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CONSEQUENCE MODELLING OF DUST EXPLOSION

N.A. RAHMAN & M.S. TAKRIFF
Department of Chemical and Process Engineering,
Universiti Kebangsaan Malaysia, Malaysia.

ABSTRACT

Dust explosion is a serious hazard in process industries where combustible dust is handled. Dust explosion commonly occurs in a confined space such as a silo, a vessel or a warehouse. Based on industrial accidents involving dust explosion, it may cause fatality, injury and property damage. Therefore, a practical approach for integrated risk management of dust explosion hazards is required. This research focuses on the development of a spreadsheet tool for predicting the severity of dust explosion. The consequence modelling is required to enable the assessment of risk associated with dust explosion. Various published models were studied for initial work of consequence modelling. Parameters considered were the dust deflagration index (K_{st}), the maximum explosion pressure (P_{max}), the maximum rate of pressure rise $(dP/dt)_{max}$ and the laminar burning velocity (S_{lbv}). Reliable value for these dust explosion parameters has been tabulated based on closed vessel laboratory tests. A case study of dust explosion involving maize starch in closed vessel was used to test and validate the developed consequence modelling tool. The modelling result was discussed by comparing the predicted value against experimental value. The spreadsheet tool that was developed in this work can be used for the purpose of risk management of a facility associated with dust explosion hazards. It can be used to assist the application to combustion suppressant agent and design of explosion venting to prevent and mitigate the consequence of dust explosion.

Keywords: Consequence modelling, dust explosion, risk assessment.

1 INTRODUCTION

Dust explosion will occur when five elements called 'Explosion Pentagon' is fully occupied. The first three elements needed to cause a dust fire (fire triangle) are combustible dust (fuel), ignition source (heat or spark) and oxygen in air. Additional elements needed for a dust explosion is dust dispersion and confinement where pressure to be generated [1]. Dust explosion can be categorized as serious hazard; it causes fatality, injury, property damage and economic losses. According to Malaysia's Department Occupational Safety and Health (DOSH) reports [2, 3] for the past 10 years, there were two cases involving dust explosion in Malaysia. First accident occurred in March 2008, dust explosion at grain storage and milling plant which caused four fatalities and two injuries. It also caused widespread damaged to the silo tower facility, the main building and the interconnected underground tunnel, which housed the continuous conveyors and ancillaries from a jetty to the basement floor of the silo tower. Second accident occurred in the early November 2010, aluminium dust explosion at a motorcycle rim manufactured factory which caused injuries to eight workers where two of them were serious injured. It also caused extensive damage to buildings and manufacturing plant, the destruction of the dust collector system and also broke windows of nearby factories. Because of serious consequences of dust explosion, a practical solution should be considered for integrated risk management system for dust explosion hazards and risk.

The risk assessment of dust explosion consists of two crucial components. They are the *likelihood* of the dust explosion occurring and the *severity* of the consequences. This research will only focus on the latter. Consequence modelling is the typically used to determine the severity of a given hazard once it is realized. Several models have been developed and reported in the literature for predicting the consequence of dust explosion. For example,

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Dahoe *et al.* [4] and Di Benedetto and Russo [5] used a similar model to evaluate the thermo-kinetic parameters of dust explosion based on the combustion reaction by assuming that the pyrolysis/devolatilization step is very fast and then gas combustion is controlling dust explosion.

It is advantageous to have a user friendly computerized tool in readily available software for predicting the severity of a dust explosion. Thus, this research focuses on the development of a spreadsheet tool on Microsoft excel® for predicting various dust explosion parameters such as the maximum rate of pressure rise ($(dP/dt)_{max}$), the maximum explosion pressure (P_{max}), the dust deflagration index (K_{st}) and the laminar burning velocity (S_{lbv}). These parameters are used to measure the severity of a dust explosion through the consequence modelling.

2 DESCRIPTION OF CONSEQUENCE MODELLING

Important parameters for consequence modelling of dust explosion are the maximum rate of pressure rise ($(dP/dt)_{max}$), the maximum explosion pressure (P_{max}), the dust deflagration index (K_{st}) and the laminar burning velocity (S_{lbv}). The K_{St} is defined as the maximum rate of pressure rise during a dust explosion in an enclosed vessel, times the cube root of the vessel volume [6] and its relation to the maximum rate of pressure rise is shown in the following equation:

$$\left(\frac{d\bar{p}}{dt}\right)_{max} \bar{X}^{1/3} = \bar{k}_{st} \tag{1}$$

Eqn. (1) is used to estimate the explosion violence. For example, the dust deflagration index, K_{St} increase indicates the robustness of an explosion [7]. Based on the value of the deflagration index, dusts are classified into four classes. These St classes are shown in Table 1.

