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CALCULATION OF THE MINIMUM IGNITION ENERGY OF DUST–AIR MIXTURES

The explosion of a dust-air mixture is a very complex process. The investigations of the ignition energy necessary for the ignition of such a mixture prove that the kind of components, the shape and size distributions of the dust particles, the content of dust and oxygen in the air and the temperature and pressure are mutually dependent. The experiments are expensive, hence in order to estimate the ignition energy a mathematical model is derived. This model is used to estimate the magnitude of the ignition energy.

The modelling of the ignition process is based on the model of volume shells. The ignition of the dust–air mixture starts in a defined volume – the globular ignition volume. Around the ignition volume there are spherical shells with the thickness ΔR concentrically arranged.

1. OBJECTIVES

The explosion of a dust–air mixture is a very complex process. Physical and chemical events take place simultaneously and influence each other.

The ignition energy is sufficient for the ignition of a dust–air mixture. The ignition energy is essential in the characteristics of dangerous situations in industrial plants where dust occurs.

The experimental investigation of the ignition energy is very expensive. The kind of components, the shape and size distributions of the dust particles, the content of dust and oxygen in the air and the temperature and pressure are mutually dependent and this dependence is of a complex type.

That is why extensive experimental tests are considered necessary for every interesting dust–air mixture and situation. Explosion tests are carried out with interesting dust in order to get the parameters characterizing the explosion.

An important reduction of the tests allowing us to obtain the explosion parameters is possible by the calculation of the ignition energy. This calculation should be based

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on a mathematical model which is used to estimate the magnitude of the ignition energy. The tests are necessary only for verification.

Therefore our goal is to achieve the reduction of the experimental expense by adapting a small number of model parameters. An important problem is a precise characteristics of the kinetics of the processes occurring during explosion by means of simple expressions.

In this paper, the model for the calculation of the ignition energy, the developed simulation program and results of calculations are dealt with.

2. MODEL DESCRIPTION

The modelling of the ignition process is based on the following assumptions.

The ignition of the dust–air mixture starts in a defined volume, i.e. the ignition volume, which is globular. Around the ignition volume the spherical shells with the thickness ΔR are arranged concentrically. The ignition volume is also designated as zero shell. This model is called "model of volume shells". Figure 1 shows this model.

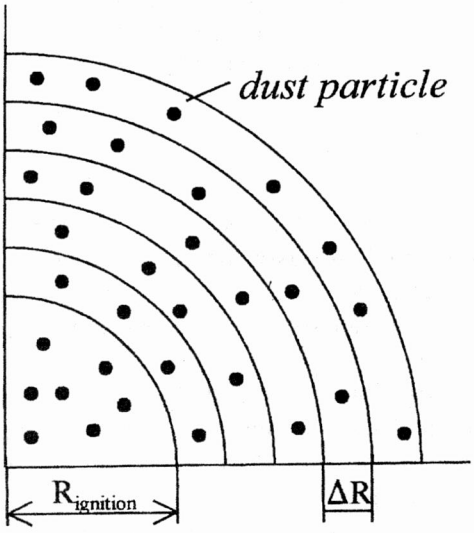

Fig. 1. Model of volume shells

Just after the energy being supplied to the ignition volume it becomes warmer. After this the first shell gets warmer, then the second one, and so on. The air temperature and the particle temperature in the shells will be different from shell to shell, but inside a shell the air temperature and the particle temperature are constant. As shown in figure 2, heat transport processes take place only at the boundary of the

shells due to the conduction from shell to shell and inside a shell between air and particles by convection. Additionally, there is a heat radiation from the particles to the locations outside the shells considered.

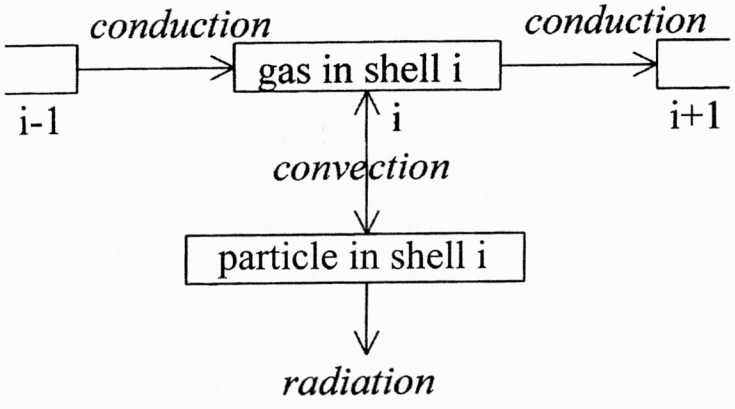

Fig. 2. Streams of heat energy in a shell

An explosion occurs if the combustion of the dust particles spreads with a high speed within the space occupied by the dust–air mixture, which means that the energy supplied from the ignition volume must be great enough to ignite the first shell. After this the first shell has to ignite the second shell and so on.

