Safe Design in Dryers for Food Industry

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In food process operations of organic dusts thermal decomposition phenomena are possible.

In this paper theoretical models are presented for the safe design of equipment employed to work on organic dusts, such as dryers.

Models are based on the well known theories of Semenov (uniform internal temperature) and Frank-Kamenetskii (non uniform internal temperature) and they are also useful to verify the thermal stability of the apparatuses during the process activities.

Key words:
Dust explosion, food powders processing, safe design, model for

Introduction

Thermal stability problems often occur in food processes which involve flammable substances in apparatuses such as reactors, dryers, silos and separation systems in general[1].

After a short analyses of some of the principal accidents (explosions) which occurred in agri food plants, and of the methods commonly employed in order to protect equipment from explosions, in this paper drying process of organic dusts will be considered and design methodologies will be shown, according to the most innovative preventive criteria, instead of protective ones, on the base of the theory of runaway reaction. In particular the calculation models for the safe design of dryers and for the functionality test of the same, will be examined. The design criteria which introduce the concept of inner safe, which is very interesting because of the implicit advantages correlated to itself, are explained.

The possibility of neutralizing, at least partly, the explosion risks correlated with an industrial process, allows to reduce safe systems and to simplify control procedures. This makes the process inner safe since it depends no more on protection and security systems.

In the present paper drying processes have been divided in two fundamental groups: completely mixed ones and not mixed ones.

The first group (uniform internal temperature, according Semenov's theory)[2] comprehends, all the fluidized bed equipment, while the second group collects those operations where substances, stored up in bulk, give origin to a non uniform internal temperature system (Frank-Kamenetskii's theory)[3].

Of great importance for the following development, are the thermal analyses of runaway reactions typical of the present process and the characterization of kinetic parameters which characterize them.

Explosions

A dust compound reactivity is very different from a compact one's and it is a function of its granulometry. In fact, many substances are little reactive as compact and become explosive when minced. Fine powders are more inflammable than rough ones, because the combustion process rate is given by oxygen diffusion into the substance: the more compact is the solid, the slower the combustion will be. For the same mass, the reactivity depends on the exposed surface of the particles (surface area), which increases if the substance is reduced to fine powder. For particles with the same form surface area depends on the granulometry and with the same mass it depends on the form.

Powder reactivity is a function even of its nature: a substance with oxidized components will react at a lower degree than non oxidized, under the same conditions; and a substance with a high level of humidity will react slower than a dried one.

The combustion heat (specific heat) is an important parameter because it determines how much heat can be produced during the explosion. The greater the specific heat of a powder, the higher the temperature the combustion gases will reach. However, if different dusts are compared in terms of dangerousness, the combustion heat should be correlated with the amount of oxygen consumed. In fact, the gas phase into which the

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Tab. 1 – *Dust explosions in food industry plans.*

