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A Near Field–Far Field model for assessing Oxygen Deficiency Hazard

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ABSTRACT

Oxygen Deficiency Hazard (ODH) due to inert gas releases can be assessed by the use of predictive models. Several models are available in the literature: the majority of them can be classified as "well-mixed" models because they assume the existence of completely and instantaneously well mixed air. In order to provide a more precise estimation of the indoor oxygen level in the breathable air close to a release point, we propose a Near Field–Far Field (NF–FF) model in which the Near Field volume is an output and can vary over time. The trend of the Near Field size can be a useful data for the risk assessor in order to determine the safety distance from point source releases, and improve the emergency response plan. Starting from balances of mass of air and moles of oxygen both in the Near Field and in the Far Field, the objective of our model is to predict the volume of the Near Field that contains a limit value for the oxygen concentration at every time instant. The approach includes several analytical formulas that model the different flows occurring in each field and between the two fields. In particular, we assume the existence of inert gas releases, forced and natural ventilation airflows, interzonal airflows, and air that has to move from the Far Field to the Near Field, or vice versa, for assuring a limit value for the oxygen concentration in the Near Field. Finally, examples of the application of this model in some case studies available in the literature are presented and discussed.

1. Introduction

Oxygen Deficiency Hazard (ODH) occurs when the indoor oxygen content drops to a level that may expose workers to the risk of asphyxiation. Details about the risk assessment of ODH can be found in Stefana et al. (2015, 2016).

A relevant cause of ODH is represented by inert gas releases. Inert gases are simple asphyxiant substances that dilute the available atmospheric oxygen. These substances are usually present in process industries and used for purging and identifying leaks in plants or pipework, for creating inert atmospheres inside or outside equipment, and for preventing unintentional chemical reactions. Furthermore, they are exploited for replacing air in all operations in which the presence of oxygen is dangerous or damaging: "replacement of oxygen with nitrogen can eliminate a dust explosion hazard while at the same time introducing an asphyxiation hazard" (Amyotte, 2014). Details about the use of inert gases and the reduction of oxygen for preventing explosions are also reported in Amyotte (2013).

ODH can be estimated thanks to the use of predictive models able to determine the oxygen level in a working environment. In some working environments, airflow mixing is created and thus a well-mixed model can predict quite well the oxygen content. In other cases, air in a workplace is not well-mixed and is subject to stratification phenomena. In these cases, a well-mixed model for estimating the indoor oxygen level can underestimate the content of this gas in working environments, potentially causing errors in the assessment of ODH.

This consideration is valid in general: for example, Sakhvidi et al. (2013) underline that a well-mixed room model "underestimates the concentration in the locations near the pollution sources", and Danyluk and Hon (2006) highlight that "in real situations, the air does not tend to

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Nomenclature

$\dot{Q}$	Volumetric flow rate ($m^3\,s^{-1}$)
$\dot{\beta}$	Interzonal volumetric airflow rate between the NF and FF ($m^3\,s^{-1}$)
b	Binary variable (dimensionless)
C	Concentration by volume (%)
FSA	Free surface area of the NF (m^2)
I	Number of inert gases (dimensionless)
IMP	Number of impurities (dimensionless)
J	Number of failure modes (dimensionless)
k	Binary variable (dimensionless)
m	Mass (kg)
n	Mole (mol)
p	Pressure (Pa)
P	Probability (dimensionless)
pp	Partial pressure (Pa)
r	Distance of the worker from the release point; in the case of hemisphere-shaped NF, it is the radius of the hemisphere (m)
R	Ideal gas constant ($J\,K^{-1}\,mol^{-1}$)
Rel	Reliability (dimensionless)
S	Number of ventilation systems (supply air or return air sub-systems), or storage and/or distribution systems (dimensionless)
s	Random airspeed at the boundary of the NF ($m\,s^{-1}$)
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), or in the air introduced in or drawn from the working environment (dimensionless)
β	Interzonal volume between the NF and FF (m^3)
δt	Time instant or infinitesimal time (s)
φ	Volume fraction (%)

Subscripts

a	Accidental release
air	Air
atm	Atmospheric value
f	Free
FF	Far Field
i	i-th inert gas
ig	Inert gas released into the working environment
imp	Impurity
in	Air introduced into the working environment by supply air sub-systems of ventilation systems
j	j-th failure mode
mec	Air drawn from the working environment by return air sub-systems of ventilation systems in a mechanical (forced) way
nat	Air introduced into or drawn from the working environment in a natural way
NF	Near Field
O2	Oxygen
occ	Occupied
oe	Outdoor environment
out	Air drawn from the working environment by return air sub-systems of ventilation systems
s	s-th system (supply air sub-system of ventilation systems, return air sub-system of ventilation systems, or storage and/or distribution system)
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), or in the air introduced into or drawn from the working environment

be perfectly mixed in rooms and, even with various corrective factors, these models tend to underestimate exposures close to the source".

In order to reduce some of these errors, safety managers can adopt a Near Field–Far Field (NF–FF) model, which better estimates the gas content near the release point, where the gas level is supposed to be lower than the average gas level in the room. In particular, this kind of approach allows to take into account, even though partially, the deviations from the completely mixed assumption. NF–FF (or two box) model considers the spatial variability in exposure intensity and imperfect air mixing (Keil, 2000; Keil et al., 2009; Persoons et al., 2011; Ramachandran, 2005; Spencer and Plisko, 2007). In accordance with Jayjock et al. (2011b), the NF–FF approach, as it currently exists, is a first attempt to address the fault of the well-mixed model.

The NF–FF model was originally described by Hemeon in 1963 (Hemeon, 1963), and then developed by Nicas in 1996 (Nicas, 1996). In particular, Nicas (1996) provides the derivation of the dynamic concentration equations.

The NF–FF model is a modified well-mixed model (Jayjock et al., 2011a,b; Sakhvidi et al., 2013), which attempts to capture the effect of source proximity on exposure and thus the exposure of workers close to the contaminant source (Ramachandran, 2005). This model has the objective to predict the Near Field (NF) and Far Field (FF) exposure concentrations (Vadali et al., 2009). Note that these two fields are a subdivision of the working environment, and the sum of their volumes is the overall volume of the working environment.

In the literature there are several examples of application of this model to estimate the concentration of different chemicals: isoflurane (Sakhvidi et al., 2013), benzene (Nicas et al., 2006), solvent (Spencer and Plisko, 2007), methanol vapours (Gaffney et al., 2008), dusts (Jones et al., 2011), sulfur hexafluoride (Furtaw et al., 1996), laser-generated particulate matter (Lopez et al., 2015), cleaning products (Earnest and Corsi, 2013), toluene (Hofstetter et al., 2013), and unspecified substance (Feigley et al., 2002). One of these studies (Nicas et al., 2006) predicts concentrations using a non-constant emission rate, as done also in other papers: for example, Nicas and Armstrong (2003b) (a spreadsheet to compute a sine function emission rate), Nicas and Neuhaus (2008) (a formulation valid in the case of a variable emission rate), Nicas and Armstrong (2003a) (Excel spreadsheets and a Matlab code for studying the two-zone model with a constant emission rate and an exponentially decreasing contaminant emission rate), and Nicas (2016) (a revisited study of Nicas and Neuhaus (2008) with constant applica-