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A predictive model for estimating the indoor oxygen level and assessing Oxygen Deficiency Hazard (ODH)

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A B S T R A C T

In some working environments there may be Oxygen Deficiency Hazard (ODH) when workers are exposed to a low indoor oxygen level. This hazard can be assessed applying a predictive model. In the literature, there are sixteen models estimating the oxygen content subsequent to releases of inert gases. These models present several weaknesses, such as the rarity of consideration of accidental releases, of Heating, Ventilation, Air Conditioning, and Refrigeration (HVAC-R) systems reliability, and of the existence of both forced and natural ventilation. For overcoming these weaknesses, we propose a new predictive model for assessing ODH caused by voluntary or accidental releases of inert gases. Our model is based on the balances of mass of air and of moles of oxygen. Our model fills some gaps identified in the literature models (e.g. the estimation of natural ventilation, infiltration, and exfiltration), and allows the identification of those parameters responsible for ODH. In order to evaluate our model, we have performed several simulation tests. We have obtained that our results are comparable to the outputs of some case studies available in the literature, and we have analysed the effects of some new aspects of the model. The model represents a helpful tool to implement in any working environment where ODH has to be assessed.

1. Introduction

According to McManus (1998; 2009b), "oxygen deficiency and enrichment create a fundamental dilemma for the practicing industrial hygienist" and "exposure to an atmosphere containing a narrow range of concentration is essential for survival".

U.S. Bureau of Labor Statistics (2014) highlights that in all U.S., in 2011, fatal occupational injuries due to "Exposure to oxygen deficiency, n.e.c." represent the 0.7458% of all fatal events and exposures, and non-fatal occupational injuries the 0.0025% of all non-fatal events and exposures. During 2012, U.S. Bureau of Labor Statistics (2014) records that fatal occupational injuries are equal to the 0.6845% of all fatal exposures, while non-fatal occupational injuries about the 0.0511% of all non-fatal exposures because of Oxygen Deficiency Hazard (ODH). European Commission (2015) points out that in 2011 there were the 3.9014% of fatal accidents and the 0.0186% of non-fatal accidents in European Union (28 countries) caused by "Drownings and asphyxiations". Because of the same injuries, European data about the year 2012 underline that there were the 3.7838% of fatal accidents and the 0.0237% of non-fatal accidents in European Union (28 countries).

In the foreword of the standard proposed by ANSI and ASSE (2009), data of fatalities between 1980 and 1993 obtained by OSHA and NIOSH suggest that oxygen deficiency represents one of the leading cause of death in confined spaces. The distribution of these data is confirmed by a review of 200 confined space fatality cases during the period 1993–2004. Also Manwaring and Conroy (1990) report some data of NIOSH about causes of death into confined spaces in 1983–1989: 47% of deaths occurred due to asphyxiation, representing the most frequent cause of death in this type of working environments. Furthermore, they underline that: "seventy-eight percent of the fatalities were directly or indirectly due to oxygen deficient or toxic atmospheres".

Moreover, ODH is also a typical hazard of laboratories. Chorowski et al. (2006) in the context of CERN, Fermilab (1986, 2009; 2015b), and Iarocci (1994) in the building of Brookhaven National Laboratory describe the frequent use of substances (such as cryogenic liquids or compressed gases) that may produce an oxygen deficient atmosphere.

ODH occurs when the indoor oxygen content drops to a level

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Nomenclature

φ	volume fraction (%)
$\%_{we,f}$	percentage of the free volume of the working environment (%)
υ	velocity ($m\ s^{-1}$)
A	area (m^2)
b	binary variable (dimensionless)
C	concentration by volume (%)
g	gravitational acceleration ($m\ s^{-2}$)
I	number of inert gases or mixtures with high oxygen content (dimensionless)
IMP	number of impurities (dimensionless)
J	number of failure modes (dimensionless)
k	binary variable (dimensionless)
m	mass (kg)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
n	mole (mol)
p	pressure (Pa)
P	probability (dimensionless)
pp	partial pressure (Pa)
$\dot{Q}$	volumetric flow rate ($m^3\ s^{-1}$)
R	ideal gas constant ($J\ K^{-1}\ mol^{-1}$)
R^*	gas constant for dry air ($J\ K^{-1}\ kg^{-1}$)
Rel	reliability (dimensionless)
S	number of ventilation systems (sub-systems of supply air or sub-systems of return air), or storage and/or distribution systems (dimensionless)
T	temperature (K)
t	time (s)
V	volume (m^3)
Y	number of other pure inert gases included in the inert gas (excluding the main pure inert gas), in the mixtures with high oxygen content, or in the air introduced in or drawn from the working environment (dimensionless)
z	altitude of the working environment (m)
β	vertical temperature gradient ($K\ m^{-1}$)
δt	time instant or infinitesimal time (s)
ρ	density ($kg\ m^{-3}$)

