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Addressing Waste Disposal Fires in Open Fields through Large Eddy Simulations

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Addressing fires in waste disposal facilities is of topical interest for firefighting and environmental protection. Statistics of fires that involve fuel matrixes made of diversified wastes are escalating and ask for an effective response, both in prevention and mitigation. Crucial to this target is the consideration of underlying phenomena, and modeling of fire dynamics and pollutant emission also via robust numerical simulations.
In this work, fires in waste disposal facilities are addressed with Large Eddy Simulation to test the capability to catch the main phenomena of the combustion of wastes made of plastic and the consequent emission of pollutants. This approach is applied to fuel matrixes in form of piles of different sizes, made of polyolefins and polyvinylchloride burned in an open field.
The atmospheric dispersion of pollutants, including soot, carbon monoxide, carbon dioxide, and hydrogen chloride are investigated under different environmental conditions. Besides, thermal aspects are addressed to come up with indications of the heat release rate.

1. Introduction

Waste disposal fires are emerging scenarios of growing interest given the widespread distribution of waste treatment and disposal facilities. On the one hand, these facilities are essential in providing the required waste stream, but on the other side, they are correlated with hazardous scenarios including large uncontrolled fires, and environmental concerns including toxic emissions (Mikalsen et al., 2020).
A European directive (2008/98/EC), several regulations, laws, and guidelines are available to address topics including the management of such facilities, fire prevention, and the handling of hazardous scenarios. As an example, in the Italian framework, technical regulation has been recently discussed concerning fire prevention in waste treatment and disposal facilities (Cembalo et al.,2019). The aim is to systematize strategies oriented to fire prevention and mitigation of fires in waste facilities given the high impact of related risk scenarios. The issue of fires in waste facilities in Italy is widely spread, just to consider that according to the Italian Fire Dept. statistics on firefighting interventions have increased by more than 70 % in recent years. Among fuel matrixes involved in fires, about 8 % are represented by wastes of various types. Overall, more than 300 fires occurred in 2019 in waste treatment and disposal facilities in Italy (Ministero dell'Interno, 2020).
The need for a systematized risk assessment is critical given the severity of scenarios that involve fires in waste disposal facilities. The historical survey shows that related scenarios take place according to uncontrolled and extensive escalating fires, including destruction, and environmental pollution that results from high toxic combustion products and by-products (Blomqvist, and Andersson, 2011; Lemieux et al., 2004).
Modeling tools are well suited to similar complex and emerging scenarios to support the estimation of safety distances, the quantification of fire effects, and the assessment of environmental impact (Persson and Simonson, 1998). Currently, no ready-to-use tools are available to deal with these topics, as regards especially safety distances and fire safety. Besides, the robust quantification of fire safety distances is essential for the preparation of emergency response plans and when dealing with local communities and permissions.
This work focused on the numerical simulation of fires involving waste materials, including plastics. The combustion process is approached with a special focus on pollutant production and heat of release rate (HRR).

The effects of environmental conditions and the size of the pile of waste materials on these aspects are discussed.

2. Features of fires in the waste disposal and treatment facilities

Typical fire scenarios that occur in the waste disposal and treatment facilities originate in storage areas where large and heterogeneous fuel matrixes are housed. A large variety of materials can be stored even blended or compartmentalized, with different combustion properties and chemical compositions.
Typical materials found in the waste disposal and treatment facilities are:

- plastic materials including polyolefins, polyamides, and polyesters
- lignocellulosic derivatives
- mixed wastes
- other materials and inerts.

Depending on the origin they can be categorized as municipal or special and industrial waste, and, according to the intrinsic properties, in hazardous or non-hazardous waste. Hazardous materials include explosives, oxidizers, flammable liquids and solids, auto-igniting compounds, corrosives, biohazardous materials, toxins and ecotoxics, and carcinogenic compounds (Council Directive 2008/98/EC).
In addition to the diversity due to waste nature and origin, also size and storage layout influence fire behavior. Smaller items are more likely to sustain rapid fire scenarios and the propagation is even influenced by the spatial distribution of wastes that are usually open-air stored, sometimes in enclosures for technical purposes.
The following aspects may affect fire growth and propagation:

