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Industrial accidents in spray dryer plants for dairy products in Europe

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ABSTRACT

Despite the fact that the information about past accidents is an integral part of accident prevention, the information about industrial accidents is not commonly available in food and agricultural sectors. Spray dryer plants for dairy products are not an exception. The aim of this paper is the creation of the representative database for industrial spray drying accidents in order to identify their major causes. The paper is divided into 8 chapters. The first two chapters deal with the general information about technology of spray drying of dairy products. The third chapter provides the outputs from the authors' database containing records of 25 accidents in milk drying facilities in Europe. These accidents took place between 1999 and 2019 in six European countries. Based on the accident database, the most common causes of accidents were identified. Processes that can cause a fire, an explosion, or damage to environment are described in the fourth, fifth and sixth chapter. The seventh chapter deals with process, technical and organizational measures; these were discussed using literature research and the results of the accident database. The eighth chapter is the conclusion with a focus on further improvement of process safety through newly developed protective tools.

1. Introduction

According to statistical data, the 28 EU countries produced 2 018 485 tonnes of whole milk powder (CLAL, 2020a) and 1 508 174 tonnes of skimmed milk powder (CLAL, 2020b) in 2019. The amount of milk produced will actually be higher, as some countries do not report their production. Two principal methods are used for drying in the dairy industry: roller drying and spray drying (Bylund, 1995). Especially the spray drying technology involves hazards that can cause fatal injuries to the operator or cause a significant financial loss. Extraordinary events associated with fires or explosions have been recorded since the second half of the 20th century when industrial milk drying was developed. Beever and Crowhurst (1989), referring to Pineau (1984), reported 35 major accidents occurring between 1967 and 1982 in the French dairy industry, 14 involved fire and explosion. However, accidents in this industrial sector are not a matter of the past. Febo (2015) states that FM Global Clients had 21 fatal injuries in the food industry. Recently, damages have been connected with the food industry mainly in milk/infant formula processing. The outputs from the authors' database of accidents also suggest this. The case of an accident in France can be mentioned (ARIA, 2019).

Although there have been many positive developments in process safety in this area over the past few years, it is clear that accidents still occur. However, it is not certain whether there has been an increase in accidents or not. This is due to the relatively small number of these plants and their changing number over the decades.

The paper deals, above all, with the process safety of spray dryers. It focuses especially on the accidents related to fires, explosions and environmental damage. The issue of equipment reliability, occupational safety, or food safety is beyond the scope of this paper.

The aim of the paper is the creation of the representative database for industrial spray drying accidents in order to identify their major causes. This information can be used to establish safety instructions for accident prevention in industrial spray drying.

2. Basic description of spray milk dryer technology

A spray milk dryer technology is supplied in various configuration. For better orientation, the example of a two-stage drying technology is shown in Fig. 1. This technology is formed by several basic parts:

- Air supply
- Milk supply
- Drying tower
- Powder separation system

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Abbrivation

MIE	minimum ignition energy
MEC	lower limit of dust concentration at which the air dust mixture is potentially explosive
MIT	minimum ignition temperature in the dust layer
MIT_c	minimum ignition temperature in the dust cloud
p_{max}	maximum excess pressure produced in a closed receptacle during an explosion of an explosive atmosphere
K_{st}	specific dust parameter characterizing the explosiveness of dust and obtained from test standardized equipment

- Exhaust
- Packaging and storing

Pre-cleaned air together with milk are supplied to the atomizer located in a drying tower. Pressure nozzles, two-fluid nozzles, and rotating discs are used as an atomization technique (Skanderby, 2011). Powdered milk is collected at the bottom of the drying tower. In the case of the two-stage drying (see Fig. 1), powder undergoes another drying step (fluidized bed dryer, belt dryer). Further, powder is sifted, packed, and stored. In hot air from the drying tower, powder is separated by various techniques, such as cyclones (see Fig. 1), bag filters, or a combination of both. Skanderby (2011) describes another powder separation system in milk drying: CIP-able bag filter or wet scrubber. Powder collected in cyclones is returned back to drying towers by fines returning system. This system can lead to the atomizer or directly to the drying tower against the flow of sprayed milk. Cleaned air, stripped of milk powder, is further taken to the exhaust. Detailed information about the spray milk dryer technology can be found, e.g. in Bylund (1995), Skanderby (2011) or Westergaard (2010).

3. Accidents

The information on accidents listed below comes from the authors' database. It contains a total of 25 accidents that occurred in the years 1999–2019 in milk drying facilities and comes mainly from sources (ARIA, 2020), (BAM, 2020), marginally also from newspaper articles. Certainly, this is not a final number of accidents; it is assumed that the number will be higher. The difference between accidents in the database and the actual number of accidents will be mainly due to the insufficient availability of information.

