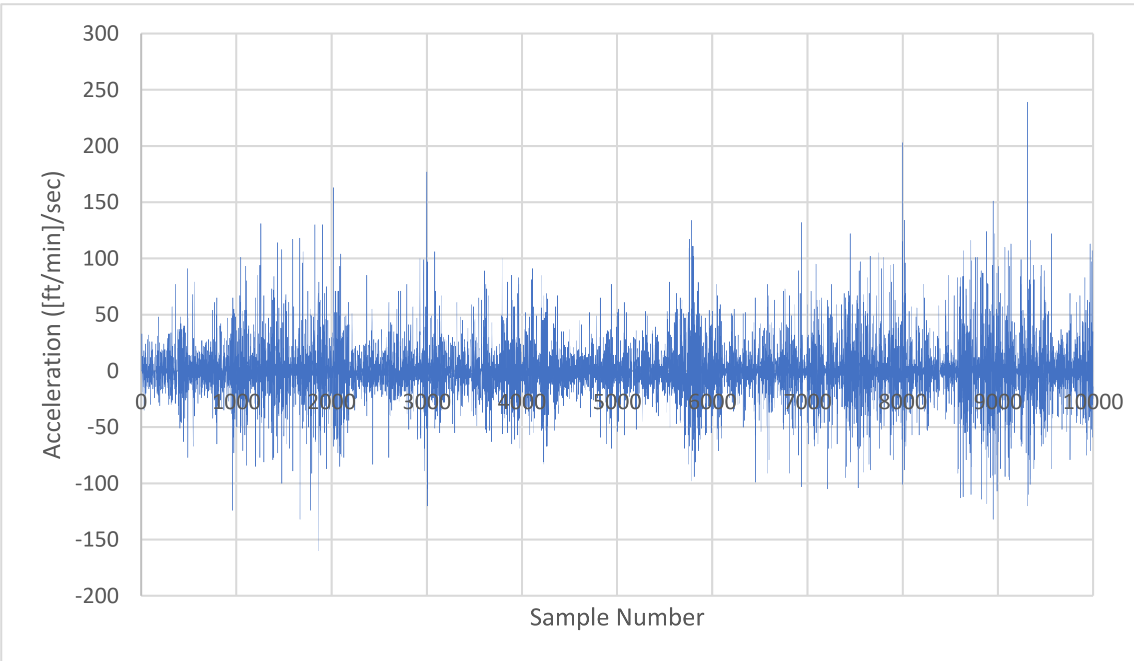

Figure 11. Plot of acceleration ([ft/min]/sec) versus sample number on 10 March, 2015. The sum of the acceleration over 9999 readings was 142 (ft/min)/sec.

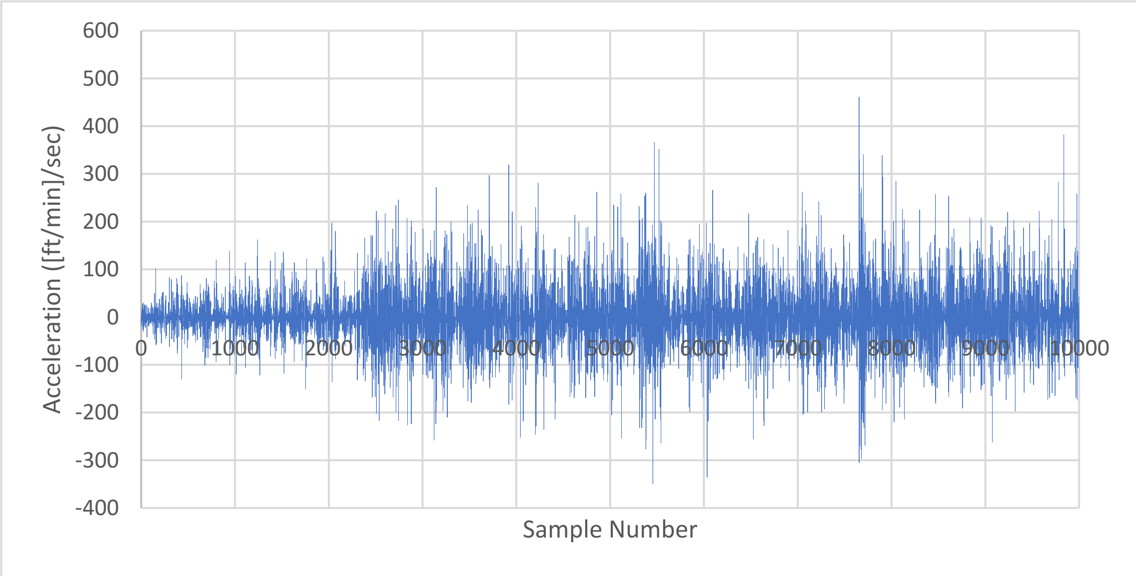

Figure 12. Plot of acceleration ([ft/min]/sec) versus sample number on 23 July, 2015. The sum of the acceleration over 9999 readings was 323 (ft/min)/sec.