- reaction to fire of the fuel matrix and flammability of constituents
- size of the waste stack, spatial distribution, and tilt of waste piles
- environmental conditions (surface temperature, sunlight radiation)
- smoldering
- water content in the fuel matrix and flame-retardant additives (e.g., in plastics)

The open-field fire dynamic is sensitive to local environmental conditions, mainly wind (velocity and direction) and temperature. Conversely to enclosed fires, the ventilation is typically assumed to be never rate-limiting, being available in bulk. This aspect is also correlated to smoldering fires, aggravated by handling operations that may alter the local ventilation that triggers a fire.

3. Modeling of open-field fires that involve wastes

The modeling of open-field scenarios that involve fire in the waste disposal and treatment facilities was approached with the CFD software developed by the National Institute for Standards and Technology (NIST), Fire Dynamics Simulator (FDS) v. 6.7.5. This tool is specifically suitable for processes that involve materials subjected to combustion, thermal gradients, and resulting in the release of soot and toxic substances (McGrattan et al., 2010).
Main features required for a proper modeling approach to open-field fires are listed below:

- robust treatment of the combustion process, and conversion to final oxidized products
- proper inclusion and management of wind and stratification effects
- adequate meshing through subgrid-scale models able to capture relevant mixing processes.

FDS solves turbulent flows according to the Large Eddy Simulation (LES) approach, in which a low-pass filter is applied to the transport equations for mass, momentum, and energy (Mocellin et al., 2015).
This work is focused on precise fuel matrixes subjected to combustion in an open field, namely polyethylene (PE), polypropylene (PP), and polyvinylchloride (PVC). Plastics were therefore considered as active components that take part in the combustion and in this work, assuming matrixes as totally made by each of the abovementioned components.

3.1 Fuel matrix and combustion

The simple chemistry approach was used to describe the overall combustion reaction of each fuel matrix in the vapor phase. For a general class of fuels with formula $C_xH_yO_zN_v$, eq. (1) applies:

$$C_xH_yO_zN_v + \nu_{O_2}O_2 \rightarrow \nu_{CO_2}CO_2 + \nu_{H_2O}H_2O + \nu_{CO}CO + \nu_s S + \nu_{N_2}N_2 \quad (1)$$

The combustion in the air with oxygen leads ultimately to CO_2, H_2O, CO, and soot ($C_{0.9}H_{0.1}$). Nitrogen in final products also includes the percentage of the air mixture. According to the fuel composition, stoichiometric coefficients of Eq. (1) are derived in line with the mass balance.
The fuel matrix made of polyvinylchloride (PVC) under well-ventilated conditions is assumed to also give hydrogen chloride (HCl) according to the following reaction of monomer (2):

$$C_2H_3Cl + (1.53O_2 + 5.75N_2) \rightarrow HCl + 0.96CO_2 + H_2O + 0.14CO + 0.90C + 5.75N_2 \quad (2)$$

The heat of combustion and yields to various products of the different fuel matrixes are reported in Table 1.

Table 1: Heat of combustion and gasification, and yield to specific products of PE, PP, and PVC (National Fire Protection Association, 2002).

	PE	PP	PVC
Heat of combustion [kJ/kg$_{fuel}$]	43400	42600	16400
Heat of gasification [kJ/g]	1.4	1.9	2.4
CO yield [kg/kg]	0.024	0.024	0.063
Soot yield [kg/kg]	0.060	0.059	0.172
HCl yield [kg/kg]	-	-	0.581

Thermal properties of bulk solid materials are retrieved from (National Fire Protection Association, 2002) and data are reported in Table 2.

Table 2: Properties of bulk solid plastic materials implemented in FDS.

