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Fibers Explosion Severity: a Parametric Study on the Fiber Geometry

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Even though explosive incidents involving organic fibrous materials have happened in a number of industries, the literature has very few research about the explosibility of fibers. This may have to do with people's lack of awareness of the possibility of explosions caused by fibers, which are frequently thought to be unlikely to explode. Nevertheless, they may provide a significant risk which needs to be taken into account throughout a risk assessment process. More specifically, only a small number of studies regarding fiber explosion modelling has been published in order to gain a better understanding of the primary controlling factors which can affect the explosion severity. Such studies primarily refers to an equivalent diameter approach, in which the elongated fiber is modelled as an equivalent sphere with an effective diameter. This approach, while useful in calculating the primary explosion characteristics, is inherently incapable of differentiating between the effects of increasing either the fiber length or the diameter. A variety of physical and chemical processes, including heat transfer between external and internal particles, pyrolysis and/or devolatilization reactions, and the combustion of volatiles, take place during a fiber explosion. These processes exhibit distinct characteristic times which vary depending on the fiber diameter and length. A comprehensive mathematical model that can account for the cylindrical-like geometry of a fiber can explain this discrepancy. This makes possible to differentiate between the effects of varying both the fiber length and the diameter, so demonstrating through a parametric analysis how such parameters can affect the severity of the explosion.
Keywords: Fibers explosibility, Dust Explosion Modelling, Fibers Safety Assessment.

1. Introduction

Although explosion accidents involving fibrous materials have occurred in several industries (e.g., Harbin linen fibers explosion in 1987, Massachusetts flock fire and explosion in 1995, Italy nylon flocks and wool dusts explosions in 2001 – see Dust Safety Science report 2020), especially in the textile sector (Yuan et al., 2015), relatively few studies on the explosibility of fibers can be recovered in the scientific literature (e.g., Amyotte et al., 2012; Iarossi et al., 2013; Marmo et al., 2018). This is possibly related to the low degree of consciousness of the risk of explosions due to fibers, which are often considered unlikely to explode. However, they can introduce a non-negligible hazard that should be considered in the risk assessment procedure (Barozzi et al., 2020). More specifically, very few papers using the modelling of fiber explosions to better understand the main controlling phenomena able to influence the explosion severity have been published. These contributes mainly relies on the equivalent diameter approach (e.g., Portarapillo et al., 2022); that is, the elongated fiber is modelled as an equivalent sphere with an effective diameter. While quite effective in estimating the main explosion parameters (e.g., Russo et al., 2013), this approach is intrinsically unable to distinguish the effect of increasing either the fiber diameter or the fiber length. As a matter of fact, in a fiber explosion different physical and chemical processes occur, such as: external and internal particle heat transfer, pyrolysis/ and/or devolatilization reactions, volatiles combustion. In a previous paper (Copelli et al., 2019), a detailed mathematical model able to account for all these phenomena in spherical coordinates (that is, basing on the assumption that the dust particles can be approximated as small spheres), then used even for modelling Minimum Ignition Energy of organic dusts (Copelli et al., 2021), has been presented and validated by comparison with several experimental K_{st} data (since

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this parameter both plays a fundamental role in estimating the magnitude of a dust explosion and it is also used to design the emergency release devices for protecting vessels and/or silos against an internal explosion). In this work, we extended the previously presented mathematical model to fibers by changing the coordinates from spherical to cylindrical. In this way, the effect of changing either the fiber diameter or the fiber length can be distinguished, therefore clearly elucidating the effect of both these parameters on the explosion severity through a parametric analysis. Results coming out from this study can be used for safety assessment purposes in all industries where fibers are produced and / or handled.

2. Mathematical model

Organic dust explosions proceed through several processes, whose relative importance can be assessed by estimating the values of various dimensionless numbers. The main processes involved are:

i) particle heating (which can be controlled by either the internal heat conduction or the external heat transfer, as identified by the Biot number (representing the ratio of the internal heat conduction characteristic time to the external heat transfer characteristic time);

ii) particle devolatilization due to pyrolysis (in this case, the Damkohler number compares the external heat transfer characteristic time and the pyrolysis characteristic time, while the Thiele number compares the characteristic time of conduction heat transfer and the pyrolysis characteristic time);

iii) combustion of the gases produced by dust pyrolysis (the ratio of the volatile combustion time to the pyrolysis characteristic time, that is the so-called Pc number, can be used).