The isobar expansion of the air due to heating is considered by enlarging the radius of the shells.

The effect of pyrolysis is neglected. The particles burn in their original composition. Oxygen is transported by diffusion to the reaction surface. The influence of both processes, i.e. diffusion and reaction, is considered on the basis of using the oxidation kinetics of WICKE and FRANK-KAMENETZKY [2].

The developing combustion heat is fed to the particles.

Further assumptions are:

the dust particles are globular,

the dust particles are homogeneously distributed in the air,

the sedimentation speed of the particles is neglected,

turbulence does not occur,

the total pressure is constant.

The change in the temperature of both gas and particles, the mass of particles, the particle diameter and the content of oxygen in the air are calculated by balances.

The resulting partial differential equations are discretized with respect to radius and time. Discretization of radius is carried out by the introduction of the volume shells with their thickness ΔR.

The resulting system of difference equations is the basis for the simulation program. By means of this program it is possible to calculate the nonstationary heating and the progress of reaction in a globular space, depending on the amount and the time of feeding the ignition energy. For every time step, the temperatures of air and particle are calculated by starting from the ignition volume and ending with the final shell.

3. SIMULATION CALCULATIONS

The simulation calculations were carried out for maize starch dust. For this kind of dust there are experimental data for the minimum ignition energy from FH Mannheim. The parameters used for simulation are shown in table 1.

Table 1

Adjustable parameters for simulation

Constants	
Initial temperature	293 K
Air pressure	101.23 kPa
Frequency factor	26500 s^{-1}
Activation energy	67700 kJ/(kg·K)
Reaction enthalpy	496377 kJ/(kmol O_2)
Dust parameters	
Dust density	1400 kg/m^3
Dust concentration	0.15 kg/m^3
Medium particle size	15 μm
Specific heat capacity	1 kJ/(kg·K)
Radiation number	5.359 J/(m^2·K)
Model parameters	
Ignition radius	1 mm
Shell thickness	0.05 mm
Time step	0.005 ms
Temperature rise	2000 K
Time of energy supply	0.5 ms
Simulation time	20 ms
Number of shells	40

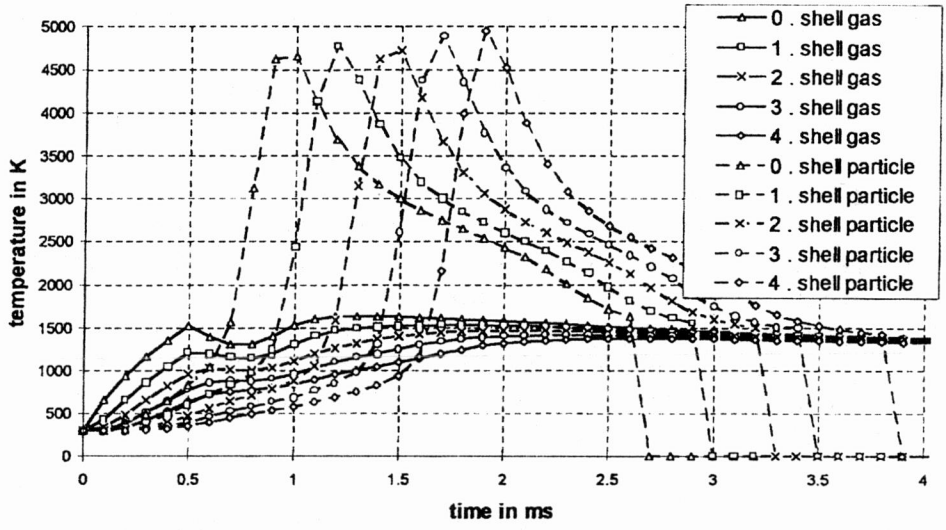

Fig. 3. Gas and particle temperature curves (class 1 – explosion)