Out of a total of 25 accidents in the database, 19 occurred in France, 2 in Germany, 1 in the Netherlands, Poland, Spain, and the Czech Republic. According to statistics, Germany is the largest producer of whole milk + skimmed milk in the 28 EU countries (681 559 tons in 2019), followed by France (529 890 tons in 2019) (CLAL, 2020a; CLAL, 2020b). The highest number of accidents in France is given by the fact that the ARIA (2020) database (where the record of most accidents was found) is operated by French authorities. Other web portals operated by the authorities of other countries do not record this type of accident. Assuming that there will be approximately the same number of accidents in Germany as in France, the real number of accidents in Europe will be much higher than 25 reported.

Fig. 2 shows that the distribution of the number of accidents is approximately the same in the individual years. Out of the reported number of accidents, 15 were fires, in 7 cases it was an explosion, and 3 cases were connected with a substance leak into the surroundings. In one case, there was a leak of methane from a ruptured supply pipe, then a leak of HNO_3 from the storage tank, and the last case was a leak of powdered milk into nearby surroundings. According to Pineau (1984), a total of 14 cases of fire or explosion were recorded in France between 1967 and 1982 (i.e. within 23 years). The authors' database shows that, between 1999 and 2019 (i.e. within 21 years) in France, there were 16 accidents related to fire or explosion. These values are very similar.

Generally, in this sector, accidents are not associated with large numbers of injuries or fatalities. Two cases of injuries were recorded throughout the period 1999–2019. The first case was only a minor injury

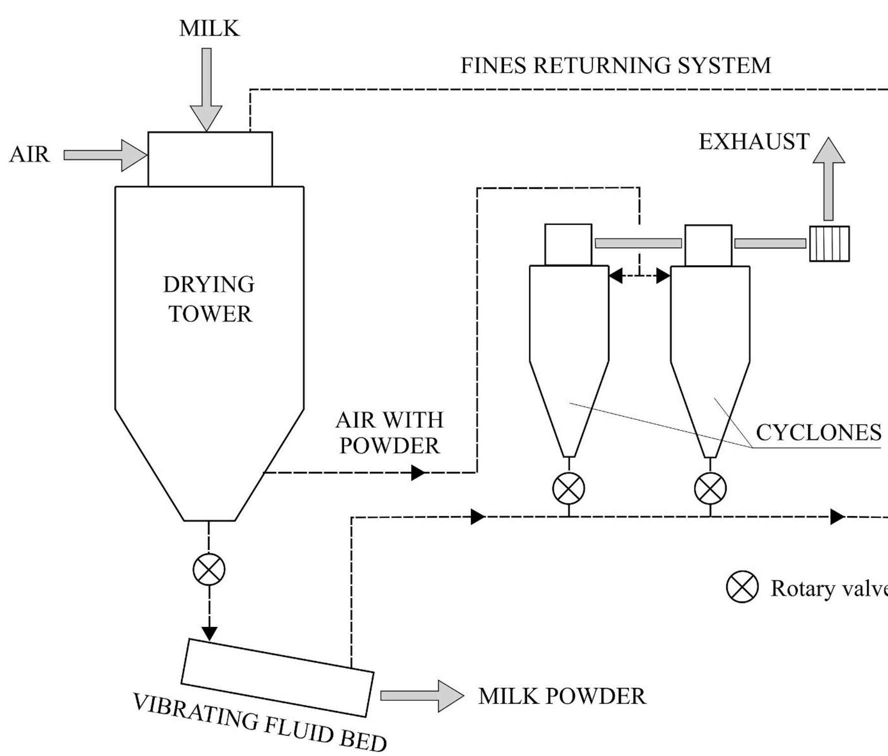

Fig. 1. Configuration variant of a milk dryer (two-stage drying).

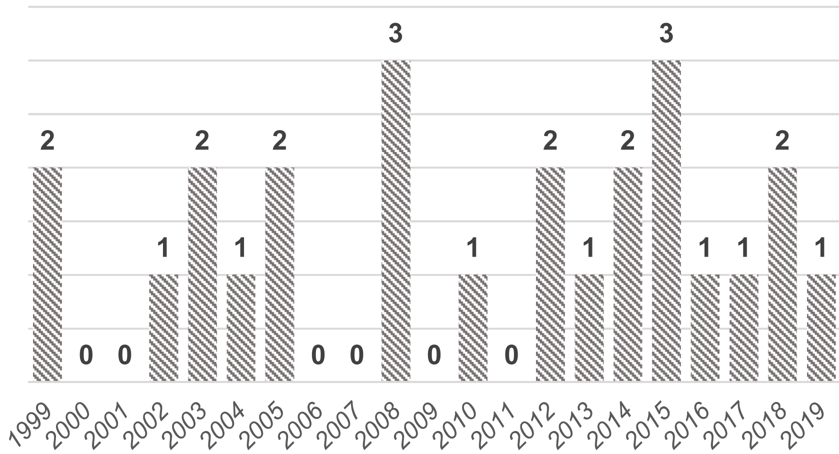

Fig. 2. Number of accidents in years 1999–2019.