These phenomena, in turns, heat the dust particles. While chemical phenomena are not expected to be influenced markedly by the particle geometry, the heating processes are.

For instance, the power entering the particle from a hot environment (which surrounds it) is proportional to the external particle surface (*A*), while the thermal inertia of the particle is proportional to the particle volume (*V*). Therefore, the ratio *A/V* (external particle surface to volume) influences the heating rate of the particle and, consequently, the velocity of the volatiles production through pyrolysis and the subsequent power released by the combustion of such volatiles. The larger the *A/V* ratio, the faster the heating rate of the particle is. Assuming that the heat transfer phenomenon develops mainly along one coordinate, different types of particles can be distinguished from a geometric point of view:

- "flat", representative of thin particles (e.g. sheets, slabs, etc..) with the dimension through the heat transfer proceeds much smaller than the other two;
- "spherical", representative of round shape particles where the heat transfer proceeds along the particle radius;
- "cylindrical", representative of particles characterized by length larger than the diameter, (that is, L/D>>1), where the heat is transferred mainly along the cylinder radius while the heat entering the two flat surfaces can be neglected.

All these geometries are depicted in Figure 1.

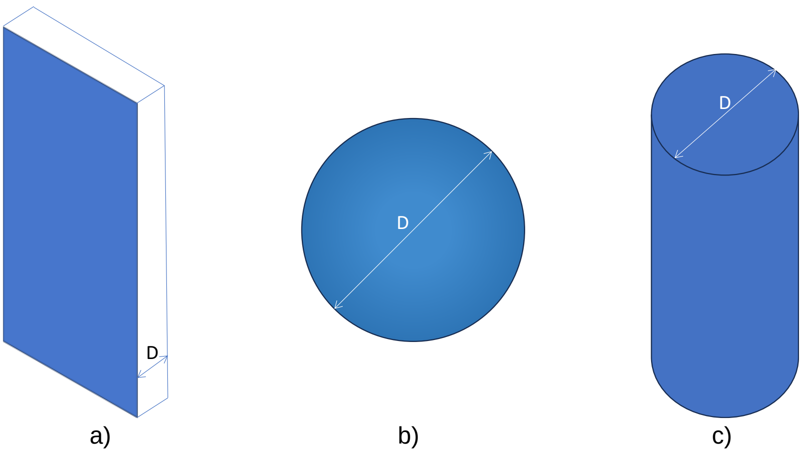

Figure 1: Different particle geometries: a) "flat", b) "spherical", and c) "cylindrical". D indicates the characteristic particle size.

The ratio of the external heat transfer area to the particle volume depends on the geometry considered representative of the particle shape through the following simple approximated relationships.
For thin "flat particles":

$$\frac{A}{V} \approx \frac{2a}{aD} = \frac{2}{D} \quad (1)$$

where a is the surface of a single face of the slab and D is the slab thickness (characteristic dimension).
For "spherical particles":

$$\frac{A}{V} \approx \frac{\pi D^2}{\frac{\pi D^3}{6}} = \frac{6}{D} \quad (2)$$

where D is the characteristic diameter of the particle.
For "cylindrical particles":

$$\frac{A}{V} \approx \frac{\pi D L}{\frac{\pi D^2 L}{4}} = \frac{4}{D} \quad (3)$$

