

# Effects of Inert Particles with High Specific Surface on Ignition and Flame Propagation in Dust/Air Mixtures

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## ABSTRACT

The purpose of the presented investigations was to identify the influence of specific surface of porous inert particles on ignition and flame propagation in combustible dust/air mixtures. It is commonly known that inert dusts are able to reduce the criticality of dust/air mixtures significantly in terms of ignitability and explosion severity. Different non-combustible materials like rock dust or chalk dust are used for dust explosion prevention. In order to assess the influence of the specific particle surface on the effectiveness of inert material, tests on the ignitability of different dust/air mixtures have been carried out. Experiments have been conducted with *Lycopodium Clavatum* as combustible dust. *Lycopodium Clavatum* was mixed with inert dusts with high and low specific surface area.

As a material with high specific surface Clinoptilolith, a natural aluminosilicate, was used. Clinoptilolith was compared to ceramic beads with indifferent particle sizes. In terms of benchmarking, Clinoptilolith was also compared to different other inerting material like dry chemicals for fire extinguishing purposes. To study the influence of initial humidity on the inerting effectiveness of Clinoptilolith, the material was tested at different grades of humidity. Tests have been carried out with the Kuhnert MIKE III Apparatus, the 20-L-Siwiek Chamber and a Tube reactor for flame speed measurements. The experimental results were compared to CFD simulations using an OpenFOAM® model.

**KEYWORDS:** Additives, combustible dust, ignition, inert particle.

## INTRODUCTION

Fire and explosion prevention takes a great part of safety efforts, raised by the process industry, because major losses in the industry are caused by such events. Apart from the possibility of the loss of lives, the damage of plants should be avoided. Therefore, three concepts of explosion prevention are known and used. If it is not possible to prevent explosive atmospheres and ignition sources, the use of substances which interrupt developing chain reactions is common [1]. An effective and fast alternative is the use of dry extinguishing agents or inert dusts. The particle acts as kinetic energy sink for developing chain reactions [2]. Basically, the way of inerting can be classified into two groups: the thermal inhibitors and the chemical inhibitors, which are the more efficient ones. The first option, the thermal extinction, works on the basis of the cooling effect by cooling down the reaction gases by partial vaporization or melting. On the other hand, the inerting process is caused by recombination of the chain carriers on the surface of the particles. Therefore, the wall of the solid particles is important to reach a useful inhibition [3]. This means that the use of inert dusts stop chain reactions and prevent propagation. Based on this mechanism, fires and explosions can be suppressed right from the beginning. In order to assess the influence of the specific particle surface on the effectiveness of Clinoptilolith as inert material, tests on the ignitability of different dust/air mixtures have been carried out.

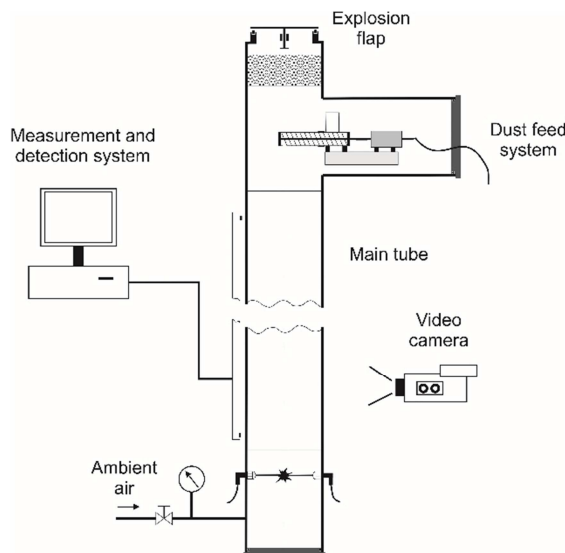
For experimental purposes *Lycopodium Clavatum* was mixed with inert dusts with high and low surface areas. As material with high specific surface area, Clinoptilolith, a natural aluminosilicate, was used. To study the influence of initial humidity on the inerting effectiveness of Clinoptilolith, the mineral was tested at different humidity grades. The experimental results were compared to CFD simulations using an OpenFOAM® model.