The consequences of a dust explosion in a confined space such as a vessel or a building can be predicted through cubic root law relationship;

$$\left[\left(\frac{dP}{dt}\right)_{max} V^{1/3}\right]_{in\ vessel} = \left[\left(\frac{dP}{dt}\right)_{max} V^{1/3}\right]_{experiment} \tag{2}$$

In practice, eqn. (2) is used as a scale-up relationship to design the actual plant-sized equipment by applying standard test results from laboratory-sized vessels [4]. The predicted values from eqn (2) will be more accurate if the experiments were carried out as close as possible to the actual conditions under consideration [7]. The validity of the cubic law as a scale-up relationship for varying size of vessels is based on the following restrictions; the similar geometrical of vessels, the flame thickness is negligible with respect to vessel radius, the burning velocity is similar in all volumes and the point ignition occurs at the centre of vessels [4].

Table 1: Dust explosion classes.

Deflagration index, K_{st} (bar·m/s)	St class	Characteristic
0	St-0	No explosion
1–200	St-1	Weak explosion
200–300	St-2	Strong explosion
>300	St-3	Very strong explosion

Several models were developed based on theories of laminar flame propagation during the closed vessel explosion such as Dahoe *et al.* [4], Nagy *et al.* [8], and Nomura & Tanaka [9]. The laminar burning is the linear rate of combustion reaction zone propagates relative to the unburned gas of flammable mixture. It was adopted from premixed gas property theory and therefore the specifications of laminar dust explosion and laminar gas explosion in closed vessel should be similar [6]. For developing the models, each of them used the same assumptions as summarized in Table 2.

In this study, these three models are compared within the limitation of the cubic law for selecting the best model of dust explosion's consequence modelling. The dust explosion parameters considered were the laminar burning velocity (S_{lbv}), the maximum explosion pressure (P_{max}), the maximum rate of pressure rise ($(dP/dt)_{max}$) and the dust deflagration index (K_{st}). Reliable value for these dust explosion parameters have been tabulated and compared with experimental data for spherical closed vessel laboratory test in the 20-L or 1 m^3 spherical vessel that have been reported in the literature. It is noted that $(dP/dt)_{max}$ was obtained when the pressure attains its maximum pressure ($P = P_{max}$), the initial pressure of the dust cloud ($P_0 = 1$ bar), and the heat capacity ratio for dry air ($\gamma = 1.4$). For example, the model by Dahoe *et al.* [4] states that

$$\left(\frac{dP}{dt}\right) = \frac{3\left(P_{max} - P_0\right)}{R_{vessel}} \left[1 - \left(\frac{P_0}{P}\right)^{1/\gamma} \left(\frac{P_{max} - P}{P_{max} - P_0}\right)\right]^{2/3} \left(\frac{P}{P_0}\right)^{1/\gamma} S_{lbv} \tag{3}$$

$$\left(\frac{dP}{dt}\right)_{max} = \frac{3\left(P_{max} - P_0\right)}{R_{vessel}} \left(\frac{P_{max}}{P_0}\right)^{1/\gamma} S_{lbv} \tag{4}$$

$$K_{st} = \left(\frac{dP}{dt}\right)_{max} V^{1/3} = \frac{3}{R_{vessel}} V^{1/3} \left(P_{max} - P_0\right)\left(\frac{P_{max}}{P_0}\right)^{1/\gamma} S_{lbv} \tag{5}$$

If the vessel radius, R_{vessel} is referred to 1 m^3 spherical vessel, then ($V = 1\ m^3$, $R_{vessel} = (3/4\pi)^{1/3}$).

$$K_{st} = \left(\frac{dP}{dt}\right)_{max} = \frac{3}{R_{vessel}} \left(P_{max} - P_0\right)\left(\frac{P_{max}}{P_0}\right)^{1/\gamma} S_{lbv} \tag{6}$$

Table 2: Model of laminar dust flame in a spherical closed vessel.