where D is the characteristic diameter of the particle and L its length.
Therefore, the *A/V* ratio always increases when decreasing the characteristic particle size, *D*; in particular, it always increases linearly with 1/D, while it is not influenced by other geometrical dimensions. In other words, changing the surface of a single face of the slab for thin "flat particles" or the fiber length for long "cylindrical particles" is not expected to influence significantly the A/V ratio. The geometry can also influence the heat transfer rate inside the particle. The characteristic time of the heat conduction process (that is, the characteristic time of the particle heating) can be approximated by the ratio of the squared distance along with the heat has to be transferred (*D/2* for all the geometries) to the thermal diffusivity of the particle. Therefore, the characteristic time of heat transfer rate inside the particle always decreases when decreasing the characteristic particle size, *D*. Thus, summarizing, the characteristic time of the particle heating is expected to decrease when decreasing the characteristic particle size, *D*, while it is not expected to be influenced significantly by other geometrical dimensions. Let us now discuss the effect of halving the volume of a particle (which means doubling the number of particles while keeping unchanged the massive dust concentration in the environment) in different ways for the three aforementioned geometries.For thin "flat particles" we can halve the volume of a single particle either by halving the particle thickness or the surface of the slab face. However, while halving the particle thickness leads to decrease the characteristic time of the particle heating, halving the slab surface of the particle leaves the characteristic time of the particle heating almost unchanged. For "spherical particles" we can halve the volume only by reducing (of a factor equal to $\sqrt[3]{2}$) the particle diameter. This means that reducing the particle volume necessarily leads to decrease the characteristic time of the particle heating.For long "cylindrical particles" we can halve the volume of a single particle either by reducing (of a factor equal to $\sqrt{2}$) the fiber diameter or by halving the length of the fiber. However, while reducing the fiber diameter leads to decrease the characteristic time of the particle heating, halving the length of the fiber leaves the characteristic time of the particle heating almost unchanged. Therefore, according to the previous considerations, modelling a non-spherical particle as an equivalent sphere with an effective diameter is not expected to correctly reproduce the heat transfer dynamics (that is, a model accounting explicitly for the model geometry is required). In a typical detailed model for organic dust explosions (e.g., Copelli et al. 2019), the geometry is involved in the constitutive equations through ∇ and ∇^2 mathematical operators, which have different mathematical formulations when changing the particle geometry, as summarized in Table 1.

Table 1: One-dimension divergence and Laplacian mathematical operators for various geometries. x and r refer to the single coordinate involved in the heat transfer phenomenon.

	Geometry		
	Cartesian	Spherical	Cylindrical
Mathematical operator			
∇f	$\frac{\partial f}{\partial x}$	$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 f) = \frac{\partial f}{\partial r} + \frac{2}{r}f$	$\frac{1}{r}\frac{\partial}{\partial r}(rf) = \frac{\partial f}{\partial r} + \frac{f}{r}$
$\nabla^2 f$	$\frac{\partial^2 f}{\partial x^2}$	$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial f}{\partial r}\right) = \frac{\partial^2 f}{\partial r^2} + \frac{2}{r}\frac{\partial f}{\partial r}$	$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial f}{\partial r}\right) = \frac{\partial^2 f}{\partial r^2} + \frac{1}{r}\frac{\partial f}{\partial r}$

Therefore, the same mathematical model discussed elsewhere (Copelli et al., 2019, to which the reader is referred to for all the details) was properly modified in the mathematical operators from spherical to cylindrical coordinates to investigate the effect of changing the fiber length and diameter on the explosion severity (summarized in the K_{st} value). It should be mentioned that the length of the fibers can strongly influence the dispersibility of the fibers in air, therefore influencing indirectly the explosion severity. This peculiar aspect cannot be accounted for by the mathematical model used to predict the K_{st} value and, consequently, it was not investigated in the present work.

3. Results and discussion

The qualitative effect of changing the fiber diameter was investigated considering a typical organic fiber (in this work corn starch was considered, see Table 1 in Copelli et al. 2019 for all the main parameters values) with 250 µm length, where the computed K_{st} values were made dimensionless with respect to the minimum value computed. Results are reported in Figure 2. We can see that below a threshold diameter value (in this case 50 µm), the computed K_{st} sharply increased up to several time the asymptotic value reached by increasing the fiber diameter (that is, 1).

