Wind and Temperature Effect on the Performance of a Mobile e-nose platform for Real Time Victim Localization

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Abstract. In this paper it is presented the influence of weather conditions on the performance of the sensors of a mobile e-nose system that measures the atmospheric air, gas components' concentrations (actually CO₂ and O₂), into a rubble void, where humans are entrapped, after a disastrous event that caused the collapsing of a building/construction. In this case, the entrapped humans in the void, they affect the air composition and temperature into the void. Additionally to the human(s) created CO₂ source(s), O₂ sink(s), and heat source(s) (from body temperature), rubble openings (possibly too many), create sources of fresh atmospheric air and sinks for letting the air from the inside of the cavity to go out of it and vice-versa. The existence of the aforementioned sources/sinks constantly affect the air composition and temperature into the void and makes gas components' concentrations dynamic rather than static. There will be studied the fresh atmospheric air sources into a cavity taking into account also the outside weather conditions. The final goal is to estimate the concentrations of CO₂ and O₂ into the cavity as a function of time, having as parameters, the external weather conditions, the openings of the void and the number of entrapped humans. Estimating the concentrations it will enable the operator of a mobile e-nose system with sensors of a specific sensitivity and specificity, to determine the possibilities of detecting the presence of humans in a rubble void.

1. Introduction
Disasters that involve partial or complete collapse of an urban structure, usually they result in the entrapment of people-victims, in poorly ventilated confined spaces with limited or no space to move around. E-nose systems specifically targeted for use in such confined and narrow spaces, they take advantage of the small air refreshing rate in the confined spaces of the rubble that allows for the existence of large variations of the air composition when a human is present in a survival space-void and acts as source of CO₂ and sink of O₂, thus changing the composition of the air inside the void. The “ventilation” of a cavity, with air sources outside (could be fresh air, or, air from an adjacent cavity), is influenced by the openings of the cavity and weather conditions such as the wind speed and direction and other airflows such as thermal flows. The differentiation of concentrations of the target gases/substances to be detected in a specific cavity, in comparison with those in fresh atmospheric air, should be above the limits of detection (noise floor of the sensors), so to be feasible for a human detection e-nose system to be efficient in rescue operations and reveal information about the presence of victims inside a cavity under investigation [1, 2]. Section 2 of the paper presents the anticipated concentration of CO₂ and O₂ into a void/cavity as a function of time (in the rest of the paper the terms void and cavity are used as

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equivalent). Section 3 studies the effect of the external wind at the levels of CO₂ and O₂ in the void as well as the temperature differences for large and small void openings. Section 4 concludes the paper.

2. Mean concentration equations in a cavity of target gases

In this section we will present the concentration equations that were considered when studying the influence of weather conditions in the concentration of target gases in a cavity with trapped human(s). The entire void is considered as a confined space of constant volume V. The openings of it will be handled as sources of fresh atmospheric air and sinks of cavity’s air simultaneously. Entrapped humans, similarly were seen as sources of exhaled air and sinks of cavity’s air at the same time. Taking into account all those sources and sinks of air of the void, as well as the pressure and temperature of the air inside and outside the cavity and assuming that the movement of air molecules inside of it creates a uniform distribution, then the mean concentrations of CO₂ and O₂ inside the void, were estimated [1, 2]. After the collapsing of a building because of an abrupt catastrophic event, the composition of the atmospheric air inside the created voids/cavities in the rubble, it is assumed to be near the same composition as that of the atmospheric air out of the cavities (400ppm for CO₂ and 20,946% for O₂). Denoting CO₂ or O₂ gas as x, then notation in the used equation is the following: Cₓe=concentration of a specific gas component in the fresh atmospheric air, Cₓe in human’s exhaled breath, Fₓ is the fresh air flow rate (lit/min) into the room/cavity, Fₓe the exhaled breath flow rate, Cₓ∈ is the concentration of this specific gas component in the air going out from the openings of the room/cavity, Fₓ its outgoing flow rate (lit/min), and Cₓe is the concentration of this specific gas component in cavity’s air. Fₓe = nₓFₓe, and Cₓe = nₓCₓe. The mean concentration then of CO₂ or O₂ in the cavity, as a function of time, is given by the formula below:

\[ C_{xe}(t) = C_{xe} \left\{ \frac{n_{Fxe} * n_{Cxe} + 1}{n_{Fxe} + 1} + \left[ n_{Cxe} - \frac{n_{Fxe} * n_{Cxe} + 1}{n_{Fxe} + 1} \right] e^{-F_{xe} * \frac{n_{Fxe} + 1}{V}} \right\} \]

