CHEMICAL ENGINEERING TRANSACTIONS
VOL. 77, 2019
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; ISSN 2283-9216
DOI: 10.3303/CET1977114

Application of Laboratory-scale Determined K_{St}-values of Metal Dust to Industrial Scale Processes

Kees van Wingerden
Gexcon AS, Fantoftvegen 38, 5072 Bergen, Norway
kees@gexcon.com

This paper presents a theory demonstrating that flame propagation rates in clouds of light metal dusts are expected to be scale-dependent and that a K_{St}-value determined in a 20-l sphere may underestimate dust explosion effects on an industrial scale. The paper also presents a review of large- scale dust explosion experiments performed with light metal dusts supporting the theory. Finally, the paper suggests which metals can be considered as organic dusts when designing explosion protection measures, i.e. for which metal dusts one can use K_{St}-values determined in the 20-l sphere and for which ones one should not.

1. Introduction

Mitigation of dust explosions hazards has been addressed in a large number of guidelines aiming at supporting industry to work safely. These guidelines are partly based on research carried out through the years. Experiments have been carried out, many on large scale, to understand how dust explosions evolve and specially to develop and test protective systems to limit the potential consequences of dust explosions. Most of these experiments were conducted with organic dusts, and very little work has been performed using metal dusts. Metal dust explosions may however behave differently from organic dust explosions on industrial scale due to the contribution of radiation to the flame propagation mechanism. Radiation levels caused by especially light metal flames can be very high due to high flame temperatures. The incident radiation at a position ahead of the flame is related to the size of the flame ball, and hence it is scale dependent potentially leading to higher combustion rates at large scale.

2. Heat of combustion and flame temperatures

Important parameters describing the properties of metal dusts are the heat of combustion per mole oxygen consumed and the flame temperature. These two parameters are obviously related. The higher the flame temperature the higher the contribution of radiation to flame propagation.
The two tables below give an overview of these two properties. The values presented in table 1 are not directly related to dust whereas the values presented in table 2 have been measured for fine dust. Both tables contain data for organic dusts for reasons of comparison.
Figures 1 to 4 present K_{St}-values and maximum explosion overpressure data obtained from the online GESTIS– DUST-EX database (GESTIS – DUST-EX, 2018) for respectively aluminium, silicon, zinc and iron. The data are presented as a function of the median particle diameter. The explosion properties were obtained in 20-l spheres and 1 m^3 vessels. Although obtained on small scale the data already give a number of indications. Aluminium (Figure 1) exhibits partly very high rates of pressure rise due to the very high flame temperatures increasing also convection and conduction processes. The maximum explosion pressures are also high confirming the high heat of combustion per mole oxygen. Similar observations are made for magnesium but not for titanium as one would expect. Silicon (Figure 2) exhibits moderate rates of pressure rise but the maximum explosion overpressures are also reflecting the high heat of combustion per mole oxygen compared to organic dusts. The results for zinc and iron are comparable to those of organic dusts.

Paper Received: 8 February 2019; Revised: 7 May 2019; Accepted: 13 July 2019

Please cite this article as: van Wingerden K., 2019, Application of laboratory-scale determined KSt-values of metal dust to industrial scale processes, Chemical Engineering Transactions, 77, 679-684 DOI:10.3303/CET1977114

3. Flame propagation mechanisms

Despite the general understanding that conduction and convection are the main flame propagation mechanisms of dust explosions, radiation is expected to play a role for light metal dust-air mixtures due to the high flame temperatures. Thermal radiation is proportional to the fourth power of the flame temperature. The high flame temperatures of e.g. aluminum dust compared to iron dust as presented in Table 2 result in a thermal radiation for aluminum, which is almost 6 times higher than for iron dust.

Table 1: Heat of combustion metal dusts [Eckhoff, 1994]

Substance	Oxidation product(s)	Heat of combustion per mole oxygen (kJ/mole O_2)
Ca	CaO	1270
Mg	MgO	1240
Sr	SrO	1180
Al	Al_2O_3	1100
Zr	ZrO_2	1100
Ti	TiO_2	910
Si	SiO_2	830
Cr	Cr_2O_3	750
Zn	ZnO	700
Mn	Mn_3O_4	690
Fe	Fe_2O_3	530
Cu	CuO	300
For comparison		
Sucrose	CO_2 and H_2O	470
Starch	CO_2 and H_2O	470
Polyethylene	CO_2 and H_2O	400
Carbon	CO_2	400
Coal	CO_2 and H_2O	400
Sulphur	SO_2	300

Table 2: Flame temperatures measured for a number of metal dusts [Cashdollar and Zlochower, 1994; Han et al., 2000]