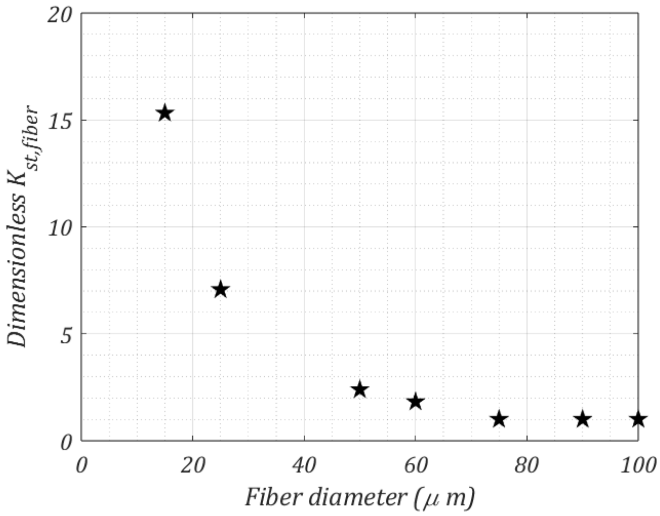

Figure 2: Qualitative effect of changing the fiber diameter while keeping constant the fiber length at 250 µm.

However, as expected, a different behavior was found when changing the fiber length for a typical organic fiber with 25 µm diameter, as summarized in Figure 3. In this case the computed K_{st} value are almost insensitive to changes in the fiber length value.

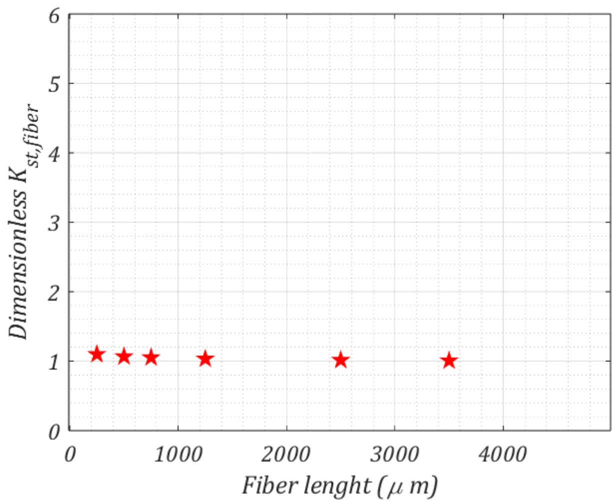

Figure 3: Qualitative effect of changing the fiber length while keeping constant the fiber diameter at 25 µm.

The differences in the K_{st} values computed accounting or not for the cylindrical geometry of the fiber is summarized in Figure 4, as a function of the fiber diameter, and in Figure 5, as a function of the fiber length. These figures report the ratio of the K_{st} values computed representing the fiber as a cylinder to those computed representing the fiber as an equivalent sphere with the cross-sectional area equal to that of the cylindrical fiber (as reported in the work of Russo et al., 2013). Particularly, the equivalent sphere diameter (D_{eq}) was calculated using Eq. (4).

$$D_{eq} = 2 \cdot \sqrt{D \cdot \frac{L}{\pi}} \tag{4}$$

where *D* is the original diameter of the fiber and *L* its original length.
Figure 4 shows a decreasing trend of the ratio between the deflagration index calculated for fibers (that is, implementing a model using cylindrical coordinates) and that one calculated for an equivalent sphere (that is, implementing a model using spherical coordinates) as a function of the fiber diameters. Particularly, it is possible to observe how considering a fiber as an equivalent sphere tends to underestimate the value of the K_{st} for small fiber mean diameters up to a factor 10 (even if the reliability of such theoretical K_{st} value could be not so high); on the contrary, when high fiber diameters are considered K_{st} value are almost the same as considering the fiber as an equivalent sphere (this last observation is quite reasonable because we are simply approaching the round shape).