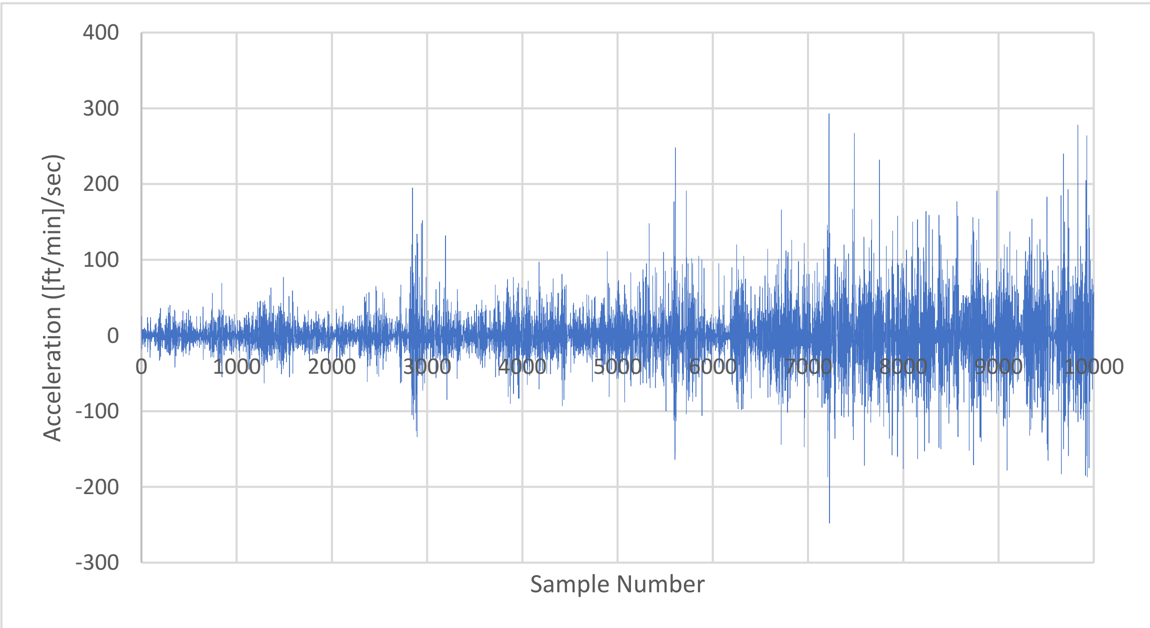

Figure 13. Plot of acceleration ([ft/min]/sec) versus sample number on 23 July, 2015. The sum of the acceleration over 9999 readings was 159 (ft/min)/sec.

4. Discussion

The subsurface infrastructure contains many isolated structures. The only means of the exchange between the internal atmosphere and the external atmosphere is/are the opening(s) in manhole covers and access hatches. Little is known or discussed about the possibilities or mechanisms of ventilation of these airspaces. Investigators at the Bureau of Mines provided the first evidence for the role of wind in the process [1,19]. The three-cup anemometer used by these investigators hindered detailed inquiry.

Results reported here form part of a larger study of ventilation of isolated subsurface structures induced by natural forces [3]. The decrease in concentration of carbon monoxide (CO) present in the exhaust of a gasoline engine was monitored as an indicator of the process. External air movement just above the ground is a potential influence. Results reported here indicated the occurrence of considerable variability in air speed when measured on a very short time base. Zero was the most commonly recorded value during cool and cold periods. The tests also demonstrated the occurrence of the most probable non-zero air speed (approximately 10.7 m/min [35 ft/min]) that is present throughout the year in all samples. In addition, many air speeds measured during these tests were considerably below human sensibility. Human sensibility is known from observation to occur around 15 to 24 m/min (50 to 80 ft/min) [17]. These observations open the possibility of a contribution to ventilation of isolated subsurface structures by air motion not sensed by humans. The inability to sense air movement at levels at which ventilation is occurring considerably hinders the perception and recognition that this process is occurring.

Identical testing conditions utilized in March, 2015 and June, 2015 provided the opportunity to determine the effect of change in the season on ventilation induced by natural forces. Statistically significant differences in near-surface air movement (air speed, standard deviation and maximum value) occurred between March, 2015 and June, 2015. A statistically significant difference also occurred in the rate of decrease in concentration of CO observed during the period [3]. Differences in air movement observed during June and July, 2015 were not significantly different.