	PE	PP	PVC
Density [kg/m^3]	930	960	1950
Specific heat [kJ/(kg K)]	1.55	2.15	1.40
Thermal conductivity [W/(m K)]	0.34	0.20	0.26
Emissivity	0.10	0.97	0.91

According to some works (McGrattan et al., 2010), the mass flux that sustains the combustion in the vapor phase is calculated according to Eq. (3), where $\dot{m}$ is the fuel mass flux, HRR is the rate of heat release, A is the exposed surface across which $\dot{m}$ occurs, and ΔH_{comb} is the heat of combustion.

$$\dot{m} = \frac{HRR}{A \cdot \Delta H_{comb}} \quad (3)$$

3.2 Environmental boundary conditions

Environmental conditions include the local temperature, the surface temperature of fuel matrixes, and the wind profile. A proper approach to these quantities is essential for a successful atmospheric dispersion modeling of combustion products (Mocellin et al., 2015).

Different average wind velocities were investigated according to conventional criteria of atmospheric stability classes and to typical weather conditions of northern Italy. In detail, an average wind velocity of 1 and 4 m/s were used, representative of the common wind velocity in the area and an overall stable weather class.

The wind was approached according to Monin-Obukhov similarity and with a profile in the z-coordinate. Safety distances were calculated under a condition of downwind constant dominant direction in such a way to demand a relaxation time scale with a computed velocity field that follows the specified wind field.

3.3 Computational domain and numerical grid

The domain has a size of LxWxH, 200x50x40 m, the downwind distance of interest for fire safety assessment is therefore limited to 200 m. In this domain, a structured mesh was adopted to meet a balanced solution between time and accuracy. Mesh insensitive results were ensured in all simulations.

According to model phenomena, i.e., chemistry, thermal field, and atmospheric dispersion, the mesh size was selected to solve the fields properly. Given that buoyant plumes have to be tracked, a minimum mesh size of 10 cm was adopted considered that waste piles with surfaces of 1, 5, and 10 m^2 were considered. Additionally, being large areas considered, a subgrid-scale model was employed (Mocellin et al., 2016a; Mocellin and Maschio, 2016b).

4. Results and discussion

Simulation in open fields was performed with different fuel matrixes, namely polyethylene (PE), polypropylene (PP), and polyvinylchloride (PVC). The fire scenario is supposed to start before an effective ignition process that ensures a rapid fire propagation to the waste pile.

Piles with 1, 5, and 10 m^2 of the extension were considered to investigate the effect of the stack size on the simulation outcomes.
Parameters investigated, based on simulation results, are listed below:

- mass fractions of soot, carbon monoxide, and hydrogen chloride (only for matrix PVC) at different locations downwind the waste pile;
- peak HRR resulting from fire simulations.

The resulting plume of a typical polyethylene 5 m^2 fire stack is represented in Fig. 1, under neutral atmospheric conditions and an average wind velocity of 4 m/s. Associated carbon monoxide (CO) profiles 100 m downstream of the fire source are reported in Fig. 2.

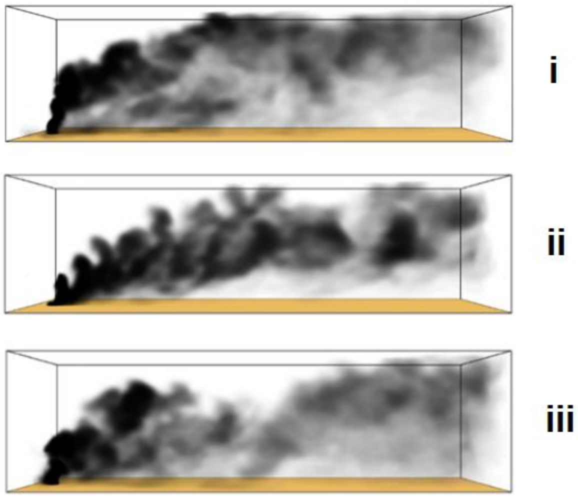

Figure 1: Plume evolution of a 5 m^2 ignited polypropylene stack. Average wind velocity: 4 m/s. i) 150 s after the ignition; ii) 300 s; iii): 1000 s.