Location	Event	Date	Dead	Injured
Port Arthur; Ontario; Canada	Primary explosion is believed to have occurred in annex 1 of the pool elevator No. 5 building. Refuse screenings were being loaded onto ship when the explosion occurred. Many NFPA codes were found to be broken e.g. poor ventilation. Grain dust present.	07/08/45	22	27
Chicago; Illinois; USA	Cause of dust explosion in protein bagging plant not established. 1 employee seriously injured, part of roof destroyed & $3^{rd}/4^{th}$ storeys of plant badly damaged by ensuing fire .	05/07/57	0	1
St. Louis; Missoury; USA	Lubrification failure at mill in animal food works caused overheating/sparking which resulted in explosion of swirling grain dust. Subsequent fire lasted 5 days, fire fighting being hampered by low ambient temperatures.	10/01/62	2	34
London; Greater London; UK	Heat from welding equipment ignited flour dust inside 15te bin. Explosion spread through building by dust inside/outside ducting. 3 killed when silo wall collapsed. 2 large fires, several small, involving pipe lagging + flexible ducting connections.	07/08/65	5	40
Stavanger; Norway	Dust explosion at port silo. Roof of one silo cell blown off and all transport elevators put out of action.	09/06/70	0	0
Destreham; Luoisiana; USA	2 explosions in a grain elevator whilst corn was being discharged from a barge. Company = "Bunge Corp".	14/09/70	0	7
Kiel: Schleswigholstein; Germany	Grain silo destroyed and surrounding buildings damaged due to an accumulation of dust in silo. Also barges/ship in kiel north harbor damaged. Company = Ludnig Wunsche.	14/12/70	2	13
Glasgow; Strathclyde; UK	The incident occurred in a plant that extracted oil from soy beans. A leak of hexane exploded when a pump switch was thrown. This initiated dust explosions in tunnels used to feed silos with grain. A second explosion followed.	09/10/71	0	8
Houston; Texas; USA	Goodpasture inc plant, Houston ship canal, mail grain elevator. 1 row of multistory concrete grain elevators destroyed. Ship damaged by debris. Elevator contained 5*10E6te grain. Underground loading system destroyed. Cause-spark from welding torch?	22/07/76	9	7
Cambridgeshire; UK	Dust recirculated into the outfall housing of a pulp driver was ignited by a hot particle. The explosion and fire damaged machinery, the outfall building ad the roof of the factory.	27/08/77	1	-
Bahia Blanca; Argentina	An explosion occurred in a grain elevator. Several area fire departments and ambulances were dispatched to the scene.	10/10/77	2	>1
Westwego; Louisiana; USA	37 grain silos totally destroyed, others damaged by series of explosions. Cause not known but low humidity/pressure piling contributory factors. Fatalities caused when concrete tower fell on office block.	23/12/77	35	0
Galveston; Texas; USA	Dust explosion during unloading of grain thought to be initiated by sparks from diesel locomotive. Explosion propagated through closed conveyor bridge into other installation buildings.	27/12/77	18	22
Liberty; Missouri; USA	Dust explosion in grain elevator. Company was desert gold feed Co.	19/01/78	3	6
Witenberg; Germany	Explosion at 0200 in shed storing coconut/palm cakes at animal feed wholesalers. Fire controlled by 0600. Second fire developed in grain silo & helped by strong wind destroyed 4000te grain, feed stores & milling equipment.	02/01/79	–	–
Durup; Denmark	Axeltoft a/s fodder producers. Defect in thermostatically-controlled oil-fired boiler- enormous dust explosion of grain silo. Injuries very serious. All surrounding factory buildings destroyed.	23/02/79	–	3
Bremen; Germany	Explosion & resulting fire at grain mill during shift changeover demolished the mill, a silo & 3 buildings. All windows broken within 1000 m; firemen took 2 days to bring fire under control. Debris scattered for miles.	06/02/79	14	17

Location	Event	Date	Dead	Injured
Napoli; Italy	7 employees plus forwarding agent injured when a large quantity of grain dust that had accumulated in silo stores, exploded presumably due to a spark.	08/01/80	0	8
Montreal; Texas; USA	Massive explosion ripped through 8 grain silos & blew top off 110ft concrete grain elevator. 2hrs after first blast second smaller explosion rocked the site. Debris rained on railroad cars & blast touched off flames that spread to adjacent plant.	26/01/80	1	7
Antwerp; Antwerpen; Belgium	Dust explosion at silo during discharge from ship blew off the roof, damaging adjacent warehouses.	27/01/81	-	-
Hawthorne: New Jersey; USA	Explosion followed by fire started in steam-heated starch roaster. Explosion wrecked the 3 storey brick building collapsing nearby railway siding & rocking buildings over 4 block area.	17/02/81	-	-
Corpus Christi; Texas; USA	Grain dust explosion destroyed 6 concrete silos. Time = 1510 (shift changeover). Ignition thought to be nearby equipment. Local industrial area evacuated. Big concrete chunks thrown into streets. Fire in elevators burned 4–4 days.	07/04/81	6	18
Council Bluffs; Iowa; USA	5 people were killed by a powerful explosion at American agri-industries council bluffs elevator. 16 people were injured. The ensuing fire destroyed 50% of the complex & extensively damaged surrounding property.	20/04/82	5	16
Tirlemont; Belgium	23 injured, including passerby when huge flame shot through sugar refinery followed by blast. Extensive damage, several walls and floors collapsed, windows shattered in 300yd radius. Cause thought to be accumulation of sugar dust.	15/10/82	0	23
Metz Moselle; France	Silo containing thousands of ton of grain collapsed following dust explosion. Huge slabs of concrete thrown 250 yards away onto nearby highway. Police found blowtorch among rubble.	18/10/82	12	1
Raymond; Missouri; USA	4 people died and at least 3 were severely burned when an explosion blasted the Raymond o-op grain company elevator.	16/11/82	4	>3
Rosario; Argentina	Dust explosion at loading elevator and silo for grain. Several injuries.	30/03/81	-	>1
Ashford; Kent; UK	A series of small explosions occurred at a flour mill. At 2336 a fire was noticed + an alarm was raised. The automatic sprinkler system was inoperable. There was the possibility that debris may fall on a nearby railway so BR temporarily stopped the line.	07/09/84	-	-
Bahia Blanca; Argentina	Dust explosion in grain elevator, cause unknown. Repairs expected to take 2 years.	--/03/85	-	-
Marion; South Dakota; USA	An explosion occurred in a grain elevator. Several area fire departments and ambulances were dispatched to the scene.	03/11/85	1	1
Namur; Belgium	Four people and seven were badly injured in an explosion & fire in a grain silo in Belgium. The explosion at the automatic store was caused by a flame igniting dust. Nearby houses & factories were damaged in the series of blasts which followed.	07/04/93	4	7
Seattle; Washington; USA	Explosion followed by fire occurred at 50^{th} level of eight story dusthouse at south end of silo in grain terminal complex. Initially water used to fight fire, but later stopped to prevent structural damage to expanding grain.	03/11/93	0	0
Geelong; Melbourne; Australia	Dust explosion & fire when repair works being carried out on equipment at grain terminal.	--/12/93	-	-
Bandar; Khomeini; Iran	Explosion & fire at wheat silo in port. Electrical short circuit suspected. Possible 20,000te wheat destroyed.	29/06/94	13	26
Burlington; Iowa; USA	Employees evacuated shortly before fire/explosion blew tops off 6 grain silos. Downtown shop windows shattered & buildings evacutaed when flames threatened underground fuel tank.	-	0	5