## CLINOPTILOLITH

The crystalline mineral Clinoptilolith belongs to volcanic rock and is characterized by a three dimensional structure of silicon compound and alumina compound. Naturally build cavities are producing such a high specific surface area of the mineral [4], that is up to 1,000 times compared to commonly used extinguishing powders. Clinoptilolith has a ssa of about 400 to 600 m<sup>2</sup>/g. Deposits all over the world and a good purity up to 90 % make the mineral useful in various applications like adsorbents, ionic exchanger or for catalytic purpose [4]. The origin of the name means “boiling stone” in greek, because of losing a great amount of water during heating the stone. This phenomenon can be explained by the storage of water in the natural build cavities [4]. This characterization was used to study the influence of humidity on the inerting effectiveness during experiments by testing different humidity grades.

## METHOD

Investigations were carried out with three different apparatus to identify effects of the inner particle surface on inerting behavior of inert particles. To identify the influence on the ignition behavior, tests on the minimum ignition energy (MIE) with the Kuhner MIKE III Apparatus were performed, according to EN ISO 80079-20-2. Tests on the influence on the combustion reactions (rate of pressure rise, and maximum pressure) were performed in the Kuhner 20-L-Siwiek Chamber (EN ISO 80079-20-2) with continuous spark igniter of 10 Joule total energy. The last apparatus used was a non-standardized method to investigate the flame velocity and the flame behavior in a dust/air mixture under low turbulence condition through photometric measurements.



**Fig. 1.** Tube method used by Kern [5].

The mentioned apparatus consists of an explosion tube with a length of 2,000 mm and a continuous spark igniter at the bottom. The dust feed system is arranged on top of the tube, therefore, a low turbulence level can be realized, and a dispersion of dust in the tube is achieved [5]. Low turbulence conditions were important to provide a proper mixture between the combustible dust and the inert particles, and also, to minimize the segregation between the start of the test and the ignition of the dust/air cloud [5]. Tests were carried out at a dust concentration of 200 to 300 g/m<sup>3</sup>, high enough to ignite the dust cloud, and low enough to prevent a distribution.

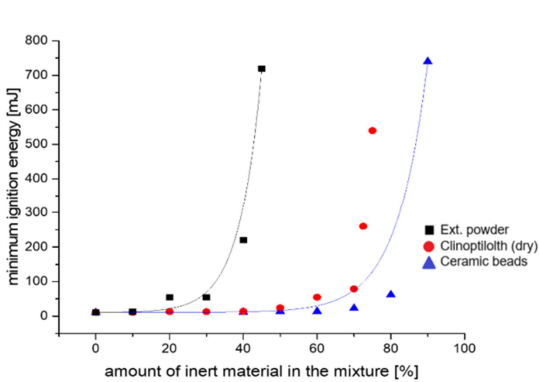
*Lycopodium Clavatum* was used as combustible dust. It is the spore of club moss and is characterized by a monodisperse behavior and a uniform particle size. *Lycopodium Clavatum* has a netlike surface structure, containing oleic acid, therefore, it is easy to ignite with a prompt deflagration [6]. Caused by the natural size of *Lycopodium Clavatum*, the used dusts were sieved to a particle size between 32 and 63 µm. The specific surface area of finer particles is higher than of the coarse ones, therefore, fine particles are a better alternative as fire suppressant. Furthermore, the number of fine particles in a dust/air cloud is higher than of coarse particles of the same weight. As a result the distance between the inert particles is smaller. Due to greater distance between the combustible dust particles the flame propagation from particle to particle gets prevented. Harris et al. [7] introduced the inerting index *Z*, which is defined as the mass ratio of the inerting material to the combustible dust. The inerting index *Z* increases as the specific surface value decreases. Greater quantities of coarse particles are needed for a specific inerting effect which would also be received by using fine particles of the same material.

For performing simulations of dust explosions with different inert powders the open-source CFD software OpenFOAM® was used. To calculate a particle-laden flow regime an Euler-Lagrangian approach was suited. The gaseous phase is regarded as a continuum and dispersed solids are tracked. Mass, momentum and energy between the phases were considered through two-way coupling [8]. The transfer of momentum and turbulent kinetic energy from the particles and the transfer of turbulence from gas to the solid phase as well as the transfer of heat and mass from laden particles in form of, for example vapour, was modelled [9]. To model turbulent flows accurately, an implementation of the Navier-Stokes equations is needed. Therefore a common K-epsilon turbulence model was chosen, which provides one equation for turbulent kinetic energy and one for the dissipated energy.

