THEORETICAL ANALYSIS OF THE HOT SPOT IGNITION OF GASEOUS SUSPENSION OF SOLID PARTICLES IN THE MIXTURE OF COMBUSTIBLE GAS AND OXIDIZER

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Dust explosions continue to be a real significant hazard in a wide range of process industries, as well as in coal mining industries. In principle, this hazard exists, whenever suspensions of combustible particles in the atmosphere containing an oxidant are formed as a part of production, treatment or handling of such dusts [1–3]. If a dust suspension is fully or nearly enclosed and the explosion pressure exceeds the maximum internal overpressure that the enclosure can withstand, the destructive explosion effects and the possibility of loss of life or limb may be particularly high.

Experimental investigations have shown that dust explosion hazards increase substantially if the oxidant atmosphere also contains a modest fraction of a combustible gas or vapor (so-called “hybrid mixtures”(HM)) [3, 4]. Such mixtures are encountered in coal mines, where both the coal dust and methane may co-exist, in production of pharmaceuticals, chemicals and food, whenever volatile organic solvents are removed from combustible powders by heated air, e.g. in fluidized beds. For a hybrid mixture, even with a small content of a combustible gas present in the oxidizer, the minimum ignition energy (MIE) may be substantially lower in comparison with the ordinary particle suspensions. For example, MIE of a coal dust/air mixture may decrease by a factor of 20-30 after addition of just 2-3% vol. of methane to the air [4]. However, the existing representations of the mechanism of combustion and ignition of a gaseous suspension do not provide explanation for a sharp decrease in MEI and a reliable prediction of the influence of the combustible gas addition on the parameters of the gaseous suspension ignition and combustion.

The model of spot ignition was considered in the present study of the process of gaseous suspension ignition with a spark discharge. The model used presupposed that the initial temperature distribution in the gas could be described by the piecewise constant function and the temperature of all particles was equal to the initial temperature of the process. The advantage of such a statement of the problem was retaining of the specific features of spark ignition (instantaneous local evolution of energy). Moreover, it allowed significant simplification of the calculation procedure, analytical solution of the problem as simple dependences of the limiting size of a spot on the major parameters of the process for high values of the dimensionless coefficient of heat exchange, Z, between the gas and the particles (Z is an analog of the Semenov criterion) and also elucidation of the role of the gas-phase reactions in the process of spark ignition of the gaseous suspension of the solid particles. For large values of the parameter Z, the minimum (critical) dimensions of the hot spot resulting in gaseous suspension ignition appeared to exponentially depend on the value of the equilibrium temperature in the spot, i.e. the temperature reached by particles and gas after equilibrating their temperatures in the spot without taking into account conductive heat losses into the cold gaseous suspension outside the hot spot.
It should be noted that the critical dimension of the spot is exponentially reduced with the increase in the equilibrium temperature. As shown by the approximate analysis, the value of this temperature is primarily dependent on the weight portion of the combustible component in the gas, the thermal effect of the gas-phase reaction, the weight portion of the solid particles in the gaseous suspension, as well as the ratio of the rate of heat release from the gas-phase reaction at the initial temperature of the spot, W_1, to the rate of gas cooling by the solid particles in the spot, W_2.

If W_1 is higher than W_2, the gas temperature in the spot initially grows through the gas-phase reaction and reaches its maximum as the combustible component completely burns out. Then the gas temperature in the spot starts decreasing as a result of heat exchange between the hot gas and the cold particles, and their temperatures finally equilibrate.

Thus, with W_1 larger than W_2, the critical size of the spot is determined by the rate of the heterogeneous chemical reaction of the particles and the oxidizer contained in the gas at the equilibrium temperature. The gas-phase reaction only results in the increase of the equilibrium temperature in the spot and, according to the obtained formulas, in the exponential decrease of the critical size of the spot. Calculations show that an increase in the hot spot equilibrium temperature by as many as six specific intervals (resulting from the gaseous reaction) is sufficient to decrease the spot critical size as well as the spark discharge energy required to ignite the gas suspension over 20 times, as compared to the case of no reactive component in the gaseous phase.

If at the initial temperature of the spot, the rate of heat release from the gas-phase reaction (W_1) is less than that of gas cooling by solid particles in the spot (W_2), the gas temperature in the hot spot starts to decrease as soon as the spot formed because of heat exchange between the hot gas and the cold particles. Since at $Z >> 1$, the time of the gas and particle temperatures equilibrating in the spot will be much less than that of spot cooling by heat conduction, one can calculate the equilibrium temperature in the spot. This temperature will be slightly higher than the equilibrium one in the spot in the absence of a combustible component in the gaseous phase, i.e. it will be lower than for the case of W_1 being higher than W_2. Therefore, the critical size of the spot will be higher than for the opposite case. It should be noted that based on the obtained results, adding a combustible gas most strongly affects the decrease in the critical size of the spot when W_1 is higher than W_2. The W_1/W_2 ratio can change with increasing the parameter Z (the rate of gas cooling by the particles W_2 is proportional to Z). It has been shown that there is a region of the minimum of the hot-spot size in the dependence of the critical size of the spot on the parameter Z at a fixed value of the dimensionless initial gradient of the temperatures in the spot. The boundaries of the region have been determined. The obtained analytical solutions allow predicting the influence of combustible gas additions on the critical conditions of spot ignition of gaseous suspensions using the data on the kinetics, the thermal effect, and the oxidation mechanism of the condensed and gas phases and then calculating the spark discharge energy required for a hybrid gaseous suspension to be ignited at various contents of the combustible gas in the initial mixture. These data can greatly help in developing adequate requirements for the systems of fire prevention and suppression in various branches of processing and mining industries, since suspensions of combustible particles in oxidizer-containing gases may occur at some of the technological stages in such industries.

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