Dust	Median particle diameter (□m)	Flame temperature (°K)
Al	15	2800
Al	40	2400
Ti	25	2850
Mg	16	2800
Hf	8	2400
Ta	10	2350
Si	4	2300
Nb	20	2100
Iron	4	1800
Iron	45	1600
Zn	4	1750
B	3	1700
Cr	10	1850
Sn	8	1550
W	1	1550
For comparison:		
Carbon	1	1700
Lycopodium	32	1370

Leuschke (1965) reports on experiments indicating that radiation plays a role for light metal dusts. Dust clouds were generated on both sides of a double glass window. It was established that the ignition and subsequent combustion of light metal dust clouds on one side of the window resulted in ignition of dust clouds on the oth side of the window. Tests were performed with zirconium, titanium, aluminum, magnesium, iron, graphite, and coal.

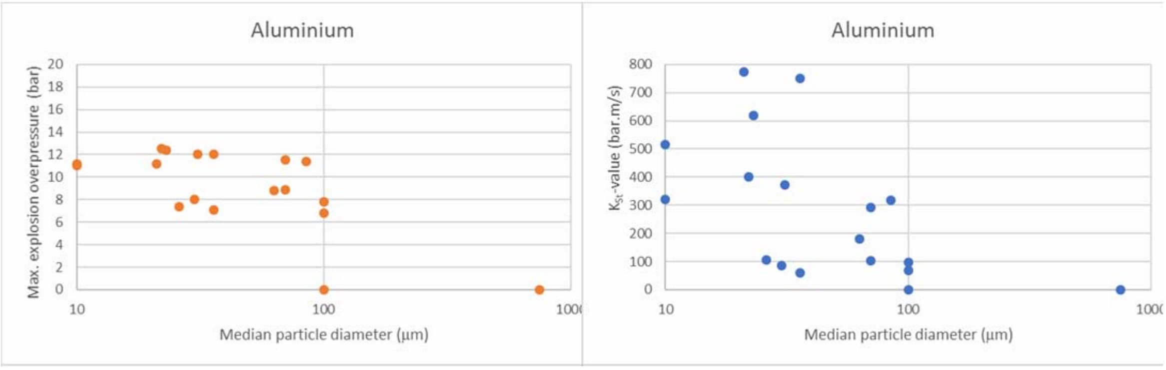

Figure 1: Effect of particle size on KSt and Pmax for aluminium dust-air mixtures