Reference	Model	Assumptions
Dahoe *et al* [4] – DZLS	$\left(\frac{dP}{dt}\right)_{max} = \frac{3}{R_{vessel}}\left(P_{max} - P_0\right)\left(\frac{P_{max}}{P_0}\right)^{1/\gamma} S_{lbv}$	• The vessels are geometrically similar • The flame thickness is negligible compared with vessel radius • The burning velocity is constant in all volumes • Point of ignition at the centre of vessel
Nagy, *et al.* [8] – NCV	$\left(\frac{d\bar{p}}{dt}\right)_{max} = \frac{3}{R_{\bar{x}essel}}\left(\bar{p}_{max} - \bar{p}_0\right)\left(\frac{\bar{p}_{max}}{\bar{p}_0}\right)\bar{s}_{lb\bar{x}}$	
Nomura and Tanaka [9] – NT	$\left(\frac{dP}{dt}\right)_{max} = \frac{3\gamma}{R_{vessel}} P_{max}\left[1 - \left(\frac{P_{max}}{P_0}\right)^{1/\gamma}\right] S_{lbv}$	

3 CASE STUDY

Dahoe *et al.* [4] performed their thin-flame model for three spherical vessels of 20-L, 1-m^3 and 10-m^3 volumes to predict the pressure evolution and the rate of pressure rise. Nagy *et al.* [10] performed experiments in vessel volumes ranging from 1.2 L to 14 m^3 of the Hartman bomb. They normalized their result by multiplying all the measured $(dP/dt)_{max}$ by the cube root of the vessel volume to product K_{St}. Eckhoff [6] summarized the previous results on the determination of K_{st} value for maize starch dust cloud in air for different volumes of vessels as presented in Table 3. From the experiment in the closed 1.2-L Hartman Bomb at dust concentration of 500 g/m^3, at atmospheric pressure and 300K, the estimated burning velocity for maize starch is 0.59 m/s with P_{max}= 7.95 bar (g) and $(dP/dt)_{max}$ = 620 bar. Silvestrinia *et al.* [11] summarized the laminar burning velocity for a maize starch in various methods and the data are provided in Table 4. Di Benedetto and Russo [5] performed dust explosion experiments on corn starch as classified in St2 class and compared their simulation result with the experimental values reported in the NFPA 68 guidelines, in the database GESTISDUST-EX and in related published literatures. The maize starch dust was selected as a case study of dust explosion in a closed vessel. The maize starch data in the standard 1-m^3 ISO vessel at dust concentration of 60 g/m^3, P_{max}=9.7 bar (g) and K_{St} = 158 bar·m/s in St 1 class were used as reference that was adopted from the GESTIS-DUST-EX database [12].

4 RESULT

Models discussed in the preceding sections were coded into an excel® worksheet for predicting the identified dust explosion parameters. The spreadsheet tool is very user-friendly and can be used to predict the consequence of dust explosions for any confine volume and type dusts, provided the required input data are available. The results of the consequence modelling for the case study are discussed subsequently.

Table 3: K_{St} values measured for clouds of maize starch dust in closed vessels based on various volumes of vessel.

Researcher	$(dP/dt)_{max}$ (bar/s)	Vessel volume, V (m^3)	K_{St} (bar·m/s)
Bartknecht (1978)	680	0.0012	73
Nagy and Verakis (1983)	612	0.0012	66
Eckhoff *et al.* (1987)	220	0.0012	23
Nagy and Verakis (1983)	413	0.009	86
Aldis *et al.* (1983)	320	0.02	87
Eckhoff *et al.* (1987)	365	0.02	100
Yi Kang Pu (1988)	10	0.026	3
Yi Kang Pu (1988)	20	0.026	6
Yi Kang Pu (1988)	60	0.026	20
Yi Kang Pu (1988)	80	0.026	25
Nagy and Verakis (1983)	272	0.028	83
Bond *et al.* (1986)	50	0.33	34
Kauffman *et al.* (1984)	72	0.95	71
Kauffman *et al.* (1984)	20	0.95	20
Nagy and Verakis (1983)	136	3.12	200
Nagy and Verakis (1983)	110	6.7	209
Nagy and Verakis (1983)	55	13.4	131

Table 4: Laminar burning velocities of maize starch.

