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Models to estimate the minimum ignition temperature of dusts and hybrid mixtures

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HIGHLIGHTS

- Seven model to predict the minimum ignition temperature of dust are presented.
- Three model to predict the minimum ignition temperature of dust are compared with experimental results.
- Two model to predict the minimum ignition temperature of hybrid mixtures were proposed and validated.
- Minimum ignition temperature of gases decrease upon addition of dust which is itself not ignitable.
- Minimum ignition temperature of hybrid mixtures are lower than that of single substance.

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ABSTRACT

The minimum ignition temperatures (MIT) of hybrid mixtures have been investigated by performing several series of tests in a modified Godbert–Greenwald furnace. Five dusts as well as three perfect gases and three real were used in different combinations as test samples. Further, seven mathematical models for prediction of the MIT of dust/air mixtures were presented of which three were chosen for deeper study and comparison with the experimental results based on the availability of the input quantities needed and their applicability. Additionally, two alternative models were proposed to calculate the MIT of hybrid mixtures and were validated against the experimental results. A significant decrease of the minimum ignition temperature of either the gas or the vapor as well as an increase in the explosion likelihood could be observed when a small amount of dust which was either below its minimum explosible concentration or not ignitable itself at that particular temperature was mixed with the gas. The various models developed by Cassel, Krishma and Mitsui to predict the MIT of dust were in good agreement with the experimental results as well as the two models proposed to predict the MIT of hybrid mixtures were also in agreement with the experimental value.

1. Introduction

An explosion is a sudden reaction involving a rapid chemical reaction generating an increase in temperature or pressure or both simultaneously. Mixtures involving combustible dust and gas or solvent (hybrid mixtures) are often encountered in the process industries: fermentation gases and cereals, pigments and solvents, solid active principles or excipients and volatile organic vapor, etc. Dust, gas, solvent and hybrid mixtures explosion can caused significant loss to industries, particularly in the industry that use, process, handle, transport or manufacture combustible dust, gas or solvent.

The present paper reports research into the Minimum Ignition Temperature (MIT) of dust/air, flammable gas/air and hybrid mixtures with emphasis on fluidized systems only. The minimum ignition temperature of dust layers is not considered in the present paper. Hot surfaces capable of igniting dust clouds exist in a number of situations in industry (furnaces, burners and dryers of various kinds) [1]. In addition, hot surfaces can be generated accidentally by overheating bearings and other mechanical parts. If an explosible dust cloud is present in the proximity of a hot surface with a temperature above the minimum ignition temperature specific for the dust, a dust explosion can occur. Considerable research has been carried out throughout the world with the aim of either preventing the occurrence or mitigating the consequences of hybrid mixtures