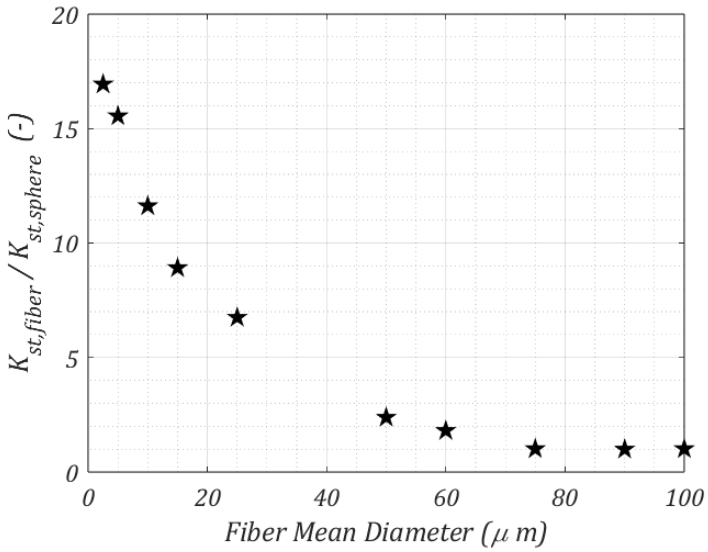

Figure 4: Qualitative effect of changing the fiber diameter when considering the fiber as a cylinder vs. an equivalent sphere (fiber length is kept constant at 250 µm).

Furthermore, when considering the effect of an increase of the fiber length, keeping constant the diameter, it is possible to observe (see Figure 5) an unusual behavior. There is always an underestimation of the K_{st} value when considering the fiber as an equivalent sphere, but such an underestimation seems to be quite constant (apart when the fiber length is very small) in accordance with the results reported in Figure 3.
Both the results reported, respectively, in Figures 4 and 5 are quite predictable because, being the radial direction the most important through which the heat is transferred, the most influencing parameter is the diameter (not the length). Moreover, due to the definition of equivalent diameter reported in Eq. (4), which is proportional to the square root of the fiber length, the diameters of the equivalent spheres are all major with respect to the original fibers diameters: this always results in an unavoidable underestimation of the K_{st} values for fibers when treated as equivalent spheres.

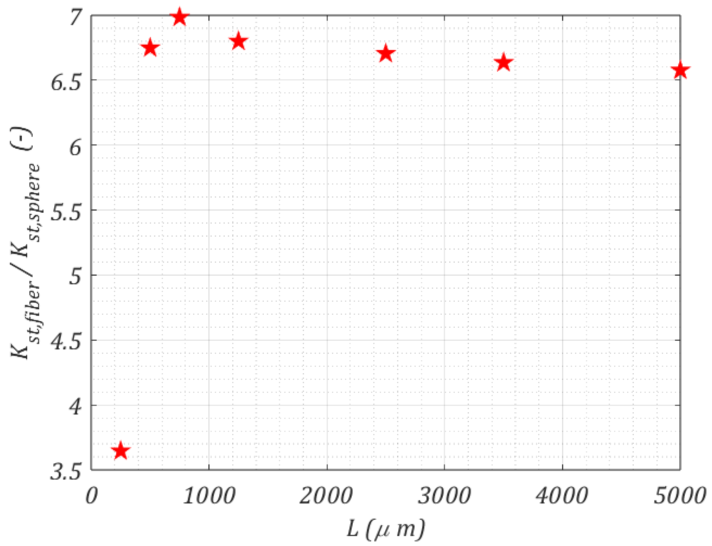

Figure 5: Qualitative effect of changing the fiber length when considering the fiber as a cylinder vs. an equivalent sphere (fiber mean diameter is kept constant at 25 μm).

4. Conclusions

In this work a mathematical model to account for the fiber geometry was proposed. According to the results achieved, different variations of the K_{st} values are expected when either the length or the diameter of the fiber are modified. Particularly, an increase of the fiber diameter implies a diminishing in the corresponding K_{st} value, while an increase of the fiber length seems to be quite uninfluencing. This behavior cannot be predicted by mathematical models representing the fiber as an equivalent sphere (that is, combining in a single lumped parameter, the equivalent diameter, the information related to both fiber length and diameter). Moreover, it was found that the K_{st} values predicted by approximating the fiber as an equivalent sphere can differ up a factor of about 10 from the values predicted when accounting properly for the fiber geometry.

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