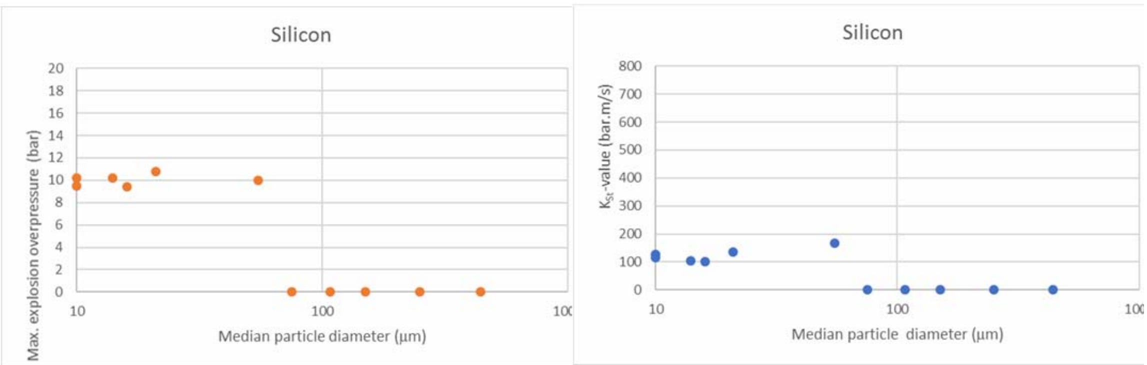

Figure 2: Effect of particle size on KSt and Pmax for silicon dust-air mixtures

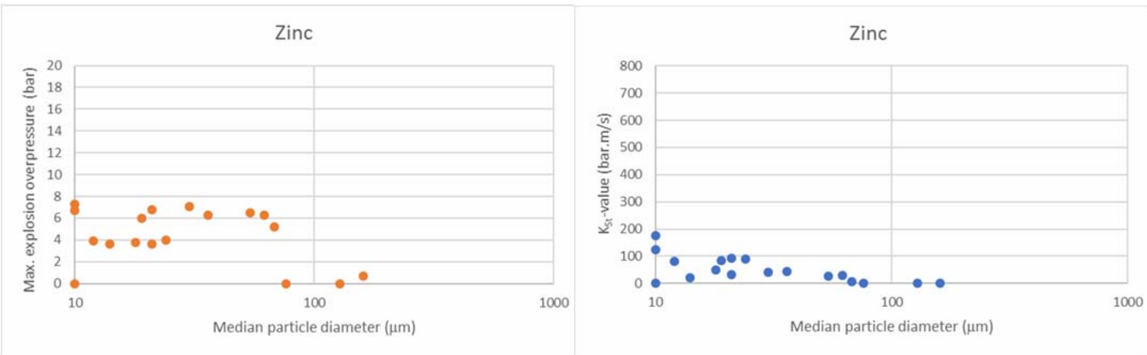

Figure 3: Effect of particle size on KSt and Pmax for zinc dust-air mixtures

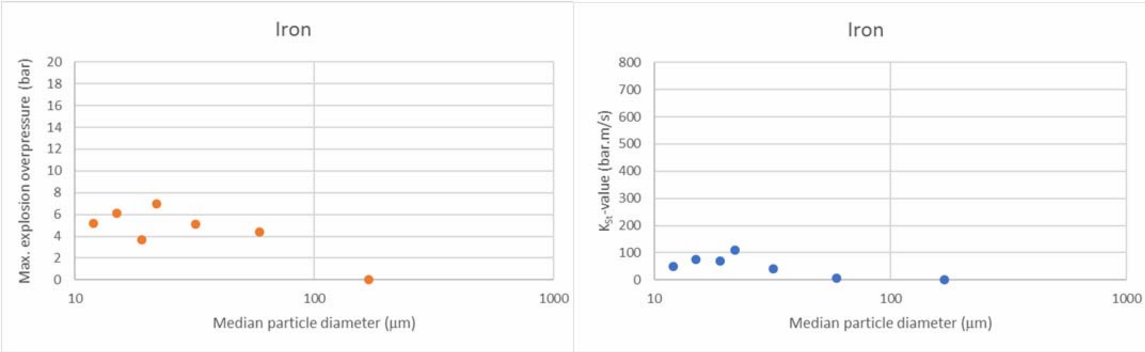

Figure 4: Effect of particle size on KSt and Pmax for iron dust-air mixtures

The burning light metal dust clouds (zirconium, titanium, aluminum, magnesium) caused ignition of most of the dust types including iron dust (zirconium, titanium) whereas combustion of iron dust and the organic dusts did not lead to ignition of any of the clouds on the other side of the window.
The experiments reported by Leuschke (1965) confirm that radiation will play a role for the combustion of light metals but it also indicates that radiation will be less important for metal dusts with a lower flame temperature such as iron. The latter was also confirmed by Dobashi (2007): radiation is not the dominating heat transfer mechanism for iron dust explosions. These observations reflect the much higher thermal radiation emitted by light metal dust flames. On the other hand, Shevchuk et al. (2001) concluded on the basis of theoretical arguments and considering five different metals that the mechanism of heat transfer from the flame front to the unburned cloud is essentially conductive. The radiative contribution would amount to only about 5%.

4. Scale dependent aspects

4.1 Effect of growing flame ball

The incident thermal radiation from dust flames can be calculated using the solid flame model. The solid flame model assumes that the fire is a still, grey body encompassing the entire visible volume of the flames, which emits thermal radiation from its surface.

According to the solid flame model the incident thermal radiation intensity at a certain position is given by (Center for Chemical Process Safety, 1994)

$$Q = \tau F E \qquad (1)$$

where the transmissivity of the atmosphere in between the dust flame and the receiver, τ, is strongly affected/determined by the concentration of dust particles in the atmosphere, F is the view factor determined by the size and shape of the flame and the distance to the receiver and E is the emissive power.
The emissive power E can be calculated according to

$$E = \sigma T_f^4 (1 - e^{-kD}) \qquad (2)$$

Where σ = Stefan-Boltzmann constant (5.67•10^{-8} W m^{-2} K^{-4}), T_f = flame temperature, k = extinction coefficient and D = diameter, or width, of the flame.
Using the solid flame model the incident radiation a particle at a certain distance from the flame receives can be calculated.
Assuming a spherical flame and assuming that the particle can "see" the full flame the view factor is given by:

$$F = r^2 / L^2 \qquad (3)$$

Where r = flame radius and L = distance between ignition point and particle position.
During the initial phases of flame propagation the view factor increases at points at a constant distance from the flame. At the same time, the emissive power increases with flame diameter implying that the incident

radiation at a constant distance in front of the flame increases with fireball growth. This would imply that the combustion rate assuming radiation has an important contribution increases with increasing flame diameter. The effect of the view factor increase will vanish at larger fireball diameters since particles just ahead of the flame will no longer be able to “see” the full fireball, the emissive power however will keep on increasing. Radiation at larger distances from the flame will be absorbed by dust in between the flame ball and the recipient.