(HNO_3 vapours were inhaled) and the second case was due to the explosion of powdered milk; one minor injury and one serious injury when the person had to be transported to the hospital. Damage estimates were found in three cases; costs were in hundreds of thousands of EUR.

Table 1 shows the locations in the milk drying technology where the accident occurred. The type of event (whether it is a fire, an explosion, or other) is also listed for each location. Hence, the drying tower is the part where the accident occurred most often. There was a total of 6 fires and 2 explosions. It is followed by a silo for storing milk powder with 5 accidents; 3 fires and 2 explosions.

The authors are aware of the fact that the sample of 25 accidents may not appear to be representative. However, issues of industrial accidents in food industry are perceived by professional public more as a marginal issue compared to the chemical industry. We assume that this is one of the reasons why it is difficult to find sufficient information about these accidents. However, there will probably be more reasons.

For example, let us compare milk dryer plants with another type of a food facility – sugar plants. A database of sugar plant industrial accidents created by Trávníček et al. (2020) contains 66 items for the years 1999–2018. The same procedures were used for this search. For comparison, in the European Union, there were 103 sugar plants with 23700 employees in 2018/2019 (CEFS, 2020). The number of milk dryer plants will be similar (probably slightly higher) than that of sugar plants. However, the number of employees per plant is lower (in Czech Republic ca. 15–20 per plant), production of milk powder is lower than that of sugar.

Note: Production of fresh sugar in 2018/2019 was 17.63 mil. tonnes in European Union (EC, 2020). Compare with data on powdered milk in the introduction.

From this information, it can be assumed that differences in accident records may be, for example, due to the complexity of sugar plant technology which is higher than that of milk dryer plants. There are more possibilities of something going wrong. Moreover, industrial sugar plants were established in the first half of the 19th century when the first accidents were also recorded. Therefore, there is a tradition in description of accidents.

Table 1
Locations in technology where the extraordinary event occurred.

Location	Fire	Explosion	Other	Total
Silo	3	2	0	5
Drying tower	6	2	0	8
HNO_3 tank	1	0	1	2
Cyclone	0	1	1	2
Filter	2	1	0	4
Fluidized bed dryer	2	1	0	3
Other[a]	1	0	1	2

[a] Hopper, gas pipeline.

3.1. Causes of accidents

Obtaining of relevant information about a course of an accident may be difficult. This can be due to various reasons. The vagueness of information can be given as an example. This is especially true for information from public databases (however, vagueness is also a part of some published investigation reports). Another problem may be a lack of information or, on the contrary, a huge amount of information, which, combined with vagueness of information, (e.g. from public databases about major accidents in chemical industry) can be even a more important problem than a lack of information. Advanced (but complicated) methods for data mining can be used; however, these methods are prone to errors. Moreover, it is complicated to recognize that these errors are errors. There is a danger of creating causalities where they are not. The larger the volume of data, the higher the probability of this phenomenon. Therefore, there is a need for great caution.

A combination of a lack of information and their vagueness is apparently the case of food and agricultural industry. This also applies to spray dryer plants for dairy products. There is no comprehensive work to analyze the accidents in this sector. Although the information is insufficient and sometimes vague, it is the only material we have to work with. In the case of small number of items, all of them should be read carefully and subsequently processed. Then, based on knowledge of technology, some causes or the course of the accident can be estimated paying a due attention to high-risk parts of the technology.

The following text is based on the description of selected accidents that were collected as typical examples. It is divided into several sections according to the parts of technology where the accident occurred. Descriptions are brief with some information being estimated. Information on measures taken to prevent the recurrence of the accident has been provided for some items; sometimes, measures cannot be stated because of lack of information. Therefore, this information serves more as a warning about high-risk parts of technology. For more details on the measures, see chapter 7. The authors believe that, despite these shortcomings, this knowledge can be applied in technology operation by responsible persons.

3.1.1. Drying tower

- The boiler failure caused the drop of temperature in the drying tower, and milk powder adhered to the walls of the drying tower. A relatively thick layer was formed. After the heat supply resumed, the temperature increased and the dust spontaneously ignited. It is possible to assume that the procedure in the case of failure of the

energy source was likely insufficiently processed. It is appropriate to update the procedure in an emergency plan as a prevention measure.
- Formation of a plug in the fines returning system, self-heating of a plug and a fall to the drying tower.
- The whey supply hose has ruptured. The product with a high water content was mixed with the dried product. Subsequently, the mixture sedimented to the sprayer, walls, and ceiling of the drying tower. The product was heated, the sediment tore off the wall and fell to the tower. The cloud of powder was created and, subsequently, an explosion occurred.