Subscripts

a	accidental release
air	air
atm	atmospheric value
f	free
i	i-th inert gas or mixture with high oxygen content
ig	inert gas released into the working environment
imp	impurity
in	air introduced in the working environment by sub-systems of supply air of ventilation systems
IN	flow that goes into the working environment
j	j-th failure mode
mec	air drawn from the working environment by sub-systems of return air of ventilation systems in a mechanical (forced) way
mix	mixture with high oxygen content released into the working environment
nat	air introduced in or drawn from the working environment in a natural way
O2	oxygen
occ	occupied by equipment
oe	outdoor environment
out	air drawn from the working environment by sub-systems of return air of ventilation systems
OUT	flow that goes out of the working environment
s	s-th system (sub-system of supply air of ventilation systems, sub-system of return air of ventilation systems, or storage and/or distribution system)
sl	sea level
v	voluntary release
we	working environment
x	x-th main pure inert gas included in the inert gas
y	y-th other pure inert gases included in the inert gas (excluding the main pure inert gas), in the mixtures with high oxygen content, or in the air introduced in or drawn from the working environment

that may expose workers to the risk of asphyxiation. The oxygen content may be decreased due to several causes, but our interest is focused on the displacement of oxygen itself by inert gases because they are odourless, colourless, tasteless, and thus undetectable by the people exposed (Arrieta et al., 2009). According to IUPAC (2014), an inert gas is "a non-reactive gas under particular conditions"; for example, nitrogen at ordinary temperatures and the noble gases (helium, argon, krypton, xenon, and radon) are unreactive toward most species. From the point of view of ODH assessment, we consider also carbon dioxide because displaces air and oxygen like an inert gas.

Table 1 summarises typical human body reactions due to oxygen deficient atmospheres proposed by several authors in the literature: Alicino et al. (2008); ACGIH (2015); Arrieta et al. (2009); Blyukher (1995); Chorowski et al. (2006); Delayen et al. (2001); Fermilab (2015b); Jefferson Lab (2014); Leikauf and Prows (2012); Luke (2004); McManus (1998; 2009a); Miller and Mazur (1984); Morgan (2014); NIOSH (1987); SLAC (2014).

OSHA (2011a) identifies an atmosphere with an oxygen content below 19.5% by volume as an oxygen deficient atmosphere; such an atmosphere shall be considered "Immediately Dangerous to Life or Health" (IDLH), with the exception of oxygen concentration for which the employer may rely on supplying respirators. According to OSHA (2011b) and Fermilab (2015a), IDLH represents "any condition that poses an immediate or delayed threat to life or that would cause irreversible adverse health effects or that would interfere with an individual's ability to escape unaided". In particular, Table 2 shows the oxygen deficient atmospheres for which the employer may rely on supplying respirators (OSHA, 2011a) and the ones classified as IDLH.

Furthermore, OSHA (2011a) identifies some respirators that shall be used in IDLH atmospheres, and thus in oxygen deficient ones, such as a full facepiece pressure demand SCBA for a minimum service life of 30 min, or a combination full facepiece pressure demand supplied-air respirator (SAR) with auxiliary self-contained air supply.

In addition to OSHA, NIOSH (1979) also defines oxygen deficiency through IDLH issue. In particular, a confined space that contains an oxygen level equal or less 16% is classified IDLH, while confined spaces in which the oxygen content is between 16.1% and 19.4% are considered dangerous, but not IDLH.

The above issues suggest that ODH requires a risk assessment, which is "a systematic examination of all aspects of the work undertaken to consider what could cause injury or harm, whether the