Optimizing ventilation of subsurface structures induced by natural forces has the benefit of minimizing the concentration of contaminants trapped in the airspace at the time of opening the manhole cover for installation of mechanical ventilation in preparation for entry and the start of work. This, in turn, is an essential contributor to minimizing the risk of work faced by these individuals. The fact that ventilation induced by natural forces occurs routinely in these structures without operating cost with the ability to diminish or eliminate air contamination prior to opening the space for entry and work activity represents an important opportunity. Optimizing the process offers major benefit at minimal cost.

Isolated subsurface underground structures possessing manhole covers containing one or more opening(s) share an important characteristic not yet recognized in this and other discussions. These structures are cavity/deep cavity (Hemholtz) resonators [28–30]. Classic Helmholtz resonators (Figure 14) have a single opening to the atmosphere, a hollow neck and an enclosed airspace. There are a number of variations in geometry as seen in experimental studies. The opening to the atmosphere may have the same or smaller diameter than the hollow neck. The opening to the atmosphere may occur in a flanged horizontal surface. The airspace may have the same or a larger diameter than the hollow neck.

Figure 14. Helmholtz resonator. This ear syringe has the same shape as the resonators designed by Helmholtz. Classic Helmholtz resonators have a single opening to the atmosphere, a hollow neck and an enclosed airspace.

Isolated subsurface structures having manhole covers containing one or more openings share characteristics with classic Helmholtz resonators. The opening in the manhole cover is a cylinder molded into the steel. The cylinder in the manhole cover has the characteristics of a hollow neck. The steel casting containing the manhole cover usually rests on a cylinder formed from brick or precast rings of concrete. The top of the structure is precast or cast-in-place concrete. The cylinder also has the characteristics of a hollow neck when removal of the manhole cover occurs. The structure underlying the concrete top may have the same or larger diameter as in the case of a manhole or may have a larger square or rectangular cross-section as in the case of a vault. All of these structures contain the geometry needed for the effect induced by the natural movement of air along the surface of the ground.

The controlled study of the movement of air across the opening in a Helmholtz resonator indicates that this movement (grazing flow) causes the formation of a shear layer that increases in depth across the gap [28–30]. Some of the structures used in the latter experiments closely resembled the real-world structure utilized in this study [3]. One or more vortices (rotating motion of air) form within the shear layer and rotate in the same direction as the inducing airflow. The number depends on the velocity of the air moving across the opening. The vortex (ices) induce/s bulk rotation of the atmosphere within the airspace of the structure in the direction opposite to the direction of airflow. Bulk rotation of the atmosphere within the airspace and interaction with the vortex (ices) in the shear layer induces the exchange between the airspace, the vortex (ices) and the external atmosphere.

The exchange between the vortex (ices) and the airspace introduces outdoor air into the airspace. Rotational motion of the atmosphere in the airspace rapidly mixes the introduced outdoor air with the air in the airspace. Mixing of air in the airspace with outdoor air decreases the concentration of contamination in the airspace. High variability in the speed of air moving across the surface of the ground may, as determined here, influence the process. The exchange induced by this mechanism is expected to exert major influence on the quality of the atmosphere in the airspace of the structure.

A previous report in this series advocated for the application of the National Institute for Occupational Safety and Health (NIOSH) Prevention through Design (PtD) initiative to ventilation induced by natural forces in isolated subsurface structures [5]. One of the parts in the PtD initiative is enquiry to characterize parameters of importance in design. This work highlights the importance of the concept in understanding the fundamentals of ventilation induced by natural forces in subsurface structures so that optimization can proceed from knowledge about reality rather than perception. The reality demonstrated in this work was previously unrecognized and holds immense importance in the optimization of a process capable of saving many lives worldwide.

5. Conclusions

Within the limits of operation of the thermoanemometer, measurements obtained during this study indicate that air moves continuously across the surface of the ground with a highly variable speed when assessed on a short time base of one or two seconds. This study also showed that zero is the most probable value in air movement, occurring throughout the year and especially during cool and cold periods. The frequency of the occurrence of zero values in the zero peak follows an annual pattern. The most probable non-zero air speed, 10.7 m/min (35 ft/min), occurred in all samples. This air speed is below the level of human sensitivity and detectable only by instruments having very high sample frequency. The frequency of the occurrence of values in the nonzero peak follows an annual pattern. The magnitude and number of nonzero values in a given sample increase during warmer months and decrease in cooler months in an annual pattern. Isolated subsurface structures exhibit the characteristics of Helmholtz resonators. The measurement of near surface air speed presented in this report combined with a decrease in contamination presented in other reports [3], and videos showing how the process occurs explain the smooth, predictable reduction in concentration of air contaminants with time, characteristic of a rapidly and thoroughly mixed atmosphere. Ventilation of the airspace occurs continuously and without cost and is potentially enhanced by the unique characteristics of the Helmholtz resonator excited by surface air movement. This realization provides the basis for future exploration of other subsurface confined spaces and the optimization of ventilation of isolated subsurface structures induced by natural forces through the application of simulation and design.

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