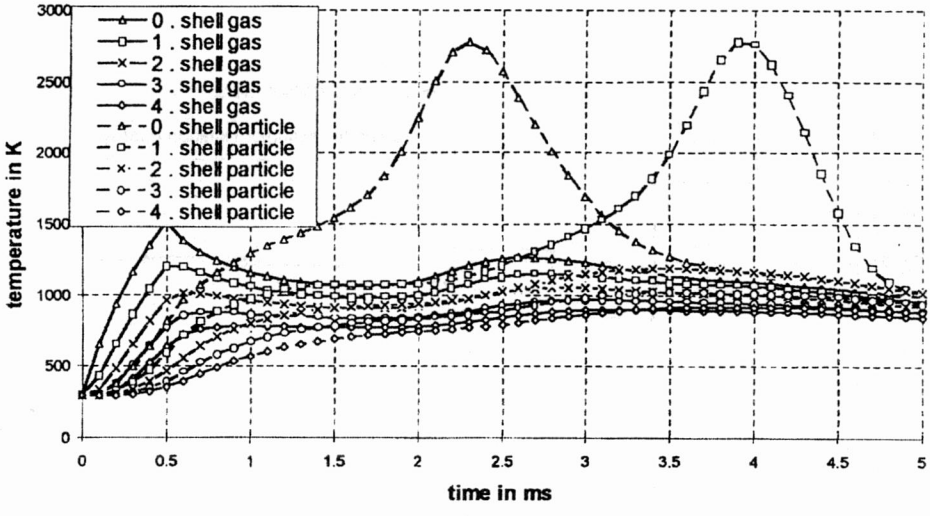

Fig. 4. Gas and particle temperature curves (class 2 – no explosion)

After evaluation of several simulation calculations it appears that the behaviour of the gas temperature allows a decision whether an ignition has taken place or not. Two main classes of the behaviour of the gas temperature are obtained.

Class 1. During the time of energy supply the gas temperature is rapidly rising in the first shells. After stopping the supply of the ignition energy, the gas temperature is slightly dropping until the explosion gets self-dynamics. Now all shells are heated rapidly. All particles in the shells are burning. The explosion is expanding. The gas and particle temperature curves of the shells 0 ... 4 are shown in figure 3.

Class 2. The gas temperature is rising rapidly only in the first shells. The heating of the following shells is not very strong and decreases with the distance from the ignition volume. The particles in the shells are not burning. The explosion is not expanding. The gas and particle temperature curves of the shells 0 ... 4 are shown in figure 4.

If an explosion takes place, the behaviour of the gas temperature has to agree with class 1. In the case of a computer-aided evaluation, it is necessary to set a criterion for a successful ignition. An ignition is successful if the gas temperatures in all shells exceed limit value, depending on the kind of dust.

4. ALGORITHM FOR SEARCHING THE MINIMUM IGNITION ENERGY

This criterion is necessary for searching automatically a minimum value of ignition energy for a dust–air mixture by means of an iterative calculation process. This iterative calculation process is a modified one-dimensional GAUSS–SEIDEL-method [3].

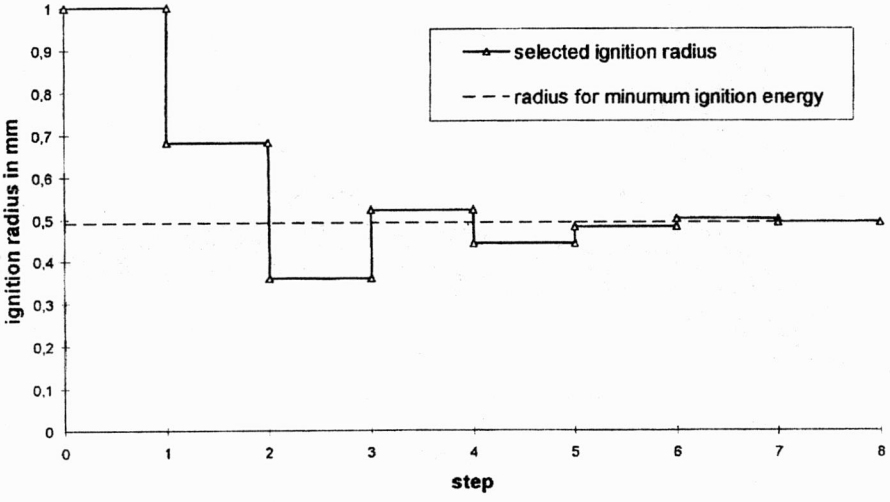

Fig. 5. Algorithm for searching the minimum ignition energy

The iteration process starts with a given value of the ignition energy adjusted by the radius of the ignition volume. If this ignition is successful the value of the ignition radius will be reduced by a constant step width until an unsuccessful ignition occurs.

After this the ignition radius will be raised by the halved step width until a successful ignition occurs. This process will be continued until minimum ignition energy is reached. An example of using this algorithm is presented in figure 5 and table 2.