3.1.2. Silo

- The probe of the powder level in a silo has been damaged becoming a fire initiator. The requirement on the expertise of a supplier at installation of these devices is stated as prevention measures by the operator.
- Static electricity has been discharged when the powder is transported to the silo.
- The occurrence of fire in the silo caused by overheating the drive (probably the conveyor drive).

3.1.3. Filtration

- Spontaneous ignition of the powdered milk powder layer in the filter of exhaust air during short-term shutdown due to the product change. The following measures were applied by the operator: installation of additional detachable manholes covers to facilitate the control of dust deposition; staff training; update of emergency plans, checklists of systems of carbon monoxide (CO) sensors calibration.
- A defective ball bearing caused heating of the surface to a high temperature. Particles of milk powder warmed up and then burned. Subsequently, these hot particles caused a fire in a bag filter. The following measures were taken by the operator: lowering the temperature in the drying tower, lowering the thresholds for a temperature measurement (because of an earlier alarm), improvements of an extinction system on the filter.

Note: Hot surfaces are one of the common causes of fire, not only in the case of spray dryer of dairy products. Sensing of critical parts of technology by thermographic systems can be used as preventive measures.

3.1.4. Fluidized bed dryer

- Hot particles formed at spray nozzles fall to the drying tower. Subsequently, these particles initiate the explosion in a vibrating fluid bed dryer.

3.1.5. Cyclone

- The powder escaped to the air when the cyclone was clogged.
- The explosion of cyclone with serious injuries. The explosion was purportedly caused by maintenance works (welding).

3.1.6. Other

- The inside of the conveyor has not been thoroughly cleaned when the sub-contractor worked on the screw conveyor. The dust spontaneously ignited after welding, and the fire spread to the adjacent parts of the technology. Prevention measures can be as follows: update of instructions for hot works including requirements for a thorough cleaning from milk powder and a requirement for the interruption of operation of the equipment for a specified period.

This implies that accidents are associated with activities that are often discussed in the chemical industry. These include a change of management, technology start-up and work of contractors.

Beever and Crowhurst (1989) also give some examples of the causes of accidents. One accident is associated with applying too much lubricating oil to the atomizer wheel. The powder soaked by oil deposited on the underside of the roof of the drier and spontaneously ignited. Another accident is associated with the deposit of powder around the fines-return-pipe, where it has been self-ignited. The self-ignited dust layer was then the initiator of the explosion. The same authors also mention hot particles, friction between moving particles (for example, around an atomizer or rotary valves), electric spark (static electricity - moving powder, spray drying) as sources of ignition of powdered milk (Beever and Crowhurst 1989). This is in line with the information from the database.

In the following chapters, the authors of the paper will describe the processes that can cause a fire, an explosion, or damage to environment. Subsequently, the prevention measures will be described in chapter 7.

4. Fires

From the examples of the causes of accidents in the authors' database, it is clear that the dominant cause of fires is the self-heating of milk powder. The self-heated dust layer has reached such a temperature that the material self-ignites. The self-heating process is often associated with the Maillard reaction. This is an exothermic reaction. The dynamics of temperature increase depends on the possibilities of heat dissipation. If the balance is negative, i.e. the heat production is lower than the heat transfer from the material to the environment, the material will not ignite. In the opposite case, the material may ignite. The heat balance depends on many factors; dominant factors are the thickness of the layer of dried powder and the ambient temperature. O'Mahony and Synnott (1988) state that the rate of the exothermic oxidative process is temperature-dependent in an exponential form.

Various mathematical models were used for determination of temperature versus time. The basis is the Frank-Kamenetskii's theory. Models for describing this dependency are derived from this theory. An example of such a model can be found in Chen (2001).

4.1. Conditions for self-ignition

In the past, the effects of various factors on the self-ignition of milk powder have been investigated. These factors are e.g.: temperature, layer thickness, particle shape, particle size, fat concentration, time to ignition, the effect of airflow on the formation of deposits, etc. Individual factors of self-ignition will be further discussed. However, some selected factors interact and cannot be understood separately. Examples include the minimum ignition temperature and the layer thickness.

4.1.1. Temperature

Ambient temperature has a major impact on the rate of the spontaneous oxidation reaction. Beever and Crowhurst (1989) state that the rate of heat generation is about 1000 times faster at 100 °C than at 20 °C, and at 200 °C more than 100 000 times faster. Another important variable that is influenced by temperature is thermal conductivity. The value of thermal conductivity increases with temperature (MacCarthy, 1985). MacCarthy presents a model describing the dependence of thermal conductivity on temperature. However, the model is limited by the temperature value, which is relatively low, approximately 43 °C. Nevertheless, thermal conductivity has an effect on the temperature rise in the initial stage of the process (Chen, 2001).