4.2 Light scattering and the absorption length of radiation

Julien (2015) performed experiments on small-scale and in the open using aluminium dust clouds. He measured the temperature of the dust cloud ahead of the flame showing that temperature increases already are seen at approximately 0.5 – 1 m ahead of the flame due to radiation. He estimated that the mean free path of a photon in a stoichiometric aluminum cloud is on the order of 4-5 cm. However, most of this radiation is scattered and not absorbed by the particles. Correspondingly, the absorption length of radiation in an aluminum cloud is at least an order of magnitude greater than the mean free path of photons as Julien (2015) reported. This is a second scaling effect limiting the effect of radiation on flame propagation in light metal dusts in a 20-l sphere whereas it will be seen at larger scales, at least in a 1 m^3 vessel. This scaling effect will however not be fulling accounted for in a 1 m^3 vessel (diameter approx.- 0.5 m) as the measurements by Julien (2015) show.

The increasing influence of radiation on flame propagation with scale in light metal dusts implies that a K_{St} value determined in standardized laboratory-scale equipment such as the 20-l sphere potentially strongly underestimates the potential rates of pressure rise in industrial-scale equipment. This will especially be the case for light metal dusts burning with high flame temperatures (see Table 2).

5. Literature review

A literature review has been performed to verify whether there are indications that higher pressures/reaction rates are present than one would expect based on measured K_{St} values.

Van Wingerden and Alfert (1992) reports on experiments involving a 5.8 m^3 bag filter unit connected to a 2 m^3 cylindrical vessel via a 22 m long, 6” diameter duct. Both vessels were vented. Dust-air mixtures were generated using a pneumatic conveying system.and ignition was always effected in the 5.8 m^3 vessel. Experiments were performed with maize starch, polypropylene, peat, wheat, and silicon. K_{St} values varied from K_{St}=55 bar.m/s for wheat to K_{St}=145 bar.m/s for maize starch. Silicon dust had a K_{St} value of K_{St}=140 bar.m/s.

In spite of the lower K_{St} value the maximum pressure generated in the 5.8 m^3 vessel using a 0.04 m^2 vent opening for silicon (0.77 bar) is higher than seen for maize starch (0.6 bar) supporting the suggested stronger and dominating influence of radiation on a larger scale for the metal dust. The contribution of radiation to flame propagation in organic dust-air mixtures remains limited in spite of the increase in scale. The difference in character in flame propagation in the connecting duct is even more striking. Flame speeds were not measured but maximum pressures in the duct seen for maize starch were approximately 0.55 bar whereas for silicon pressures > 2.5 bar were seen in spite of an isolation device mounted at a distance of 10 m from the 5.8 m^3 vessel during the silicon tests only. The high flame speeds in the pipeline causing the high pressures seen for silicon will for an important part be caused by the optically thick flame resulting in a high emissive power and therefore strong contribution of radiation.

Going and Snoeys (2000) report on experiments performed with aluminum dust (K_{St} value= 170 bar.m/s) in a 2.6 m^3 vessel with a 0.56 m^2 vent opening. The resulting pressure of 0.25 bar is higher than predicted using NFPA 68 (National Fire Protection Association, 2018) which must be attributed to the increased influence of radiation at a larger scale.

Similar results are presented by Moore and Cooke (1988). Experiments performed in an 18.5 m^3 vessel provided with a 0.95 m^2 vent using a K_{St}=350 bar.m/s aluminum dust resulted in a pressure of 3.75-4.6 barg. An aluminum dust of K_{St}=600 bar.m/s resulted in a pressure of 3.4-8.2 bar. Both pressures are higher than expected on the basis of a former version of the venting guideline VDI 3673 (Verein Deutscher Ingenieure, 1978) which again is attributed to the larger scale these experiments were performed at.

Experiments reported by Holbrow et al. (2000) aimed at determining the radiation hazards due to vented explosions. The experiments were performed in vessels of 20 m^3 and 18.25 m^3. Tests with aluminum (K_{St} = 528 bar.m/s) were performed in an 18.25 m^3 vessel using a vent of 6.26 m^2. Reduced explosion pressures between 0.14 and 0.45 bar were measured which were higher than expected on the basis of the VDI 3673 guideline (Verein Deutscher Ingenieure, 1978). The experiments were also used to estimate the surface emissive power which was shown to be up to 2900 kW/m^2 which was a factor of 10 higher than those seen for several organic dusts (coal, anthraquinone, and toner).