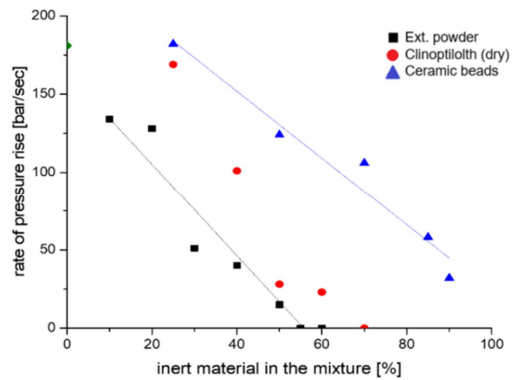
## EFFECTS OF SPECIFIC SURFACE AREA

The influence of the inerting effect caused by porous material was investigated to visualize the effect based on the interaction of the radicals with the particle surface. Firstly, tests on the minimum ignition energy were done to identify the influence of the specific surface area on the ignition behavior of combustible dust. The higher the minimum ignition energy, the higher the energy necessary to ignite the dust/air mixture. A high ignition energy minimizes the risk of an ignition, for example by electrostatic discharging. As a first inhibitor ceramic beads were used. These ceramic beads were used due to a low specific surface area (ssa) and a uniform particle size. Because of this property effects on the particle surface were expected to be low, and therefore, the heterogenic inhibition should be low. Tests confirm these assumptions as it can be seen in Fig. 2. The amount of ceramic beads has to be high enough to provide enough particle surface area to catch all combustion reactives. Up to 70 % mass ceramic beads in the *Lycopodium*/inert dust mixture, there is no observable change in the minimum ignition energy. In contrast, the mineral Clinoptilolith is renowned for its high ssa caused by naturally occurring cavities. An inhibition effect occurs when there is a lower amount of the inert material in the mixture – starting at an amount of about 55 % Clinoptilolith in the dust cloud. However, the same rapid increase in the minimum ignition energy at the beginning of inerting can be seen for both inert particles used.

As a benchmark a commercial extinguishing powder was investigated. The value of the ssa lies between the two other tested inert materials. The used powder is a mixture of ammonium dihydrogen phosphate and ammonium sulfate with a surface value of about 0.1 to 0.4 m<sup>2</sup>/g and is used as powder to extinguish fires of all fire classifications, class A, B, and C. Such dry chemicals are distinguished for a quick extinguishing success, a high extinguishing rate and a great storability [2]. However, it has to be taken into account that this powder produces endothermic chemical reactions which precipitate the extinguishing effect. Therefore, no clear statement concerning the influence of the ssa can be made. These endothermic reactions take the energy of the flame, stop the combustion process and stop the ignition [2]. Also the produced products show inhibitory effects. On the one hand, an effect of these dry chemicals is the smothering effect, caused by decompose products of the powder cloud. Both, thermal radiation caused by endothermic reactions of the powder, and heat transfer between powder and flame lead, on the other hand, to a cooling effect [2]. As seen in Fig. 2, the inerting effect in the mixture resembles the inerting behavior of the other porous inert materials tested [11].



**Fig. 2.** Results minimum ignition energy (MIKE III) [10].



**Fig. 3.** Results rate of pressure rise (20-L-Chamber) [10].

The second investigated parameter deals with the pressure after the ignition of the dust/air mixture. The aim of these tests was to identify the influence of the specific surface area on the produced pressure. Therefore, tests with various values of inert dusts in a combustible dust/air cloud were done. The investigated maximum rate of pressure rise ( $dp/dt$ ) gives an idea of the pressure development during the ongoing explosion in the 20-L-Chamber. Results can be seen in Fig. 3. There is a difference in the potential violence of the dust explosion between an adding of ceramic beads (low ssa) and Clinoptilolith (high ssa). All mixtures show a negative correlation between the amount of inert material in the mixture and the ( $dp/dt$ )-value. It can be seen that the curve from Clinoptilolith lies closer to the curve of the extinguishing powder, in fact, closer than in Fig. 2. This might indicate that wall effects have an influence on the potential violence of the dust explosion, but not on the minimum ignition energy.