3. Air sources and sinks, at the boundary of a rubble cavity, affecting the performance of the e-nose system.

Concerning the airflow rate Fₓ of fresh atmospheric air towards the inside of the void and the airflow rate Fₓe from the inside of the void to outside (Fₓ=Fₓe), they depend upon the areas and resistances of the various apertures (openings), created randomly at the time of the building collapsing, and the pressure differences between the incoming flow paths and the outgoing ones. Openings of a rubble void they allow a number of airflow paths to be created, among cavity’s ends that they have different pressures. Pressure differences may be due either to wind, and/or to differences in density of the internal and outside fresh air because of temperature difference (stack effect). In addition, the surrounding fabric temperatures into a cavity and heating/cooling loads inside the cavity as well as the existence of entrapped humans, will influence internal air temperature. Wind creates higher pressure outside the rubble in comparison with the pressure into the cavity. Stack effect creates a pressure difference that depends on the temperature difference as it will be explained further in this section. Incoming flow paths are created at the openings where outside total pressure (wind and stack effect), is higher than the inside when outgoing flows are formed at the openings where the inside pressure is higher than the outside. Varying wind speeds and directions will generate fluctuating pressure difference and flowrates in voids near the border of the rubble because of the wind. Inside and outside temperatures, obviously they also may vary throughout the day and across the seasons and they create variable flowrates in voids. Usually annual wind speed may span from 0-10m/sec at any of the 8 cardinal directions and temperature from -10°C to +40°C. This is the reason that the fresh incoming airflow rate is highly variable since we do not know the prevailing weather conditions at the time of the disastrous event and the conditions into a cavity. Since pressure differences depend on a number of factors like, local wind speeds (outside of rubble) and their corresponding “pressure coefficients” created at the openings of the void, the inside and outside (air) temperatures, the size and nature of openings of the void, the nature of flow paths
within the void, and the created flow regimes [3], [4]. The variables and the parameters affecting these flow paths and regimes are so many that make the problem chaotic and considerable simplification is necessary in any mathematical representation. Nevertheless as already mentioned, even rough approximations are sufficient for the targeted application. The effect of the aforementioned factors will be further analyzed in order to define the fresh air flow rate \( F_s \) into the cavity.

3.1. Wind effect
In case of existence of wind outside the rubble then it has as an effect to drive air into the void through the openings on the windward side of the cavity where the surface pressure is high. Wind’s deflection on the upwind face of the rubble, induces a positive pressure on it. The air flow then separates resulting (most of the times), in negative pressure regions developed along the other sides of the rubble. A negative pressure distribution is usually developed along the leeward or upper side. Fresh air then passes from the one side of the void to the other side and exits through apertures on the leeward or upper side where the lower pressure is created and a flow path is formed. The higher the wind speed the higher will be the incoming fresh airflow rate \( (F_i) \) and the outgoing cavity air flow rate \( (F_o) \) because of the wind effect \( (F_i = F_o) \).

Relative to the static pressure of the free wind, the time-averaged pressure acting on any point on the surface of a rubble may be represented by the following equation [3]:

\[
P_{w_i} = 0.5 \rho v_z^2 C_{pi}
\]

\( P_{w_i} \) = surface pressure due to wind (Pa), \( \rho \) = density of air \((\approx 1.2754 \text{ Kg/m}^3)\), \( C_{pi} \) is the wind pressure coefficient at a given position on the rubble surface (generally independent of the wind speed) and \( v_z \) is the mean wind velocity at height \( z \) (m). The wind pressure coefficient, \( C_{pi} \), is a function of wind direction and of spatial position on the rubble surface.

We assume two distinct wind cross flow cases. The first case considers voids that on their front surface have small openings of few tenths of centimetres length and just few millimetres wide (e-nose would enter the void by a side wider opening). In this case the kinetic energy of the wind dissipates by generating a positive pressure difference between the external surface of the opening and the inside of the void. The resultant pressure imbalance between the outside and the inside causes air to flow through the openings. At the upper or leeward side openings, if they are exposed as well to the wind, there is generated suction pressure that draws air outside of the cavity. If there are no other sides exposed to the wind, then just the lower pressure (most probably 1 atm), of the rest of the rubble will create the same effect just with less pressure difference. This is supposed to be valid for a total area of all openings of the void, less than the 30% of the total front area of the void exposed to wind according to [2], and thoroughly studied by [3]. Airflows through small randomly created openings (first case), tends to be of a laminar nature, and their individual magnitudes are a function of the applied pressure difference across the rubble openings and their length, cross sectional area and internal geometry. The relationship may be described by the following empirical law [3]:

\[
F_{f_{wi}} = l_{ci} \cdot k_1 \cdot (\Delta p_i)^n
\]

\( F_{f_{wi}} \) = volumetric flow rate through a small opening \( i \) (lit/sec), \( l_{ci} \)=total length of the opening \( i \) (meters) assuming that the width is just a few millimeters wide, \( k_1 \approx 1.2 \frac{\text{lit}}{\text{sec} \cdot \text{m} \cdot \text{Pa}^n} \) (flow coefficient per unit length of opening), \( \Delta p \) = pressure difference across the opening (Pa), \( n \approx 0.6 \) (flow exponent that characterizes the flow regime and its typical value for such small openings it is usually between 0.6 and 0.7).