The experiments Julien (2015) performed on small (balloon; diameter 0.3 m) and large scale (conical cloud with a width of 2 m at the top) revealed laminar burning velocities of about 20 cm/s and 40 cm/s respectively.

Explosion suppression tests performed with silicon and two types of aluminium dust in vessels of 1 m^3 and 4.4 m^3 show that early detection assuring that the flame has not grown big yet is resulting in most effective suppression (Taveau, 2015). The K_{St} values for the aluminium dusts measured in a 20 l sphere were significantly lower (< 2) than those measured in a 1 m^3 vessel.

6. Discussion/Conclusion

The number of large-scale experiments involving metal dust explosions is limited but both the analysis and the few results of large-scale experiments suggest a scale effect due to radiation for light metal dusts. Relying only on KSt values determined in standardized equipment when designing protective measures such as explosion venting, explosion suppression and explosion isolation for light metal dusts is therefore not recommended. The standard NFPA 68 (National Fire Protection Association, 2018) advises to determine the KSt-value for metal dusts of aluminium, hafnium, magnesium, tantalum, titanium and zirconium and similar alloys and mixtures in a 1 m3 vessel or multiply the KSt-value determined in a 20 l-sphere by a factor of 2. This may however not be sufficient as is shown above (see e.g. the results by Taveau et al. (2015) and Julien (2015)).

Based on the current study it is suggested that the following metals can be treated as organic dusts (flame propagation dominated by convection and conduction), i.e. where the KSt-values from 20-l sphere tests can be used: Fe, Zn, Sn, Mn, W, Cr and Cu. For light metals including Al, Mg, Ti, Zr, Hf, Ta, Si, Sr, Ca and Nb these KSt-values cannot be trusted and tests at a larger scale are necessary. The scale will depend on the metal but for Al, Mg and Ti tests are proposed at a scale > 1 m3.

More research is necessary to understand the flame propagation mechanisms and therefore scaling of light metal dust explosions better.

References

Cashdollar, K.L. and Zlochower, I.A., ,1994, Explosion temperatures of metals and other elemental dust clouds, Process Safety Progress, 13 (3), 139–145

Center for Chemical Process Safety, Guidelines for evaluating the consequences of vapor cloud explosions, flash fires and BLEVEs, AIChE, 1994

Dobashi, R., 2007, Flame propagation during dust explosions, Proceedings of the 5th International Seminar on Fire and Explosion Hazards, Edinburgh, UK

Eckhoff, R. K., 1994, Dust explosion hazards in the ferro-alloys industry, Proc. 52nd Electric Furnace Conference, Nashville, USA

GESTIS - DUST-EX database (http://staubex.ifa.dguv.de/explosuche.aspx?lang=e). Date of reference to database on internet 15.08.2018

Going, J.E. and Snoeys, J., 2000, Explosion protection with metal dust fuels, Process Safety Progress, 21 (4), 305–312

Han, O.-S., Yashima, M., Matsudu, T., Matsui, H., Miyake, A. and Ogawa, T., 2000, Behavior of flames propagating through lycopodium dust clouds in a vertical duct, Journal of Loss Prevention in the Process Industries, 13, 449–457

Holbrow, P., Hawksworth, S.J. and Tyldesley, A., 2000, Thermal radiation of vented dust explosions, J. Loss Prev. Process Ind., 13, 467-476

Julien, P., 2015, On the study of flames in aluminum and iron suspensions, PhD Thesis McGill University, Montreal

Leuschke, G., 1965, Beiträge zur Erforschung des Mechanismus der Flammenausbreitung in Staubwolken, Staub, 25, 180-186

Moore, P.E. and Cooke, P.L., 1988, Suppression of metal dust explosions, British Materials Handling Board Report no. 88.49

National Fire Protection Association, 2018, Standard on Explosion Protection by Deflagration Venting, NFPA 68

Taveau, J., Vingerhoets, J., Snoeys, J., Going, J. and Farrell, T., 2015, Suppression of metal dust deflagrations, Journal of Loss Prevention in the Process Industries 36, 244-251

Shevchuk, V. G., Eckhoff, R. K. and Zolotko, A., 2001, Instability and Wave Combustion Regimes of Dust Flames, Proceedings of the Third International Seminar on Fire and Explosion Hazards, Windermere, UK, 591-598.

Verein Deutscher Ingenieure, 1978, VDI-guideline 3673, Pressure release of dust explosions

van Wingerden, K. and Alfert, F., 1992, Dust explosion propagation in connected vessels, VDI-Berichte, 975, 507-528