The last investigated parameter was the flame velocity, as shown in Fig. 4. Based on the experimental method, the flame front propagates as deflagration in a parabolic shape though the tube [5]. By mixing inert particles in the combustible dust, a decreasing of the flame velocity with the increase of the inert dust can be seen. The higher the specific surface area of the inert material, the faster the decreasing of the flame speed. The more inert particles are in the mixture, the higher is the available ssa, and therefore, a decreasing of the flame velocity can be seen with an increase of porous inert material. The amount of inert material in the mixture where no flame propagation occurs lies between 20 and 25 %. Away from these amounts, the flame cannot propagate from one particle to the next. Clinoptilolith has a high decrease of the flame velocity at a concentration of

inert particles between 5 and 10 % in the mixture. By a further increasing of the amount of Clinoptilolith in the dust/air mixture the flame velocity is decreasing more slowly [11, 12].

## EFFECTS OF PARTICULATE ADDITIVES WITH WATER AND SALT

As mentioned before, the mineral Clinoptilolith is characterized by losing a great demand of water during heating the stone. Aim of an experimental series was to identify this phenomenon and to investigate if stored water in the natural build cavities of the mineral can be activated during deflagration processes as inhibitor. Commonly, it is known that the minimum ignition energy is rising as the humidity of the fuel is rising [13]. However, the opposite can be seen (cf. Fig. 5). The amount of moistured Clinoptilolith has to be higher than the amount of the dry mineral to receive the same inerting effect. The reason for this may be the formation of water vapour, which contributes to combustion [11]. Also mixtures for 75 % Clinoptilolith (dry) and 80% water-laden Clinoptilolith (2% and 4% water) have been tested. The MIE exceeded 1000 mJ for these mixtures and could not be measured.

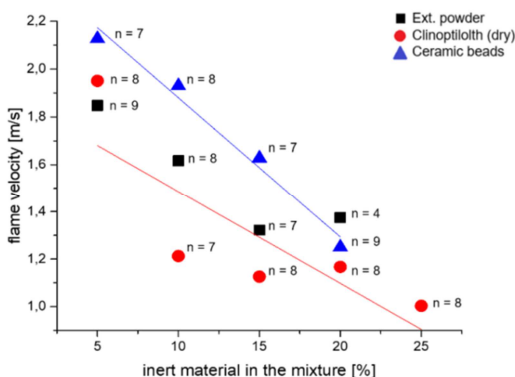


Fig. 4. Results flame velocity (Tube) [10].

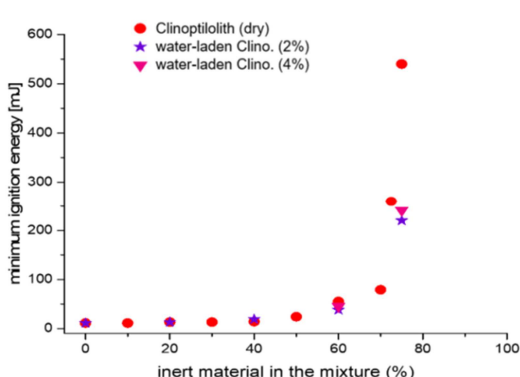


Fig. 5. Results minimum ignition energy in mixtures with water-laden particles (MIKE III) [11].