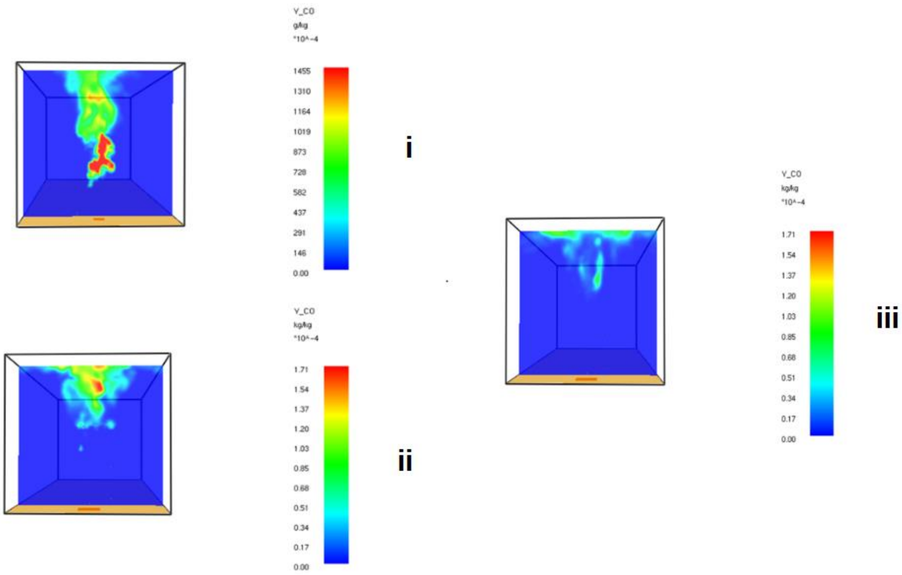

Figure 2: Carbon monoxide mass fraction (kg/kg) 100 m downstream of the polypropylene ignited stack. Average wind velocity: 4 m/s. i) 150 s after the ignition; ii) 300 s; iii): 1000 s.

Results show that an increase in the local wind speed has the effect of decreasing the time-averaged mass fraction of pollutants (CO, soot, CO_2, HCl) in the medium-field, although the same parameter is almost insensitive in the far-field (> 80-100 m) and in some cases aggravated. This behavior is owed to the combined effect of turbulent mixing and convective mechanism but also residual chemical reactions of suspended combustion products not fully oxidized. Table 3 lists the calculated average concentrations of pollutants for the case of a 5 m^2 polyethylene fire stack.

Table 3: Average pollutant mass fraction (g/kg) that results from a fire of 5 m^2 stack of polypropylene in an open field, at different downwind locations and wind speed.

	1 m/s			4 m/s		
Distance	10 m	100 m	200 m	10 m	100 m	200 m
Carbon monoxide	0.07	-	-	0.05	0.001	-
Carbon dioxide	1.95	0.08	0.06	1.80	0.28	0.22
Soot	0.18	0.009	0.008	0.08	0.01	0.008

On average, investigated polyolefins (PE and PP) give comparable results in terms of pollutants once environmental conditions are preserved. Instead, PVC behaves differently. Hydrogen chloride that comes from combustion in open fields is not appreciably sensitive to environmental conditions and except for side reactions (not included in this study) is diluted downstream. Peak values range between 4 and 10 g/kg depending on stack extension and are observed within 50 m from the fire location. Once acute exposure limits to hydrogen chloride are considered, it should be noted that IDLH is always exceeded. Safety distances for hydrogen chloride acute inhalation (IDLH) are at least 150 m from the fire source regardless of stack size.
The effect of the stack size on some pollutants measured at different downwind distances is reported in Fig. 3.