powder is dispersed, often contains a very limited amount of oxygen (if compared with stoichiometric ratio), which determines how much heat is released per volume unit by the explosive system.

As example, sucrose or starch develop a combustion heat of 470 kJ mol^{-1} of O_2 consumed.

The energy released, together with the fast developing of the event, determines the accidental magnitude, as synthesized in Table 1, which reports that some explosion events happened in agri food industries.[4]

The traditional protection systems for equipment containing flammable dusts are:

– gas inerting;

– ignition sources removal;

– dust concentration under the low flammability limit (LFL);

– mixing of powders with inert material;

– explosion proof vessels;

– explosion suppression;

– explosion venting.

Among these the explosion venting is the most utilized and economic technique. However it must be said that:

– It can't be effective for all plant types;

– It still needs theoretical and practical acknowledgement in order to elaborate calculation algorithms of general validity.

Some experimental by means of industrial scale equipment, were carried out in order to know if laboratory results were realistic if compared to industrial problems.[5]

The results obtained can be elaborated by means of the scale-up law, known as "cubic law".[6] The cubic law derives from many experimental tests conducted in big vessels (from 1 to 60 m^3) and correlates the volume of recipients where the explosion occurs, with the maximum value of pressure rate, according to the following equation:

$$(\mathrm{d}p/\mathrm{d}T)_{\max} \cdot V^{1/3} = K_{\mathrm{st}}$$

Table 2 reports average values of the K_{st} for some food dusts.

To be true, K_{st} values vary in a more or less wide range depending on product composition (which can be different) and on powder particle size. E.g., the following ranges of K_{st} and maximum pressure developed during explosion can be given for powder milk and sugar:

Powder	$p_{\max}$ (10^5 Pa)	K_{st} (10^5 Pa m · s^{-1})
Powder milk	8.1 – 9.7	58 – 130
Sugar	8.2 – 9.4	59 – 165

The highest pressure, instead of according to cubic law, becomes no more dependent on volume equipment when is over 10^{-2} m^3.

Table 2 – *Average values of K_{st} for some food powders.*

Powder	$K_{\mathrm{st}}/10^5$ Pa m s^{-1}
Dextrose	18
Fish flour	35
Filtered fructose	102
Wheat	112
Filtered coffee	90
Potato flour	69
Lactose (from cyclone)	81
Powder milk (skim)	109
Rice	190
Soy	110
Tea	68
Sugar	82
Caffeine	165

Dryers

Drying operation, employed in agri food processes, often represents a critical point for safety in production systems. In fact, this operation is carried out under variable conditions, as far as humidity, temperature and dust concentration in the atmosphere inside the drier.