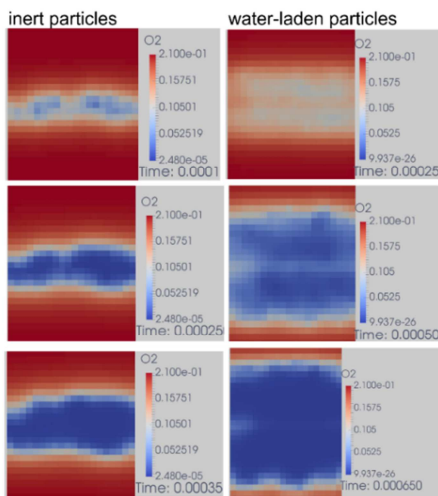
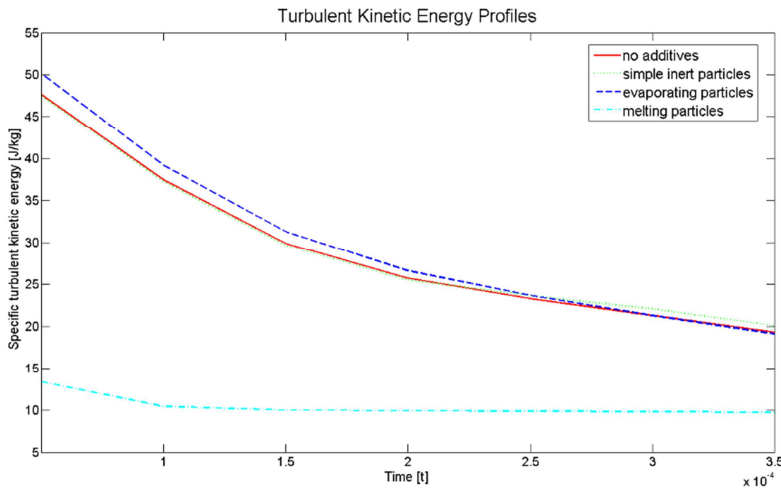


Fig. 6. Simulation results showing the temperature development around the plasma channel of the ignition spark.

Experimental results were compared to CFD simulations using an OpenFOAM model. Studing simulation results, it can be observed that the evaporating water pushes the flame front forward. Thereby the flame front increases and the combustion generates higher heat flows within the first few time steps at the ignition. As soon as the flame front has its final appearance, the heat flux of the combustion shows similar gradients as the dust/air mixture with and without inert particles. A comparison of the ignition behavior between the dry Clinoptilolith and the water-laden mineral on basis of the water mass fraction can be seen in Fig. 6. Evaporating influences turbulent conditions, and therefore, lower ignition energies might occur. It was decided to display the turbulent kinetic energy over the first few steps as shown in Fig. 7. The blue graph (dashed line) displays the behavior of the case in which water-laden particles were introduced in the system. It can be clearly seen that more turbulence is present during the first few time steps, even though all other cases were also ignited at the same energy level.



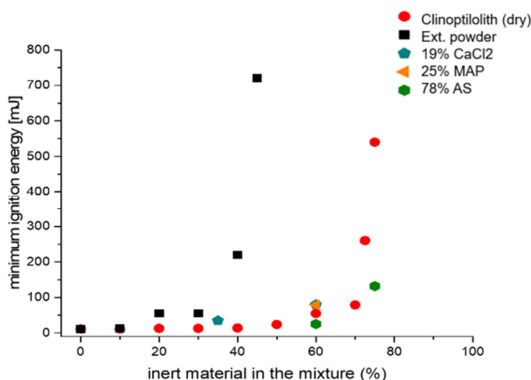
**Fig. 7.** Simulation results showing the comparison of the specific turbulent kinetic energy of the gas phase [8, 11].

Caused by high temperatures generated at the ignition process, an increase of the volume around the spark can be detected. This expansion in volume leads to a lower concentration range of particles at the surrounding [10]. Besides the limitation of the diffusion, the fuel acts as limiting factor. As it can be seen in Fig. 8, the combustion process with moistened Clinpotilolith starts very fast at the beginning. Differences to dry inert particles can only be investigated through mass transfer into the gas phase, therefore, this effect can be explained through the evaporation of the water (i.e. a sudden release of vapour). The vapour acts promoting for the combustion process by improving the mixing conditions on molecular scale. Furthermore, the vapor supports the propagation of the flame in regions of unconverted oxygen and fuel.