An important parameter is the minimum ignition temperature (MIT) value. MIT of the dust layer is the lowest temperature at which the dust layer on hot surface ignites (Barton, 2002). According to EN 13237, this term is defined similarly: "The lowest temperature of the hot surface at which the dust layer will ignite under specified test conditions." The MIT value depends on the dust thickness. According to the technical standard

EN 50281-2-1, dust is tested with a thickness of 5.0 mm. Due to dust deposits (which are difficult to control), the knowledge of MIT values is important also for dust thicknesses larger than 5.0 mm.

Examples of MIT values are given in Table 2 which shows that there is a great variability in these values. It is given by the conditions of the experiment. For the items where the apparatus is not given, it can be assumed that the MIT value has been determined using the method given by EN 50281-2-1 (probably outside Mujumdar, 2006). The method is based on heating of a thin layer of dust on an electrically heated plate. The ambient temperature range is specified by the standard – i.e. 15 – 35 °C. Values by Duane and Synnott (1981) are obtained with the use of the electrically heated oven. It corresponds better to the conditions in a drying tower and other parts of technology.

It is evident that MIT decreases with increasing material thickness. For this reason, it is also advisable to monitor the powder temperature before entering the silo. The highest possible temperature of the powder depends on the type of product and the proposed storage silo dimensions. The temperature of the powder, which may cause self-ignition of stored milk powder, may be significantly lower than the temperatures shown in Table 2.

4.1.2. Layer thickness

As mentioned above, the thickness of the layer is closely related to the heat balance and thus to the potential risk of self-ignition. From the operational point of view, this is a very important parameter that needs to be monitored and, if necessary, the powder layer should be removed.

Beever and Crowhurst (1989) give examples of minimum values of the layer thickness when self-ignition occurred at temperatures of 200 °C and 100 °C (see Table 3). A temperature of 200 °C is assumed to be close to the highest temperature reached in the drying tower. It also reveals that the value of temperature is associated with the time-to-ignition – order of an hour or less at 200 °C and a few hours at 100 °C.

O'Mahony and Synnott (1988) also point out that the size and shape of the tested sample influences the values of critical thickness. The study states that significant differences in critical layer size are at low temperatures (50 °C). It draws attention to the fact that, in the case of the commonly used cube test, extrapolation may lead to errors in the prediction of safe silo sizes for the storage of spray-dried milk powders at temperatures in the region of 40–50 °C.

4.1.3. Fat concentration

Some sources report that some dry milk products are more dangerous due to the higher fat content; e.g. skimmed milk compared to whole milk (Miranda et al., 2013). This assumption is confirmed by the fact that, during the analysis of fire accidents in Ireland over a 10-year period, the same number of accidents was found when drying the skim and fat-filled powders. However, the production of skimmed milk was 10 times higher than that of whole milk (Duane and Synnott, 1992).

Several factors can be considered to cause this. These factors include the effect of total fat content on MIT, higher stickiness of fat-filled powders (this implies a higher tendency to form layers), increased fat content with a high level of unsaturated fatty acids, and protein content in milk.

Table 2
Minimal ignition temperature of milk powder in layer.

Product	Fat [%]	Sample size [mm]	Apparatus	MIT [°C]	Source
Whole milk	27	25 × 25 × 25	Electrically heated oven	177.2	Duane and Synnott (1981)
	–	–	–	375[a]	Miranda et al. (2013)
	–	–	–	330	Beck et al. (1997)
Skimmed milk	1	25 × 25 × 25	Electrically heated oven	181.8	Duane and Synnott (1981)
	–	–	–	200	Mujumdar (2006)

[a] Mean value.

Table 3
Critical thicknesses for self-ignition of milk powders.

Product	Minimum thicknesses for self-ignition at 200 °C (mm)	Minimum thicknesses for self-ignition at 100 °C (mm)	Source
Skimmed Milk	17	170	Beever (1984)
	9	120	Saprygin and Kiselev (1968)
Whole Milk	7	100	Saprygin and Kiselev (1968)
Buttermilk	9	130	Duane and Synnott (1981)
Buttermilk	8	100	Duane and Synnott (1981)

Duane and Synnott (1981) conducted experiments with various types of dried milk products (skimmed milk, buttermilk, etc.) to study the effect of total fat content on MIT and concluded that the dependency was not significant. In another study, Duane and Synnott (1992) again investigated the effect of total fat content on MIT, the effect of the degree of fat saturation on MIT, and the protein content of milk. The authors are in favour of the opinion that a combination of these factors has an effect on the value of MIT.

Chong et al. (1999) state that, as the fat content increases, the activation energy (E) also increases. These authors further state that, at ambient temperatures less than about 180 °C, the tendency to ignite is reduced and the fat content is reduced. The tendency to ignite at higher temperatures became similar for all powders (Chong et al., 1999).