Besides, equipment protection by means of traditional system is not simple, because of both economical and technical aspects.

The operation is generally carried out under ambient pressure and so the apparatuses are designed in order to support only little over pressure values. So, if explosion venting is chosen as protection system, the large vent must be realized with one or more m^2 of surface.

The alternative for drying process consists in realizing such an equipment which can be resistant to high pressures or of employing inert gases instead of air. Both solutions don't seem to be economically profitable. Then, the inner safe systems are doubly convenient, both, for technical-economical aspect and, moreover, for the choice of innovative prevention solutions rather than of traditional protection ones. Then design criteria will be exposed concerning two types of inner safe dryers: uniform and non uniform internal temperature dryers.

In order to apply correctly the following equations, one needs to acknoweledge exactly chemical and physical properties of dried products, such as heat reaction and activation energy. Calorimetric techniques, such as DSC, are particularly suitable for evaluating the above parameters.

Uniform internal temperature dryers

In a system where the temperature is uniformly distributed, like a fluidized bed, the Semenov's[2] boundary conditions are fulfilled because of the turbulent regime of the system which brings about a uniform distribution of temperature. The equation of heat balance for a drier may be written, considering that the volumetric flow rate variation between the input and output section is negligible, as follows[7]:

$$\Phi = \mathrm{d}q/\mathrm{d}t = Q[c_\mathrm{p}(T_2 - T_1) + c_\mathrm{pv}(H_2T_2 - H_1T_1) + r_\mathrm{L\text{-}G}(H_2 - H_1)] \quad (1)$$

For a discontinuous drier, at the last step of the drying process, both the drying rate and the difference of absolute humidity between input and output drying gas flow tend to zero. Then $H_2 \approx H_1$. And:

$$\Phi = \mathrm{d}q/\mathrm{d}t = Q\,(c_\mathrm{p} + c_\mathrm{pv}H_1)(T_2 - T_1)\cdot\rho \quad (2)$$

At the last step of the drying process, particles temperature increases, while the heat exchange decreases. Of course this is the critical spot from a safety point of view for this type of device. Neglecting the term $c_\mathrm{pv}\,H_1$, which does not offer an important contribution to the heat exchange, one obtains:

$$\mathrm{d}q/\mathrm{d}t = Q\,c_\mathrm{p}(T_2 - T_1)\cdot\rho \quad (3)$$

the above equation may be applied properly for the above conditions, but it may be also applied for safety purpose to the starting steps of dryers since the adopted hypotheses are conservative.

By introducing the Semenov's criterion[2], under critical conditions, being $\Delta T_\mathrm{cr} = RT^2/E$, one can obtain the following expression for Q/V ratio (where V is the dryer's volume):

$$(Q/V)_\mathrm{cr} = l\,\frac{(-\Delta H_\mathrm{r})\,k_0\exp(-E/RT)}{\rho\cdot c_\mathrm{p}\,RT^2/E} \quad (4)$$

Writing the heat generation term, the zero order hypothesis has been introduced which is generally accepted by studying the divergent reactions, so that the term which refers to the concentration (or degree of reaction conversion), has been rejected.

It follows that if ratios $(Q/V) > (Q/V)_\mathrm{cr}$ are kept, internal safety conditions of the apparatus will be guaranteed, since the heat developed by eventual exothermic events will be soon removed by means of the air flow employed for drying, so that the explosion is prevented.

Non uniform internal temperature dryers

A substance layer, inside of a steady bed apparatus, has been considered which is limited by two infinite parallel planes at a distance $2r$, touched by a cooling fluid. By supposing that en exothermic reaction starts inside the layer, a relation between the thickness of the layer and fluid characteristics (type, flow rate, temperature and exchange surface) can be calculated so that the reaction could be maintained under control.[8]

By considering T_c the temperature at the layer center, T_o the outlet air/layer surface temperature and x the spatial coordinate in the layer, from the center to the surface, as can be seen in fig 1:

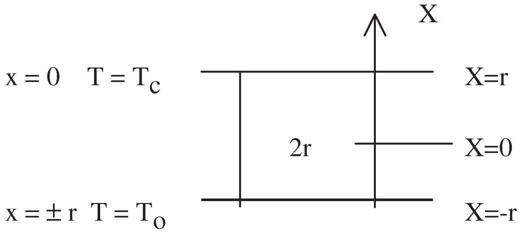

Fig. 1 – *Dust layer scheme.*

The temperature T_o depends on the inlet cooling fluid temperature T_a and its behavior can be obtained by setting the thermal balance of the heat developed by an undesired reaction and of the heat removed by the cooling fluid using the conservative hypothesis of zero order kinetic:

$$\int(-\Delta H_\mathrm{r})k_0\exp[-E/(RT)]\,\mathrm{d}V = Gc_\mathrm{p}(T_0 - T_\mathrm{a}) \quad (5)$$

In expression (5) the temperature is a function of the place, decreasing along the x axis from the center to the surface.

However from the Frank-Kamenetskii's theory one obtains that the highest temperature difference between the center and the surface of a body, obtainable before the reaction diverges, is:

$$(T_\mathrm{c} - T_0) = 12\,RT_\mathrm{o}^2/E$$

where T_c is the temperature at the layer center.

By substituting in expression (5) the constant value T_c for the temperature, the heat production is overestimated, giving a conservative evaluation suitable for safety purposes.

$$T = (T_\mathrm{c})_\mathrm{max} = T_0 + 12\,RT_0^2/E$$

Keeping, moreover, in mind that:

$$\exp\left(-E/R(T_\mathrm{c})_\mathrm{max}\right) = \exp(-E/RT_0)\cdot\exp(12)$$

because

$$T_\mathrm{c\,max} - T_0 \ll T_0$$

then the thermal balance becomes:

$$(-\Delta H_{\rm r})Vk_0 \exp[-E/(RT_0)] \exp(1.2) = Gc_{\rm p}(T_0 - T_{\rm a}) \qquad (6)$$

According to the Frank-Kamenetskii's theory[3] the largest critical thickness of the layer to avoid that the reaction diverges, is given by:

$$r_{\rm cr}^2 = \frac{\lambda\,\delta_{\rm cr} R}{3(-\Delta H_{\rm r})\,E\,k_0} \cdot \frac{T_0^2}{\exp(-E/RT_0)} \qquad (7)$$

where $\delta_{\rm cr}$ is the Frank-Kamenetskii's dimensionless parameter which values 0.88 in the case of plane symmetry.

For $T_0 = T_0^*$ one obtains r as a function of $T_{\rm a}^*$. The solution does not constitute an acceptable safety condition, because small alterations can provoke an explosive development of the reaction.

To find out the highest T_0 acceptable, one combines the equations (6) and (7), being $V = 2rS$ and placing

$$A = G\,c_{\rm p}/S$$

This combination allows us to evaluate the largest r value of the dried dust layer compatible with the thermal stability of the system:

$$r^2 = f\,(T_{\rm a},\, G\,c_{\rm p}/S) \qquad (8)$$

The solution of the equation (8), implicit in r, can be found numerically.

Then even in this case, by adopting an half thickness $r < r_{\rm cr}$, the process is kept internaly safe so that the removal of the heat exceeding from dried mass through thermal exchange with outside surrounding is guaranteed. Fig. 2 shows, as example, the behavior of critical thickness $r_{\rm cr}$ as a function of the cooling fluid temperature and of the parameter $Gc_{\rm p}/S$.

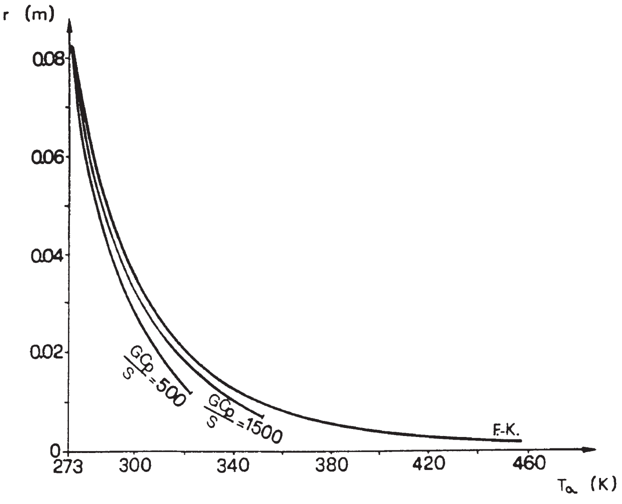

Fig. 2 – *Behavior of r as a function of the cooling fluid temperature* $T_{\rm a}$ *and the ratio* $Gc_{\rm p}/S$.