**Table 1.** Calculation results of minimum ignition energies (particle size 30  $\mu\text{m}$ )

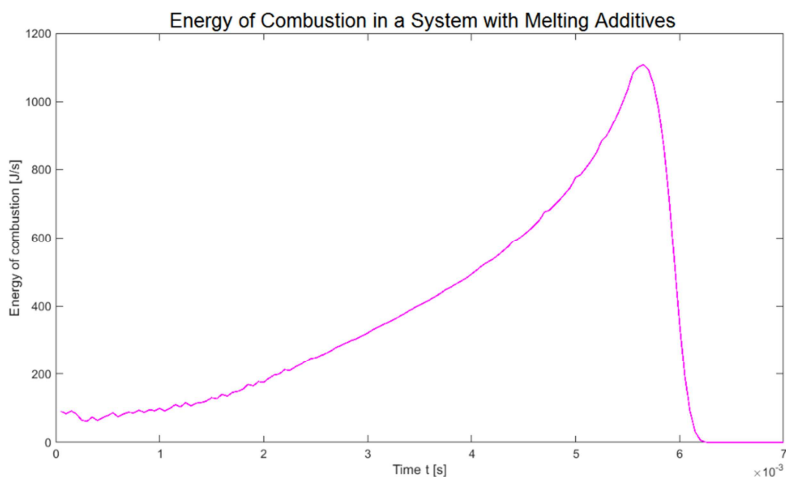
Species	MIE
Combustible dust	25 mJ
Mixture with Clinoptilolith	26 mJ
Mixture with water-laden Clinoptilolith	17 mJ
Mixture with salt-laden Clinoptilolith	24 mJ

Calculations of the minimum ignition energy show that values of water-laden Clinoptilolith are lower than similar particles. There might also be an effect of hydrogen formation in the early stages of ignition, but this effect was not further studied. Besides the possibility of loading water in the natural built cavities of Clinoptilolith, it is possible to load salt in such emerged spaces. Investigations were done to identify effects of melting particles on ignition and flame behavior. The used mineral was loaded with calcium chloride ( $\text{CaCl}_2$ ), ammonium dihydrogen phosphate (MAP) and ammonium sulfate (AS) to observe the influence of various salts on the ignition behavior and to compare it with commonly used extinguishing powder (Fig. 10).



**Fig. 10.** Results minimum ignition energy in mixtures with salt-laden particles (MIKE III) [10].

Calcium chloride is a hygroscopic salt, which enters the liquid state at a temperature of  $30^\circ\text{C}$ , caused by containing water of crystallisation. MAP melts at a temperature around  $190^\circ\text{C}$  and is known for its non-reactive products. The low hygroscopic mineral ammonium sulfate melts at a temperature of  $230^\circ\text{C}$ .



**Fig. 11.** Released energy of combustion.

Based on investigations on the ignition process of a dust/air mixture containing melting particles, it can be assumed that the heat of combustion that is released is primarily consumed by the heat of fusion. These decreased temperatures lead to lower turbulence and thus to bad mixing conditions. According to Sutherland, decreasing temperatures decline molecular diffusion, which is also expected to be the reason for observed thicker reaction zones. Compared to other reaction profiles (cf. Fig. 8), the combustion in systems with melting particles shows a rather homogeneous increase of combustion energy up to the final maximum, as it is displayed in Fig. 11.

After an ignition of a dust/air mixture with a specific content of melting particles, the flame propagation practically ceases. Irregular expansions of hot zones limit the flame movement for more than half a second. The low reaction rate and the slow flame propagation can be explained by the poor mixing on molecular level. Tomasch observed that the combustion is oxygen-limited, however considerable amounts can still be found in a comparatively broad region behind the reaction zone. Even in boundary regions diffusion is the crucial process, although, normally due to turbulence the reaction converges kinetic limitation. Melting particles in the dust cloud constitute the major heat as long as solid is available. The flame front is fed from areas in the back instead from areas in front. Therefore, the behavior of propagation is different and the flame is able to sustain itself. Afterwards the ignition (around 0,39 s) particles in the area above the ignition zone are fused (see Fig. 12). In regions with maximum temperatures (cf. Fig. 13) the melting process starts and enlarges slowly. Around 0.45 s after ignition, streaks of enhanced temperatures can be observed in the whole geometry. Hot zones separate from the flame front, area of low temperatures appears and ignites spontaneously, as well as several small regions in the tube. Combustible zones are growing fast and reach the hole geometry. According to Tomasch, first few particles are completely molten above the flame front after 0,47 s. Ongoing observations show that the temperature is increasing in these cells and no melting is possible anymore.