4.1.4. The age of powdered milk

Duane and Synnott (1981) suggest that the age of the powder may affect the MIT value. They reported that the value of MIT of buttermilk tested very soon after manufacture was lower than MIT of the sample tested after a protracted period of storage. Chong et al. (1999) in their study conducted ageing of powdered milk (whole milk and skimmed milk) using a heated oven. Subsequently, they calculated critical thickness parameters based on the measured values. Results of experiments with whole milk supported the findings presented by Duane and Synnott (1981). In the case of skimmed milk, the results of experiments were not provable.

4.1.5. Particle size

The particle size distribution is another factor that could affect the value of MIT. Duane and Synnott (1981) studied skimmed milk samples with a different particle size distribution. The results show some differences in MIT values, but the authors attribute these variances to a different chemical composition of experimental samples.

4.1.6. Design and operation regime of a dryer

The shape of the dryer, the material from which the dryer is made, and the operating regime of the dryer can affect the airflow inside the system. This can lead to changes in the formation of deposits in various parts of the dryer and thus indirectly affect the self-ignition of the material inside the dryer. Ozmen and Langrish (2003) consider that the following parameters may influence the formation of deposits: swirl vane angle, inlet air temperature, liquid feed flowrate, nature of the surface, electrostatic effects, different combinations of surface material and time.

The findings of Ozmen and Langrish (2003) show that the largest settling occurred in the conical section of the dryer.

In their pilot-scale spray dryer, the authors discovered that the swirl vane angle (i.e. flow inside the dryer) has a strong effect on the powder deposition on the dryer walls. Furthermore, the inlet air temperature and the feed flowrate can affect the moisture content and temperature of the particles (Ozmen and Langrish 2003). These authors point to the fact that the sticky-point curve may be an important parameter for monitoring the powder stickiness. In contrast, the use of non-stick materials to prevent the powder deposition has shown to be ineffective (Ozmen and Langrish 2003).

5. Explosions

The number of accidents related to the explosion is significantly lower than the accidents related to fire as is apparent from the authors' database. However, the accidents that are accompanied by an explosion lead to high financial damages (Miranda et al., 2013) and/or injuries, and, in the worst case, to fatalities. The information in the database indicates that the explosion is, in most cases, initiated by a hot particle or by spontaneous self-ignition of the powder layer in the environment with sufficient quantity of dispersed dust.

Table 4 shows the explosion characteristics from various literature sources. The maximum explosion pressure p_{max} ranges from 0.65 MPa to 0.98 MPa. Dust explosion constant K_{st} ranges from 8.3 to 14.1 MPa m·s^{-1}. The variability of these values may be due to various factors, e.g. different measurement methodologies, often not obvious from the sources. Another factor may be a different degree of dispersion of the substance, possibly due to a particle size distribution of the dust sample. From the point of view of the highest value of dust explosion constant K_{st}, it is clear that milk powder belongs to the explosion class St1, i.e. to the lowest explosion class.

6. Leakage of chemical substances

In general, various chemical substances are used in the dairy industry for cleaning-in-place (CIP) (Thomas and Sathian, 2014), e.g. various alkaline, acidic substances, oxidizing agents, etc. These substances commonly contain sodium hydroxide (NaOH), mineral acids, such as nitric acid (HNO_3), and, where necessary, sanitizers, such as sodium hypochlorite (NaCl-hypo) or peracetic acid (PPA) (Feltoe, 2018). These substances are of caustic or alkali nature. Peracetic acid (PPA) is even a toxic substance. When these substances leak from the tanks into the surroundings, employees are particularly vulnerable to inhalation of their fumes. If toxic substances leak out of the plant, environmental damage can also occur.

Two accidents listed in the authors' database are related to the storage of chemicals, both of which were HNO_3. The acid was stored in tanks of 20 m^3 and 40 m^3. In the first case, the acid leakage probably occurred when handling the tank or parts of the tank while, in the second case, it was a fire. The cause of the fire is not clear. These substances are often stored in high concentrations; this is the reason why the attention must be paid to the storage of these chemicals. For example, nitric acid reacts strongly with some substances. Further, mixing an acid with certain substances (e.g. flammable liquids) can release hazardous mixtures of chemicals that may be the cause of fire or explosion. The release of a toxic cloud of nitrous oxides is another hazard.

The case reported from the brewery industry may be a deterrent example. Hedlund et al. (2014) describe the case of unintended mixing of nitric acid with a cleaning agent containing isopropanol, which caused an explosion.

Another danger lies in cross-contamination and the resulting damage to the product by chemicals, but this is beyond the scope of this paper.

7. Measures taken to minimize the likelihood of occurrence and impact of accidents

7.1. Risk assessment

Risk assessment is a basic measure for accident prevention. Under Directive 1999/92/EC, there is an obligation to prepare an Explosion Protection Document, which also includes a risk assessment.