Conclusions

The proposed models represent a verification criterion and/or a link for safety design equipment utilized in the drying operation of thermal unsteady organic dusts which often occurs in food industry.

The proposed equations, in fact, allow to correlate equipment size with process, plant and thermokinetic parameters.

For uniform temperature distribution the critic parameter is the ratio between the flow rate of the cooling fluid employed (that is generally air) and equipment volume. For non uniform temperature distribution, instead, the critic parameter is the thickness of the layer of the substance inside the dryer. In both cases, to respect these parameters means to realize simple and inner safety systems as far as there is the need either for operative procedure (lower influence of human factors) or and for control, protection and safety instruments. This agrees with the advancing trends of the sector which prefers the concept of inner safety as prevention possibility, better than assuming extra expense for protection operations aimed to mild dangerous effects for man and environment.

Notation

A – heat transfer coefficient, W m^{-2} K^{-1}
$c_{\rm L\text{–}G}$ – evaporation latent heat, kJ kg^{-1}
$c_{\rm p}$ – cooling medium specific heat, kJ kg^{-1} K^{-1}
$c_{\rm pv}$ – vapor specific heat, kJ kg^{-1} K^{-1}
E – activation Arrhenius energy, kJ kmol^{-1}
G – fluid flow rate, kg s^{-1}
H_1, H_2 – air absolute humidity, kg vapor kg^{-1} dry air)
$(-\Delta H_{\rm r})$ – heat of reaction, kJ mol^{-1}
$k_{\rm o}$ – frequency coefficient, mol m^{-3} s^{-1}
$K_{\rm st}$ – dust characteristic constant, 10^{5}Pa m s^{-1}
$p_{\rm max}$ – the highest pressure, 10^{5}Pa
$(d_{\rm p}/d_{\rm t})_{\rm max}$ – the highest pressure increasing rate 10^{5}Pa s^{-1}
Q – volumetric flow rate m^3 s^{-1}
q – heat, kJ
R – ideal gas law constant, 8.31 J mol^{-1} K^{-1}
S – surface of the layer, $V/2r$, m^2
T – absolute temperature (K)
T_1, T_2 – temperatures (1 = input, 2 = output), K
$T_{\rm a}$ – fluid temperature at the input side, K
$T_{\rm a}^*$ – the highest fluid temperature acceptable, K
$T_{\rm o}^*$ – the highest layer-surface temperature acceptable, K
$T_{\rm c}$ – temperature at the layer center, K
$T_{\rm o}$ – fluid temperature at the outlet side, supposed being identical with outlet air/layer surface temperature (conservative hypothesis), K
$\Delta T_{\rm cr}$ – critic temperature difference, K

V – system volume, m^3

Φ – heat flow rate, dq/dt, kJ s^{-1}

r – half thickness of powder layer, m

r_{cr} – critic half thickness, m

δ_{cr} – Frank-Kamenetskii's dimensionless shape parameter

ρ – density of dry air, kg m^{-3}

λ – layer thermal conductivity, J m^{-1} s^{-1} K^{-1}

References

1. *Spigno G., De Faveri D. M.*, Sicurezza intrinseca nella progettazione di essiccatori per l'industria alimentare, ICP, (27) **10** (1999) 68
2. *Semenov*, Some problems of chemical kinetics and reactivity, Academie Verlag Berlin, 1961
3. *Frank-Kamenetskii,* Diffusion and heat transfer in chemical kinetics, 2nd ed. Plenum Press, New York/London, 1969.
4. *Romano A., Piricò F.,* Raccolta di episodi noti di esplosioni di polveri, Sem. "La prevenzione delle esplosioni di polveri nelle attività produttive", Parma, 10 ottobre 1997
5. *Eckoff R. K.*, Dust Explosions in the Process Industries, Butterworths-Heinemann, Oxford, 1991
6. *Bartknecht W.,* Explosions, Spribger Verlag, Berlino, 1981
7. *De Faveri D. M., Pagella C., Vidili A., Ferraiolo G.,* Runaway reaction and safety measures in organic processes, International Symposium on runaway reaction, Cambridge, USA, 7–9 March 1989
8. *De Faveri D. M., Zonato C., Pagella C.*, Safety design in processing organic powders, Chem & biochem. Eng. Q. **6** (1) (1992) 7