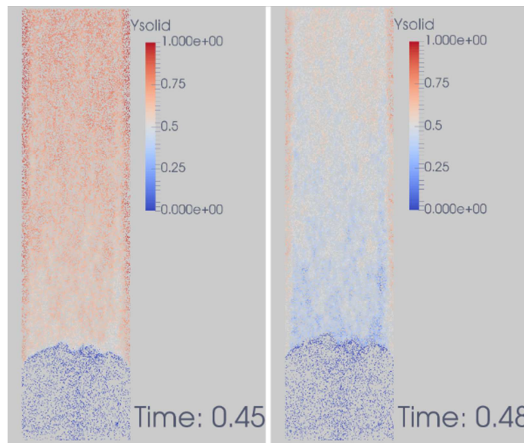
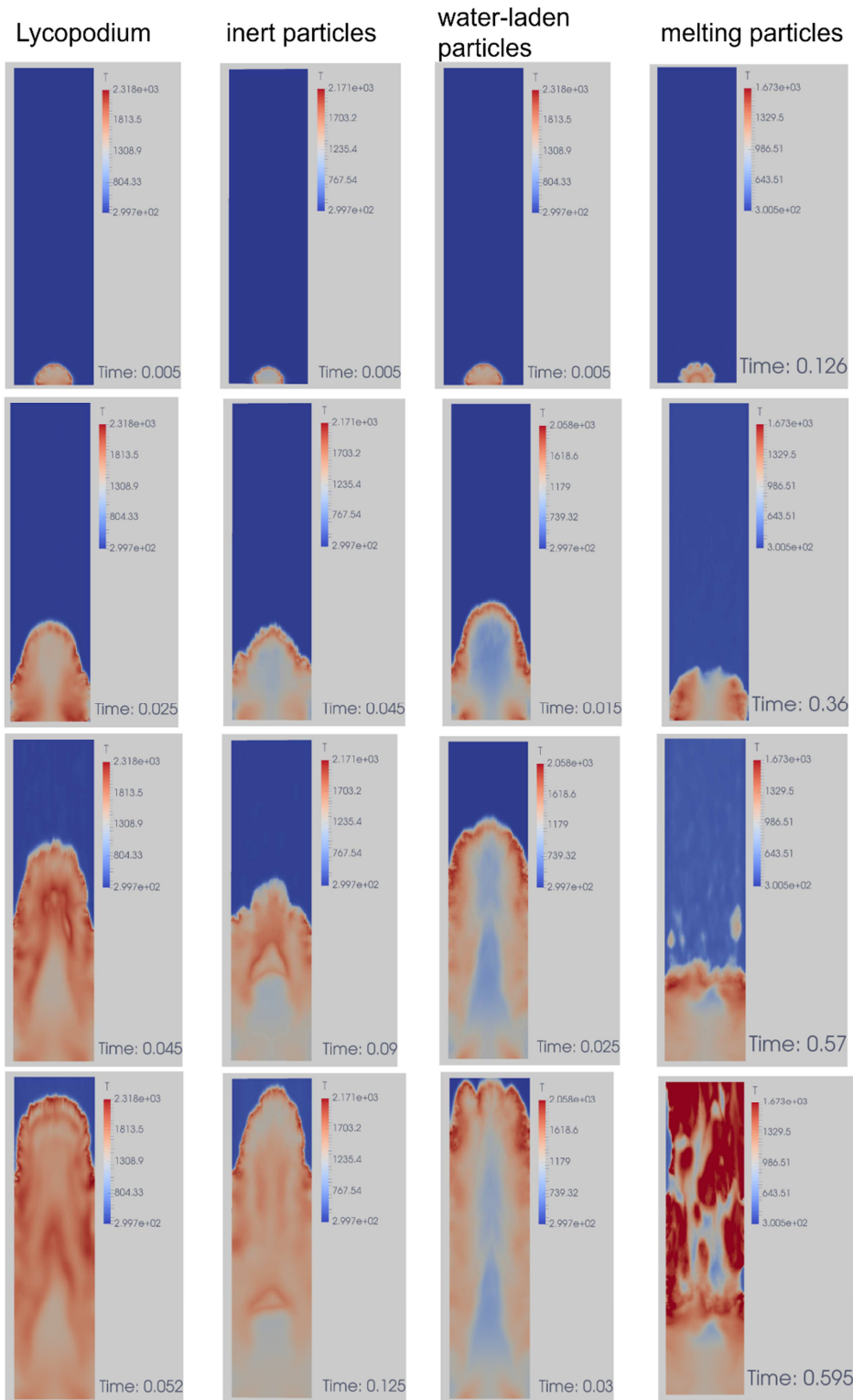


Fig. 12. Melting process after ignition (coloration with solid mass fraction).