Within the risk assessment prepared in accordance with the above directive, it is possible to use a whole range of risk assessment tools; their selection must be adapted to the complexity of the facility and the level of risks associated with the operation.

Some extended information on the risk assessment procedure can be found in the Non-binding guide to good practice for implementing Directive1999/92/EC "ATEX" (explosive atmospheres) (European Commision, 2005). It refers to a simple method based on the evaluation of the time of occurrence of a dangerous atmosphere. The second approach is to use a database of good practice in the size of protection zones around typical facilities. However, in certain respects, this method of evaluation may not be sufficient.

The last method, especially suitable for complex systems, consists in the use of engineering methods of risk identification and assessment. Such approaches to risk assessment can be found in the literature; for example the study of Markowski and Mujumdar (2004) presents one possible approach to risk assessment in facilities with potentially explosive atmospheres. As a case study, a milk spray dryer is given here. Markowski and Mujumdar (2004) take the risk assessment methodology from the EN 1050 standard (now replaced by ISO 12100ISO 12100, 2011). For this purpose, the currently valid standard ISO 12100ISO 12100, 2011 or even ISO 31000 (2019) can now be used. Similar steps of risk assessment by Markowski and Mujumdar (2004) are also given in the RASE Project (Rogers et al., 2000).

In principle, Markowski and Mujumdar (2004) divide the risk assessment into four steps: system description, hazard identification, risk estimation, and risk assessment. They use the What if/Checklist method for the hazard identification phase. For the risk estimation phase, they propose to use generic data and for the risk assessment phase, the assessment using a risk matrix. This concept is further developed in the studies by Markowski (2006 and 2007). In order to assess the risk in potentially explosive environments, a risk matrix has been developed. Furthermore, the tool exLOPA (or dLOPA) is introduced here, which is the original LOPA tool focused on the environments with a risk of explosion. Designing of the risk matrix is presented in the

Table 4
Explosive characteristics of milk powder.

Product	Fraction [μm]	V_{ev} [dm^3]	MEC [g·m^{-3}]	MIT_c [°C]	MIE [mJ]	p_{max} [MPa]	$(dp/dt)_{max}$ [MPa·s^{-1}]	K_{st} [MPa·m·s^{-1}]	Source
A	–	1000	60	490	50	0.98	–	12.5	Barton (2002)
A	80–110	–	50	490	50	0.654	0.158	–	Mujumdar (2006)
A	45.4	75	–	–	–	0.76	–	11.7	Klippel et al. (2013)
B	–	–	60–150	300–420	>50	0.77	–	10.2	Miranda et al. (2013)
B	46*	1000 (20)	30	–	–	0.75	–	10.9	Beck et al. (1997)
C	–	–	60–150	300–420	>50	0.79	–	14.1	Miranda et al. (2013)
C	88*	1000 (20)	60	520	–	0.86	–	8.3	Beck et al. (1997)

A - Skimmed milk (fat concentration about 1%), *B* - Skimmed milk is expected, but the fat concentration is unclear, *C* - Whole milk is indicated in the source, but the fat content is unclear, *D* - *t*he term milk powder is given in the source, the fat concentration is unclear, * - median values.

studies of Markowski (2006, 2007) without further specification. In general, a qualitative risk assessment using risk matrices presents a certain danger. As a danger, for example, people generally tend to choose values from about the middle of a given range (Smith et al., 2009). This may be the case of assessing the expected severity of an accident. Therefore, increased caution must be exercised when designing the new risk matrices or modifying the already established ones. If this need arises in practice, the knowledge from the following studies can be used (Smith et al., 2009; Duijm, 2015).

In the risk assessment, it is also recommended that the accidents which occurred at the facility in the past should be taken into account. Markowski and Mujumdar (2004) mention historical data about accidents as a necessary part of the System Description phase in the risk assessment document. A review of historical data is referred to as one of the methods of risk assessment, see the document RASE Project (Rogers et al., 2000). The information from Chapter 3 can thus be advantageously used in the processing of the mandatory explosion protection document.

7.2. Process measures

Knowledge of the physical nature of the dried dairy product, its explosive characteristics and a perfect knowledge of the drying process, including the physical conditions to which the material in the drying tower is exposed, are an important predictor of successful mastering of safety management. This will also enable to predict the problematic part of the technology from the point of view of safety.

Chapters 4 and 5 refer to important parameters for safe operation of the milk spray dryer. These are, for example, MIT_c, p_{max}, $(dp/dt)_{max}$, minimum thicknesses for self-ignition, etc. The values given in these chapters are important from the point of view of the basic orientation in the field of control of the drying process of dairy products. However, due to the many factors that affect the explosive and other characteristics of powdered dairy products, it is strongly recommended to determine these properties experimentally. Drying parameters must then be set with respect to these detected properties. Since, in practice, more than one product can be dried in one plant, it is necessary to determine these properties for each product separately.