Table 2

Algorithm for searching the minimum ignition energy

No.	Ignition radius (mm)	Ignition energy (mJ)	Explosion	Step width (mm)
1	1	12.81	yes	−0.32
2	0.68	4.03	yes	−0.32
3	0.36	0.6	no	+0.16
4	0.52	1.8	yes	−0.08
5	0.44	1.09	no	+0.04
6	0.48	1.42	no	+0.02
7	0.5	1.6	yes	−0.01
8	0.49	1.51	yes	MIE*

* Minimum ignition energy.

5. MODEL ADAPTATION

The values of the minimum ignition energy obtained on the basis of simulation calculations are compared with the experimental data from FH Mannheim. The simulation values were adapted to the experimental values by variation of the activation energy parameters and frequency factor. Those parameters characterize the reaction rate of the surface reaction of the combustion process and depend on the special kind of the dust particles.

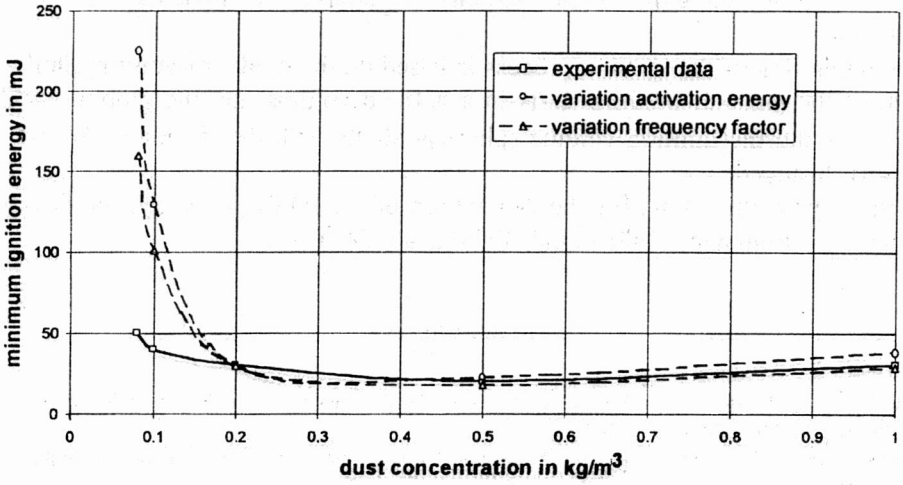

Fig. 6. Minimum ignition energy versus dust concentration

In figure 6, the dependence of the minimum ignition energy on the dust concentration is shown. It can be seen that the adaptation is considered satisfactory in the dust concentration ranging from 0.2 to 1 kg/m^3.

6. FURTHER INVESTIGATIONS

A wide range of tasks, which should be performed, is as follows:

- repetition of those investigations with other kinds of dust material,
- replacement of the monodispersal system of dust particles with a polydispersal system (at first with a system consisting of three fractions of particle sizes),
- including of pyrolysis by description of a reaction kinetics.

7. CONCLUSIONS

The kind of components of the dust-air mixture, the shape and size distributions of the dust particles, the content of dust and oxygen in the air and the temperature and pressure are mutually dependent. That is why an extensive experimental tests are considered necessary for every interesting dust–air mixture and situation.

An important reduction of the experimental tests in order to obtain the explosion parameters is possible by calculating the ignition energy based on a mathematical model. This model is used to estimate the magnitude of the ignition energy. The aim was to reduce the experimental expense by adapting a small number of model parameters.

The modelling of the ignition process is based on the model of volume shells. The ignition of the dust–air mixture starts in a defined volume, i.e. the globular ignition volume. Around the ignition volume spherical shells with the thickness ΔR are concentrically arranged.

In this paper, the model for the calculation of the ignition energy, the developed simulation program and results of calculations are dealt with.

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OBLICZENIA MINIMALNEJ ENERGII ZAPŁONU MIESZANIN PYŁOWO-POWIETRZNYCH

Wybuch mieszaniny pyłowo-powietrznej jest bardzo złożonym procesem. Badania wykazały, że energia zapłonu takiej mieszaniny zależy od ilości pyłu i tlenu w powietrzu oraz od temperatury i ciśnienia. Badania laboratoryjne są kosztowne, więc aby określić energię zapłonu, zaproponowano model matematyczny. Modelowanie procesu zapłonu oparto na modelu warstw objętościowych. Zapłon mieszaniny pyłowo-powietrznej rozpoczyna się w ściśle zdefiniowanej objętości – kulistej objętości zapłonu. Dookoła objętości zapłonu znajdują się kuliste warstwy o grubości ΔR ułożone współśrodkowo.