The second case for wind effect, considers large openings of “window” size, so to allow the air passing through the cavity without much kinetic energy dissipation. Airflow through large openings of window size (second case), is an orifice type opening and the equation becomes the common orifice Bernoulli equation [5], that is the same with that of the stack effect:
\[ F_{fw_i} = C_{d_i} \cdot A_i \cdot \sqrt{\frac{2 \cdot \Delta p_i}{\rho}} \]

\( F_{fw_i} \) = volumetric flow rate through a large opening \( i \) (m\(^3\)/sec), \( C_{d_i} \approx 0,61 \) (Discharge coefficient), \( A_i \) = the area of the opening (m\(^2\)), \( \rho \) = density of air (kg-m\(^{-3}\)).

Applying the formulas above, for small and large openings on the front area of the cavity in an Urban/Suburban terrain, for any wind speed an e-nose system would detect any kind of entrapped human, even for the maximum expected \( \Delta p \). In the extreme case of 10m/s wind speed vertical to the surface of the void opening and for maximum \( \Delta p \), a 3 years old child, it was found that it might be difficult to be detected by both CO\(_2\) and O\(_2\) sensors, if small openings have more than 6cmx6cm window size.

3.2. Temperature effect (Stack Effect)

Stack effect is the air flow rate of the outside fresh atmospheric air into a cavity (\( F_0 \)), driven by temperature difference \( \Delta T \) (\( \Delta T = T_c - T_i \)) between the outside and the inside of the cavity. It is important to examine both, positive and negative temperature differences.

The pressure difference because of temperature difference (stack effect), it happens because outdoor cooler air is denser than warm air inside the cavity and consequently their hydrostatic pressure is different. Actually gravity is the reason for the stack effect and the pressure difference. The cold air from outside (of temperature \( T_i \)), is heavier and with higher pressure and it enters through low positioned gaps and openings into the cavity that has warmer, lighter and of lower pressure air. The displaced inside air (of temperature \( T_c \)), escapes through gaps and openings at a higher level \( z_i \) of the large enough rubble voids (more than 2-3 meters height). This direction of movement could be reversed in the rare case of a very hot summer day, around noon time as mentioned already, when the external air temperature is 1-3\(^\circ\)C higher than the indoor temperature and thus it may result a lower temperature into the cavity than outdoor temperature (\( T_c < T_i \)), and the colder air from the void will escape through low positioned gaps and openings, and warm air from outside will enter the void to balance pressure.

To estimate the stack effect air flow rate, similarly with the air flow through large (“window” size), void openings, according to the Bernoulli model, the volumetric flow rate through an opening because of the stack effect alone, depends on the pressure drop \( \Delta p \) across the opening, and on the “geometrical” opening area \( C_{d_i} \cdot A_i \). Each opening of a cavity provides \( F_{c,i} \) because of the \( \Delta p \), pressure difference across it as follows:

\[ F_{c,i} = C_{d_i} \cdot A_i \cdot \sqrt{\frac{2 \cdot |\Delta p_i|}{\rho}} \]

\( i \) identifies the opening, \( F_{c,i} \) is the flow rate through the opening (m\(^3\)/s), \( C_{d_i} \) is the discharge coefficient for the cavity, \( A_i \) is the area of the opening (m\(^2\)), \( \Delta p_i \) is the pressure difference (Pa) and \( \rho \) is the air density (kg/m\(^3\)). In case of summer (\( T_c < T_i \)), there is an outgoing air flow rate \( F_{c,i} \), given by a similar relationship.

When the flow is generated by the density difference (i.e. in the absence of any wind effects), it has been shown [6] that the pressure difference in the equation above is \( \Delta p_i = (\rho_f - \rho_c) \cdot g \cdot z_i \). The quantity \( z_i \) represents the height of the opening above the lowest level of the cavity, \( P_c \), \( P_f \) and \( \rho_c \) are the air density outside and inside the cavity respectively, and \( g \) is the gravitational acceleration.