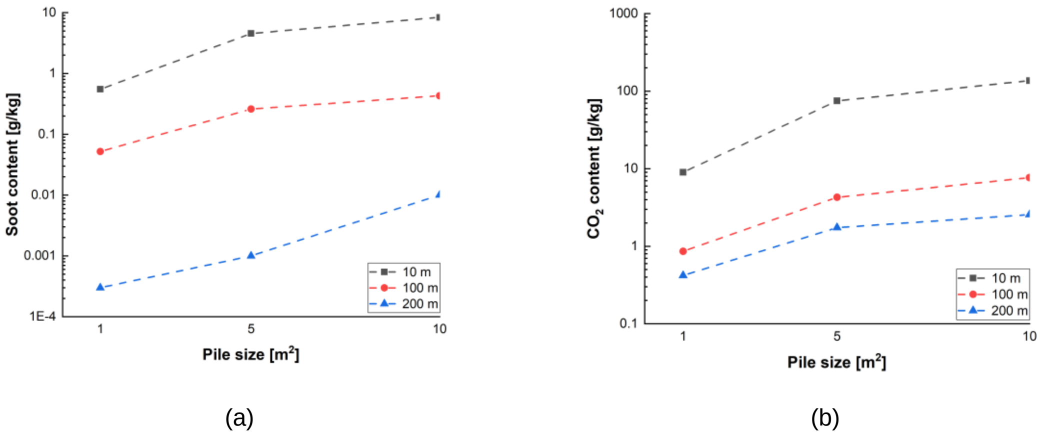

Figure 3: Average soot and CO_2 content (g/kg) measured at different distances from the pile. Effect of the variation of the pile size.

Increasing the pile size from 1 to 10 m^2 enhances the production of pollutants. This is observed for soot and carbon dioxide, and hydrogen chloride in the case of PVC. Carbon monoxide does not reflect this trend and at large distances (> 100 m) no relevant differences are calculated.
Under the modeling hypothesis and approach adopted, it can be stated that the averaged content of pollutants varies almost linearly with the pile size. This is found within 200 m from the fire source and considering a constant downstream wind velocity.
As concerns, the thermal aspects of the pile fire, the maximum heat release rate (HRR) values calculated are reported in Table 4. Polyolefins have comparable maximum HRR given similarities in the heat of combustion and reaction features. The maximum HRR is in the order of 5.4 MW for a pile size of 1 m^2. An increase in this parameter leads to a correlated growth of the maximum HRR. Pile as wide as 10 m^2 are associated with emitted thermal powers of 60-70 MW. The rigorous management of the stack size would be an effective fire safety measure to limit the consequences. It should be considered that fire scenarios in open fields do not suffer limitations on ventilation, therefore peak HRR might be greater than in confined spaces.
Scenarios related to the combustion of PVC are less severe from the thermal perspective, the maximum calculated HRR is around 40 MW for a pile size of 10 m^2. This includes, but not exclusively, the effect of a lower heat of combustion. Despite the reduced thermal effects, it is noteworthy that pollutants emitted by PVC are by far more toxic and this imposes further considerations related to acute exposure to combustion products.

Table 4: Maximum calculated HRR for different fuel matrixes and pile sizes.

Fuel matrix	*Pile size [m²]*	*Maximum HRR [MW]*
PE – polyethylene	*1*	*5.4 ± 1.1*
	5	*40 ± 8*
	10	*68 ± 10*
PP – polypropylene	*1*	5.4 ± *0.5*
	5	38 ± *5*
	10	*62 ± 6*
PVC – polyvinylchloride	*1*	*4.0 ± 0.4*
	5	25 ± *9*
	10	39 ± *8*

5. Conclusions

Numerical simulation is a valuable support to the investigation of fire scenarios that involve complex fuel matrixes, including waste piles usually stored in the waste disposal and treatment facilities. The occurrence of fires in such facilities is an urgent issue, considered the frequency and severity of related scenarios.

In this work, a numerical Large Eddy Simulation approach was successfully applied to get into details of pollutants and thermal aspects related to the fire of waste piles made of selected plastics. Open-field fires of stacks of different sizes of polyethylene, polypropylene, and polyvinylchloride under different environmental conditions were investigated. Simulations tracked the number of pollutants at different downstream locations and the maximum HRR.

Pile size and environmental conditions alter the quantity of pollutants emitted and results show that a linear correlation can be assumed between pile size and quantity of investigated pollutants within 200 m. Time-averaged pollution decreases with stronger wind conditions in the medium-field. The maximum calculated HRR is sensitive to the pile size and range from 4.0 – 5.0 MW (1 m^2 pile) to 68 MW in the case of a 10 m^2 stack of polyethylene. In contrast to polyolefins open-field fires, maximum HRR associated with the combustion of polyvinylchloride is reduced and ranges from 4 to about 40 MW.

Further studies are planned, including the effect of varied fuel matrixes made of mixtures of plastics materials and ligneous-cellulosic compounds.

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