Researcher	Method	Concentration (g/m^3)	S_{CL} (m/s)
Proust (1993)	Square duct 200 × 200 mm^2	235	0.27
Van Der Wel (1993)	Burner	400–800	0.2
Van Der Wel (1993)	20-L sphere	400	0.13
Mazurkiewicz and Jarosinski (1991)	Burner	–	0.13
Mazurkiewicz and Jarosinski (1994)	Square duct 50 × 50 mm^2	260–760	0.14
Pedersen and Van Wingerden (1995)	Cylindrical tube d =128 mm	75–200	0.59
Krause *et al*. (1996)	Cylindrical tube d = 60 mm	370–1200	0.22
Krause *et al*. (1996)	Cylindrical tube d = 100 mm	80–430	0.4
Dahoe *et al*. (2002)	Tube + burner (flat flame)	330	0.29

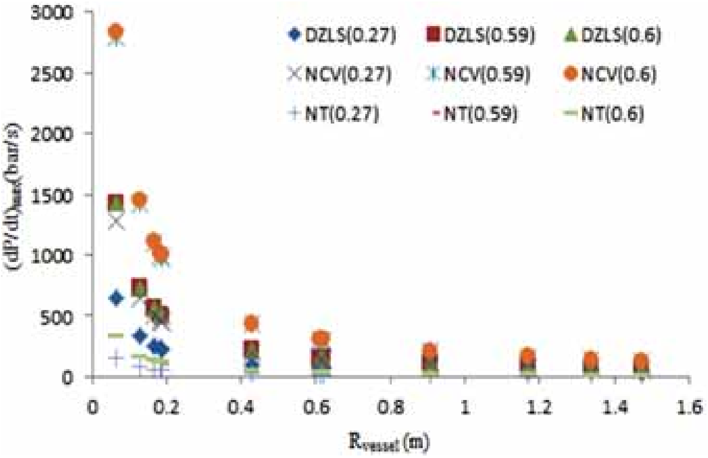

Figure 1: The maximum pressure rate, $(dP/dt)_{max}$ as a function of vessel radius, R_{vessel} for maize starch. ($P_0 = 1$ bar, $\mathbf{P_{max} = 10.713}$ **bar**, $\gamma = 1.4$, $S_{lbv} = 0.27$, 0.59 and 0.6 ms^{-1}).

Consequence modelling calculations were performed on maize starch with three burning velocities (S_{lbv} = 0.27, 0.59 and 0.6 m/s) and vessel volumes ranging from 1.2 L to 14 m^3 by DZLS's model (Dahoe, Zevenbergen, Lemkowitz and Scarlett), NCV's model (Nagy, Conn and Verakis) and NT's model (Nomura and Tanaka) for comparison within the limitation of cubic root law. Figures 1 and 2 present calculated values of the maximum rate of pressure rise $(dP/dt)_{max}$ as a function of the vessel radius, R_{vessel} vs. experimental data. Both figures show that the maximum pressure rate, $(dP/dt)_{max}$ was affected by changes in the volume of vessel for the three burning velocities. The $(dP/dt)_{max}$ are inversely proportional with values of R_{vessel}. The smaller volume of vessel produces a higher maximum pressure rate $(dP/dt)_{max}$. However, $(dP/dt)_{max}$ increased with increasing the values of P_{max} and S_{lbv}. The value of $(dP/dt)_{max}$ for DZLS's model was found to be more accurate rather than NCV's model and NT's model if we compare with experimental data.

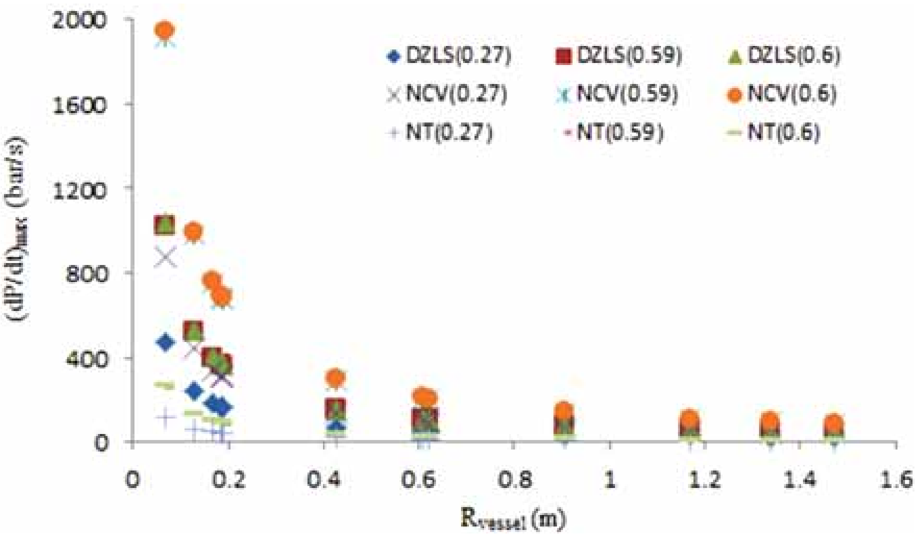

Figure 2: The maximum pressure rate, $(dP/dt)_{max}$, as a function of vessel radius, R_{vessel} for maize starch. ($P_0 = 1$ bar, $\mathbf{P_{max} = 8.963}$ **bar**, $\gamma = 1.4$, $S_{lbv} = 0.27$, 0.59 and 0.6 ms^{-1}.)