It is shown in [4] that when \( T_i < T_c \) then \( \frac{\rho_f - \rho_c}{\rho_f} = \frac{T_c - T_f}{T_f + 273} \), and in the very rare case of \( T_i > T_c \) then \( \frac{\rho_c - \rho_f}{\rho_c} = \frac{T_f - T_c}{T_c + 273} \) (\( T_i, T_c \) = temperature in Celsius degrees). The total then incoming air flow rate because of the stack flow alone, would be \( F_T = \sum_i F_{c,i} = \sqrt{\frac{2 \cdot |(T_c - T_f)\cdot g \cdot z_i|}{\rho_f}} \cdot \sum_i C_{d_i} \cdot A_i \), (assuming that all incoming openings are at the lower level of the void and that the outgoing ones at the top of the void at height \( z \)).

At the same time the outgoing from the void air flow rate \( F_c \) at height \( z \), would be \( F_c = F_T \).
3.3. Stack and wind effect combined.

It is very rare that stack effect and wind effect not to act simultaneously and even in that case, it would be for very limited time. Consequently both effects have to be examined together. Wind effect creates an “i-j” airflow path between two openings of a cavity eg. i and j, because of the pressure difference. Wind and stack effects they are combined only in airflow paths between a low opening at the base of a cavity and another at the top of the cavity where stack effect discharges its associated airflow path. Assuming an airflow path “i-j”, between a low opening “i” and another “j” and Δpij, the pressure between those two ends. The pressure because of the wind effect at the first opening “i” is assumed to be \( P_{wi} = 0,5 \times \rho_f \times C_{pi} \times v_{i}^2 \), and at the opening “j”, \( P_{wj} = 0,5 \times \rho_f \times C_{pj} \times v_{j}^2 \) (assuming that \( v_z \) is the same at the two different ends). \( C_{pi} \) and \( C_{pj} \) are the pressure coefficients at the “i” and “j” airflow path ends, \( \rho_f \) is air density in Kg/m³, \( v_z \) is the common (presumably), wind speed of both ends m/sec. Only at the lower opening there has to be added \( \Delta p_s \) (\( \Delta p_s= P_f-P_t \)), the stack effect pressure difference between the outdoor air and the air inside the cavity. \( \Delta p_s \) as mentioned in the previous section is always positive except at the rare case of an extremely hot summer day around noon time.

Thus, the pressure difference across any lower opening “i” whose inlet is situated in the external flow, assuming that the external wind flowing around the opening does not affect the discharge coefficient \( C_{d_i} \) of the opening, wind effect is combined with stack effect, and the total pressure \( P_{W+S,i} \), on that opening “i”, it can be written as: \( P_{W+S,i} = P_{wi} + \Delta p_s = 0,5 \times \rho_f \times C_{pi} \times v_{i}^2 + (\rho_f - \rho_c) \times g \times z_i \). At the other end “j” of the airflow path the pressure would be \( P_{wj} = 0,5 \times \rho_f \times C_{pj} \times v_{j}^2 \). Then the total pressure difference \( \Delta p_{W+S,i-j} \) between the two ends, is given by:

\[
\Delta p_{W+S,i-j} = 0,5 \times \rho_f \times (C_{pi} - C_{pj}) \times v_{i}^2 + (\rho_f - \rho_c) \times g \times z_i - 0,5 \times \rho_f \times C_{pj} \times v_{j}^2
\]

Consequently the specific airflow path it will provide a total airflow rate of fresh air into the void, \( F_{f,i-j} \) because of the total pressure difference across it caused by both wind and stack effect.

\[
F_{W+S,i-j} = C_{d_i} A_i \sqrt{\frac{2 \times (0,5 \times \rho_f \times (C_{pi} - C_{pj}) \times v_{i}^2 + (\rho_f - \rho_c) \times g \times z_i)}{\rho_f}}
\]

In the rare case of an extremely hot summer day around noon time with combined together wind and stack effect, then the total airflow \( H d F_{W+S,i-j} \) is:

\[
H d F_{W+S,i-j} = C_{d_i} A_i \sqrt{(C_{pi} - C_{pj}) \times v_{i}^2 + 2 \times \frac{(T_f - T_c) \times g \times z_i}{T_f + 273}}
\]

In this rare case, stack effect as it evident from the above equation, the performance of the e-nose system is improved since the incoming fresh air flow rate in the void is decreased.