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Nomenclature

A	$B\,C(\text{fuel})^n C(O_2)^m$
A_c	Pre-exponential factor in particle-gas reaction rate [cm/s]
A_d	Pre-exponential factor in volatile matter oxidation rate [1/s]
A_S	Outside surface area of furnace metal casing [cm^2]
A'	$C_g k_r H$ [J $K^{1/2}$/cm^2 s]
B	Pre-exponential factor, as Table 4-1
B'	Radiation coefficient [J/(cm^2 s K^4)]
c	Specific heat capacity [J/g K]
c_{air}	The specific heat of air [J/g K]
c_{ps}	Mean specific heat of mixture at temperature Ts [J/g K]
C	Molar percentage [%]
C_0	Concentration of oxygen at reaction temperature T_s [mol/cm^3]
C_f	Concentration of butylene [%]
C_d	Initial dust concentration [g/cm^3]
C_g	Concentration of oxygen [g/cm^3]
C_{ga}	Concentration of oxygen at the particle surface [g/cm^3]
C_{gF}	Concentration of oxygen at reaction or furnace temperature [g mol/cm^3]
C_{pi}	Mean specific heat of constituent i in the mixture [J/mol K]
D_p	Initial diameter of dust particle [cm]
D_{pn}	Diameter of dust drops unconverted at temperature T_i [cm]
E	Activation energy of fuel [J/mol]
E_d	Activation energy for devolatilization reaction [J/mol]
f	Frequency factor [cm/s]
G_s	Mass of dust [g]
h	Heat transfer coefficient [J/m^2 s K]
h_g	Coefficient for heat exchange between particle and gas [J/cm^2 s K]
h_1	Convective heat transfer coefficient of fluid [J/cm^2 s K]
h_n	Heat transfer coefficient from dust liquid droplet to surroundings [J/cm^2 s K]
h_s	Coefficient for heat exchange between cloud and surroundings [J/cm^2 s K]
H	Heat of reaction [J/mol]
H_d	Heat of combustion of dust [J/g]
H_g	Heat of combustion of gas [J/g]
H_v	Heat of devolatilization of dust [J/g]
k	Thermal conductivity [W/m K]
k_c	Coefficient of heat transfer [1/s]
k_1	Thermal conductivity of fluid [J/cm^2 s K]
k_r	Reaction rate constant [J/mol s] or [cm^3 $K^{1/2}$/s] or [1/s]
l	Dust cloud radius [cm]
l_0	Characteristic length [cm]
L	Total heat loss by conduction and radiation [J/g]
LEL	Lower Explosivity Limit [vol%]
L_r	Total rate of heat loss by radiation per particle [J/s]
$\dot{m}_c$	Mass combustion rate of particle [g/s]
M_d	Mass of dust [g]
M_{dt}	Molecular weight of dust [g/mol]
M_g	Mass of gas [g]
MEC	Minimum Explosive Concentration [g/cm^3]
M_{ot}	Molecular weight of oxygen [g/mol]
M_p	Mass of dust particle [g]
n,m	Order of reaction, as Table 4-1 [–]
n_d	Order of reaction with respect to fuel [–]
n_0	Order of reaction with respect to oxygen [–]
n_p	Number of dust particles in the furnace or in an elemental dust cloud= $\frac{6C_d V_f}{\pi D_p^3 \rho_d}$
N_i	Moles of constituent i in the mixture [–]
Nu	Nusselt number ($Nu = \frac{h_1 l_0}{k_1}$)
q	Heat flux [W/m^2]
Q_d	Rate of heat devolatilization reaction [J/s]
Q_G	Rate of heat generation per unit volume [J/s cm^3]
Q_{Ga}	The rate of heat generation per unit area [J/cm^2 s]
Q_L	Rate of heat loss per unit volume [J/s cm^3]
Q_{La}	The rate of heat removal per unit area [J/cm^2 s]
Q_p	Total rate of heat generation per particle [J/s]
Q_v	Total rate of heat generation due to volatile matter oxidation [J/s]
r_d	Radius of dust particles [cm]
R	Gas constant [J/mol K]
S	Surface area of dust cloud [cm^2]
S_d	Factor accounting for the specific surface area of dust [–]
S_p	Effective surface area of dust [cm^2]
t	Time [s]
T	Temperature [K]
T_a	Temperature of environment [K]
T_F	Furnace temperature [K]
T_i	Minimum ignition temperature (MIT) [K]
$T_{i,d}$	Minimum ignition temperature of particles [K]
$T_{i,g}$	Minimum ignition temperature of gas [K]
$T_{i,hybrid}$	Adiabatic minimum ignition temperature of hybrid mixture [K]
T_0	Initial temperature of dust cloud [K]
T_s	Temperature of particle surface [K]
T_w	Wall temperature, here considered as the self-ignition temperature [K]
U	Overall coefficient of heat transfer from furnace wall to outside environment
V	Volume of reactor [m^3]
V_e	Experimental MIT value [K]
V_s	Simulated MIT value [K]
V_f	Volume of furnace [cm^3]
V^*	Volatile matter content of particles [%]
w	Wseven [g]
y_d	Mass fraction of dust in dust–gas mixture = $\frac{C_d}{C_g + C_d}$
y_g	Mass fraction of gas in dust–gas mixture = $\frac{C_g}{C_g + C_d}$
Y_0	Mass fraction of oxygen [–]
% e	Percent error [%]
% d	Percent difference [%]

Greek symbols

ϵ_1	Emissivity of luminous flame [–]
ϵ_2	Emissivity of particle [–]
ϵ_3	Emissivity of furnace wall [–]
λ_g	Gas conductivity [W/m K]
ρ	Density of the gas–air mixture [g/m^3]
ρ_{air}	Density of air [g/cm^3]
ρ_d	Density of dust [g/cm^3]
ρ_g	Density of gas [g/cm^3]
σ	Stefan–Boltzmann constant [J/cm^2 K^4 s]
τ	Combustion time [s]
τ_b	The time a material to reach auto-ignition temperature [s]