## CONCLUSION

In this study the influence of the specific surface area of porous material on the ignition behavior and flame propagation were identified. Therefore, the mineral Chlinoptilolith as inert dust particle was mixtured with Lycopodium as combustible dust. Tests were done with fine particles (between 32 and 63  $\mu\text{m}$ ) to receive comparable specific surface areas. It can be said that the specific surface area of porous material has an influence on the dust explosibility. This can be seen on the ignition behavior, and on the potential violence of the deflagration, as well as on flame propagation tests. However, the influence on the ignition is smaller. The overall data shows a decreasing correlation between increasing amount of inert particles. Inert materials have an influence on both, turbulent and molecular diffusion. Furthermore, to observe the effect of evaporation and melting, inert particles got laden with water and salt. Thereby it turned out that these additives, acting as energy sink, influence the propagation of the flame front, however, not the ignition process in the same extent. Caused by the release of volumina at evaporation, turbulence is rising. If there is a melting process due to salt-laden particles in the dust cloud, hot zones get cooler, and therefore buoyancy lowers. Subsequently, the reaction rate decreases and flame propagation slows down.





**Fig. 13.** Ignition and flame propagation with various additives in the dust mixture [11].

## REFERENCES

- [1] Steen, H.: Handbuch des Explosionsschutzes, Wiley-VCH, Weinheim, 2009.
- [2] M. Friedrich, Untersuchungen über das Verhalten und die Wirkungsweise verschiedener Trockenlöschmittel Forschungsberichte des Landes Nordrhein Westfalen Nr. 1168, 1960.
- [3] M. Dewitte, J. Vrebosch, A. van Tiggelen, Inhibition and Extinction of Premixed Flames by Dust Particles, *Combust. Flame* 8 (1964) 257–266.
- [4] A. Dyer, An introduction to zeolith molecular sieves, Wiley, Chichester, 1988.
- [5] H. Kern, Explosible Dust/Air Mixtures Inverstigations on flame propagation under non atmospheric conditions, Dissertation, Montanuniversitaet, Leoben, 2013.
- [6] T. Skjold, Selected aspects of turbulence and combustion in 20-litre explosion vessels. Development of experimental apparatus and eperimental investigation, Master Thesis, University of Bergen, Bergen, 2003.
- [7] M.L. Harris, M.J. Sapko, I.A. Zlochower, I.E. Perera, E.S. Weiss, Particle size and surface area effects on explosibility using a 20-l-chamber, *J. Loss Prevent. Process Ind.* 37 (2015) 33–38.
- [8] Fluent Inc. (publisher):Fluent 6.0 User´s Guide, Volume 4, Chapter 18 - Introduction to Modelling Multiphase Flows, Lebanon NH, USA, 2001.
- [9] A. Bakker, 14. Multiphase Flows Lecture Noates, Dartmouth College. Available online at [www.bakker.org/dartmouth06/engs150/](http://www.bakker.org/dartmouth06/engs150/), checked on 01.08.2016.
- [10] K. Hüttenbrenner, H. Kern, Entzündbarkeit von Staub/Luft-Gemischen bei Verwendung von Inertstäuben mit hoher Porosität, *Technische Sicherheit* (2018), 25–30.
- [11] K. Hüttenbrenner, C. Donner, H. Kern, H. Raupenstrauch, Investigations on the influence of the specific surface on the ignition and flame bahavior of combustibile dust/air mixtures, 11th International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions, Dalian, China, 2016.
- [12] K. Hüttenbrenner, H. Kern, H. Raupenstrauch, Mitigation of dust explosions by porous inert material, 13th Minisymposium Chemical and Process Engineering Innsbruck, 2017.
- [13] Bartknecht, W.:Staubexplosionen, Springer Berlin Heidelberg, Berlin, Heidelberg, s.l., 1987.