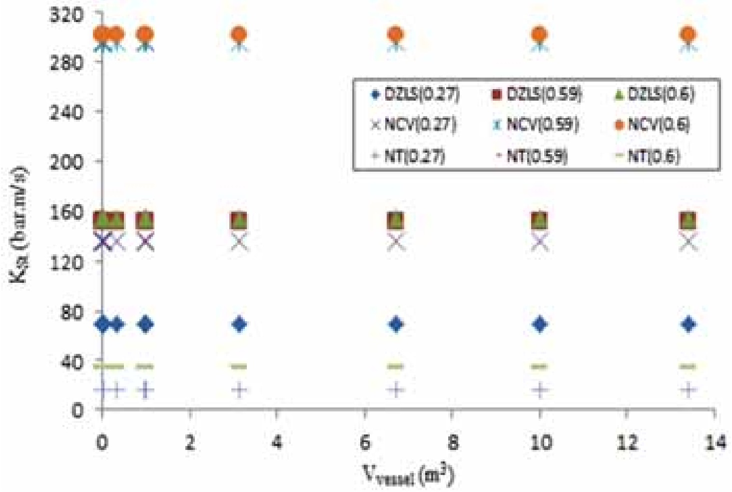

Figure 3: Model values of the dust deflagration index, K_{St}, as a function of vessel volume, V_{vessel}, for maize starch. ($P_0 = 1$ bar, $\mathbf{P_{max} = 10.713}$ **bar**, $\gamma = 1.4$, $S_{lbv} = 0.27$, 0.59 and 0.6 ms^{-1}.)

Figures 3 and 4 present the calculated values of dust deflagration index, K_{St} as a function of the vessel volume, V_{vessel} vs. experimental data. Both figures show that the K_{St} remain constant for varying volumes of vessels for each model. But this result does not agree with the experimental result performed by Nagy *et al.* [10] and Eckhoff [6], where all the three smallest vessels of 1.2, 9 and 28 L volumes, gave almost similar K_{st} values, whereas for the larger vessels of 3, 6.5 and 14-m^3 volumes were all about twice as large. However, in this result, the

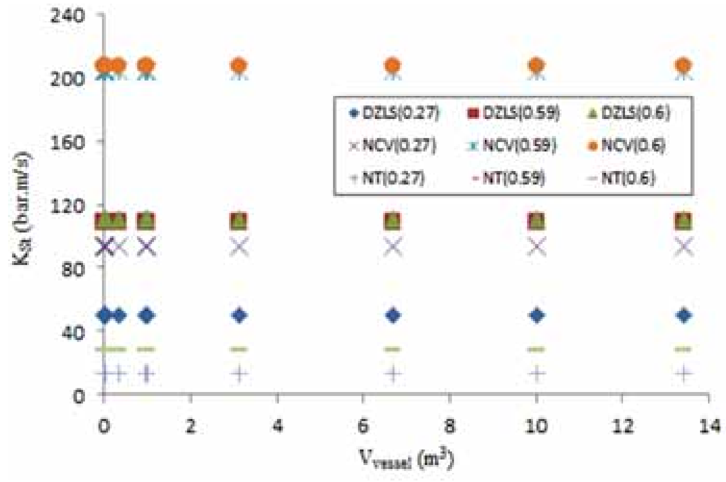

Figure 4: Model values of the dust deflagration index, K_{St} as a function of vessel volume, V_{vessel}, for maize starch. (P_0 = 1 bar, $\mathbf{P_{max} = 8.963}$ **bar**, γ = 1.4, S_{lbv} = 0.27, 0.59 and 0.6 ms^{-1}.)

K_{st} was affected by changes in P_{max} and S_{lbv}. The K_{st} are increased with increasing the values of P_{max} and S_{lbv}. As a K_{st} result, NZLS's model with P_{max} = 10.713 bar gave the closest value (K_{St} = 153 bar·m/s) to experimental value (K_{St} = 158 bar·m/s) compared with NCV's model and NT's model. Therefore, it shows that NZLS's model is more relevant than the others.