In any other situation, the performance of the e-nose system is deteriorated since the incoming fresh air flow rate in the void is increased because of the combination of both wind and stack effect. It is found that pressure differences because of wind effect in best scenario with minimum values, they need more than 5m/sec wind speed to be more than 1Pa. Worst case scenarios with maximum values of pressure difference (vertical direction of the wind and proper shape of rubble), goes over 1Pa with wind speed just over 1m/sec. Pressure differences because of stack effect with a reasonable temperature difference of 5°C and cavity height 2m, as presented in the previous section it is expected to be around 0.45Pa. It is evident then that it is expected that the combination of stack effect with the wind effect it is expected to deteriorate the performance of the e-nose system in low wind speed when for high wind speeds it is expected to have negligible effect.
Applying the above equation, there are calculated in Table 1 for a 2 meters height void and with temperature difference between outdoor temperature and void temperature of 5°C, for large openings on the front area of the cavity, there are calculated for urban/suburban terrain and for various wind speeds, the maximum total possible length of area of large openings in voids, for minimum and maximum pressure difference \( \Delta p \), for being possible an adult male or a baby to be detected by the \( \text{CO}_2 \) and/or \( \text{O}_2 \) sensors of an e-nose system.

| Wind speed m/s | Description of entrapped human | \( A_i \) (m²) for max. \( \Delta p \) CO\(_2\) sensor | \( A_i \) (m²) for min. \( \Delta p \) CO\(_2\) sensor | \( A_i \) (m²) for max. \( \Delta p \) CO\(_2\) & \( \text{O}_2\) sensors | \( A_i \) (m²) for min. \( \Delta p \) CO\(_2\) & \( \text{O}_2\) sensors |
|----------------|-------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 0.25           | child 3y                       | 0.0645                                          | 0.0673                                          | 0.0366                                          | 0.0382                                          |
|                | adult male                     | 0.2194                                          | 0.2289                                          | 0.1245                                          | 0.1300                                          |
| 3              | child 3y                       | 0.0177                                          | 0.0520                                          | 0.0100                                          | 0.0295                                          |
|                | adult male                     | 0.0601                                          | 0.1766                                          | 0.0341                                          | 0.1003                                          |
| 5              | child 3y                       | 0.0108                                          | 0.0396                                          | 0.0062                                          | 0.0225                                          |
|                | adult male                     | 0.0369                                          | 0.1345                                          | 0.0209                                          | 0.0764                                          |
| 10             | child 3y                       | 0.0055                                          | 0.0230                                          | 0.0031                                          | 0.0130                                          |
|                | adult male                     | 0.0186                                          | 0.0781                                          | 0.0106                                          | 0.0443                                          |

Comparing wind effect stand-alone detection capabilities of the e-nose system and Table 1 that shows the detection capabilities of the e-nose system of both wind and stack effect acting concurrently, it is confirmed that for the best scenarios of minimum \( \Delta p \) from wind effect, \( \text{CO}_2 \) sensor detection capabilities are affected significantly from stack effect, only in the case of minimum wind speed (0.25m/s). For the worst scenarios of \( \Delta p \) from wind effect, \( \text{CO}_2 \) sensor detection capabilities are affected from stack effect, again significantly in the case of minimum wind speed (0.25m/s), and slight deterioration for 3m/s wind speed. Similarly are the results for \( \text{O}_2 \) sensor detection capabilities deterioration because of combined wind and stack effects. Only in low wind speeds (less than 1m/s), the detection capability of \( \text{O}_2 \) sensor it is affected significantly. Nevertheless even in this case void apertures could be up to 20x20cm in the best or worst case scenario and a child 3 years old to be detectable by both sensors and 25x25cm in both scenarios to be detectable just by the \( \text{CO}_2 \) sensor.

### 4. Conclusions

In this paper it is studied the effect of weather conditions on the performance of a targeted e-nose system that measures the atmospheric air gas components’ concentrations (actually \( \text{CO}_2 \) and \( \text{O}_2 \)), into a rubble void, where humans are entrapped, after a disastrous event that caused the collapsing of a building/construction. Specifically it was taken into considerations the external weather conditions and the effect of the possible external wind as well as the possible temperature differences between the void and the outdoor environment. In all cases there were identified the expected levels of \( \text{CO}_2 \) and \( \text{O}_2 \) to estimate the capabilities of detection of the presence of humans in a rubble void by a mobile e-nose system with sensors of a specific sensitivity and specificity.

From the analysis carried out in this study, manufacturers of e-nose systems targeted at USaR rescue operations, they will be able to design their future systems by implementing in their user interface the results of this work. A future e-nose system by receiving the weather information (wind and temperature), and examining the void direction/position and the visible apertures of it it could inform the operator about the estimated capabilities of the e-nose system. This will enable users to decide if it will be reliable enough to use the system and prioritize the available search tools and not loose valuable time that may cost the human lives.
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