5 DISCUSSION AND CONCLUSION

An excel® spreadsheet for predicting the consequence of dust explosion was successfully developed in this work based on published models and validated with published experimental data. It is a user-friendly tool that requires standard input data before the consequence of a dust explosion in a given volume of confinement can be calculated. The online GESTISDUST-EX database would be a good reference for various parameters required by the spreadsheet tool that has been developed. It is noted that the geometry of the referred experimental work was all done in spherical vessels; thus the use of the spreadsheet for other geometry may be used with some degree of caution on the accuracy of the results. In addition, other factors such as dust concentration and particle size may also affect the consequence of a dust explosion. The spreadsheet tool for dust explosion consequence modelling was validated by running a case study of dust explosion involving maize starch. The results of the consequence modelling were compared with experimental data for a similar geometry of confinement. The results of the spreadsheet tool closely matched the experimental data. Thus, it is concluded that the spreadsheet that was developed for predicting the consequence of dust explosion can be used with confidence.

The spreadsheet tool for predicting the consequence of dust explosion that is developed in this work can be used for the purpose of risk management of a facility associated with dust explosion hazards. It may used to predict the maximum pressure rise as a result of a dust explosion in a certain volume of confinement and, thus, the impact of the explosion can be predicted. In addition, the information can be used in the design of venting for relieving a vessel to avoid rupturing of the vessel in an event of dust explosion or to determine the time interval to apply a combustion suppressant agent such as CO_2 to stop the combustion process.

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REFERENCES

[1] Combustible Dust in Industry: Preventing and Mitigating the Effects of Fire and Explosions; Safety and Health Information Bulletin, SHIB 07-31-2005, available at www.osha.gov/dts/shib/shib073105.html

[2] Combustible Dust Explosion; Department of Occupational Safety and Health, Ministry of Human Resources, Malaysia, available at http://www.dosh.gov.my/index.php?option=com_content&view=article&id=103:combustible-dust-explosion&catid=440&Itemid=1127&lang=en

[3] Combustible Dust Explosion at Motorcycle Rim Manufactured Factory; Department of Occupational Safety and Health, Ministry of Human Resources, Malaysia, available at http://www.dosh.gov.my/index.php?option=com_content&view=article&id=295:combustible-dust-explosion-at-motorcycle-rim-manufactured-factory&catid=439&Itemid=1126&lang=en

[4] Dahoe, A.E., Zevenbergen, J.F., Lemkowitz, S.M. & Scarlett, B., Dust explosions in spherical vessels: The role of flame thickness in the validity of the 'cube-root law'. *Journal of Loss Prevention in the Process Industries*, **9(1)**, pp. 33–44, 1996. doi: http://dx.doi.org/10.1016/0950-4230(95)00054-2

[5] Di Benedetto, A. & Russo, P., Thermo-kinetic modelling of dust explosions. *Journal of Loss Prevention in the Process Industries*, **20**, pp. 303–309, 2007. doi: ttp://dx.doi.org/10.1016/j.jlp.2007.04.001

[6] Eckhoff, R.K., *Dust Explosions in the Process Industries*, 3rd edn., Gulf Professional Publishing: Houston, Texas, USA, 2003.

[7] Crowl, D.A. & Louvar, J.F., *Chemical Process Safety - Fundamentals with Applications*, 2nd edn., Prentice-Hall, 2002.

[8] Nagy, J. & Verakis, H.C., *Development and Control of Dust Explosions*, Marcel Dekker, Inc.: New York, 1983.

[9] Namura, S.I. & Tanaka, T., Prediction of maximum rate of pressure rise due to dust explosion in closed spherical and non-spherical vessels. *Industrial Engineering Chemical Process Design and Development*, **19**, pp. 451–459, 1980. doi: http://dx.doi.org/10.1021/i260075a021

[10] Nagy, J., Seiler, E.C. & Conn, J.W., *Explosions Development in Closed Vessel*. Report Inv. No. 7507. U.S. Bureau of Mines: Washington, DC, 1971.

[11] Silvestrinia, M., Genovaa, B. & Leon Trujillo, F.J., Correlations for flame speed and explosion overpressure of dust clouds inside industrial enclosures. *Journal of Loss Prevention in the Process Industries*, **21**, pp. 374–392, 2008. doi: http://dx.doi.org/10.1016/j.jlp.2008.01.004

[12] GESTIS-DUST-EX Database, Combustion and Explosion Characteristics of Dusts, available at http://dguv.de/ifa/Gefahrstoffdatenbanken/GESTIS-STAUB-EX/index-2.jsp

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