The main controllable operating parameter of drying facilities is the inlet air temperature. This is no different in the case of dairy dryers. The inlet air temperature can be expected for two-stage drying in the range of approximately 200–260 °C (Westergaard, 2010). A typical temperature distribution in a drying tower for an inlet air temperature of 200 °C is evident in the study of Beever and Crowhurst (1989). Markowski and Mujumdar (Mujumdar, 2006) generally recommend that in the case of a spray dryer or fluid dryer, the maximum operating temperature in the technology should be by 50 °C lower than MIT. With regard to the temperature distribution in the drying tower and, if we consider the lowest temperature of the MIT dust in the air given in Table 4, this recommendation will be fulfilled during normal operation. If it is a question of dust ignition in the layer, it is described in more detail in Chapter 4.

Higher inlet air temperatures mean more demanding operating conditions of the technology. Therefore, reducing the inlet air temperature can be one of the measures to make the operation of the facility safer. However, at the cost of reducing the performance of the technology. According to a record from the database, one of the operators of the skim milk dryer in France took this measure (it was one of the measures) after the fire, when the inlet air temperature was reduced from 250 °C to 240 °C.

7.3. Technical measures

The aim of technical measures is to completely prevent or reduce the impact of the accident on the surroundings, or to warn the operator in time to intervene and avert the accident. Technical measures can be divided into preventive and protective. The aim of preventive measures is to prevent the actual occurrence of fire, explosion or leakage into the environment. The aim of protective measures is to reduce the effects of fire or explosion on workers and technology, if an emergency situation has already occurred.

7.3.1. Fire and explosion prevention

The basic preventive measures used in milk drying technologies are those whose application will (preferably) eliminate the ignition sources. In practice, rather to reduce the likelihood of ignition source occurrence.

One of the major causes of fire or dust mixture explosion in milk dryers is the presence of hot particles. The hazard lies mainly in the high temperature of the hot particle (e.g. see the information on the accident in chapter 3.1). The locations and reasons for the formation of hot particles differ. The database shows that hot particles are formed, for example, upon the contact with overheated parts of machinery (e.g. a damaged bearing), or the particles are separated by a stream of air from the layer where the self-heating process has already begun. Monitoring of critical parts of the technology using thermocouples or thermal imaging systems can be used to prevent the formation of hot particles through the contact with hot surfaces. This measure also extends to the area of maintenance, where the problematic element can be replaced in a timely manner and, at the same time, this saves financial costs due to the unexpected maintenance or increased energy intensity of the operation of the part.

Markowski and Mujumdar (Mujumdar, 2006) also state that hot particles from a heater can also be a potential risk of ignition. As a prevention, they suggest periodic cleaning of the burners or efficient filtration of the intake air.

Other potential sources of ignition are electrostatic discharge, live equipment, hot works (including frictional sparks), or self-ignition.

The database shows that one accident is attributed to the electrostatic discharge. This case occurred while transporting the powder to a silo. The transport of the powder was ensured pneumatically. The powder was probably charged due to mutual friction, and the charge was discharged before entering the silo. There was a slight development of smoke and damage to 500 kg of milk powder. It is not clear from the incident report which conveyor material was chosen. In general, proper grounding of equipment and a periodic inspection of this grounding, or the choice of conductive materials, are recommended.

The electrical devices used are another possible source of ignition. A preventive measure is the obligation to use such devices that are suitable for the given environment. These devices must also be carefully inspected. As stated in chapter 3.1, in one case, the probable cause of ignition was a short circuit of the probe for measuring the level of powder in the silo. Approximately 200 kg of milk powder was burned.

Self-ignition of the powder layer is associated with the formation of sediment. However, a complete sediment prevention is difficult to manage in some spray driers. In the drying tower, deposits of powder are most likely near the roof of the drying chamber and near the conical base (Duane and Synnott, 1981). Beever and Crowhurst (1989), Beever (1984) also refer that wall surfaces may be wet after washing or using incorrect starting procedures. In such circumstances, dust may easier stick to the walls of the device. From the accidents listed in the database, it is also clear that one of the causes of fires is the self-ignition of sedimented layers of dust in the filters. Technical measures against sediment formation are mentioned by Beever and Crowhurst (1989). They mention knocking hammers, vibrators, scrapers, or air brooms. In practice, a manual removal of a layer of sediment during operation can also be encountered. However, this can be considered as an example of an inappropriate method.

In the database, two cases of accidents are also listed as being caused by hot works carried out on the technology. However, measures against emergencies due to hot works are rather associated with organizational measures (see Chapter 7.4).

The installation of methane detectors in the locations where there is a risk of natural gas leakage, such as natural gas combustion sources, can be seen as a preventive measure. Serious natural gas leakage directly in the dryer technology is not recorded in the database. However, the case of an accident of a gas pipeline leading near the dryer technology is described here. A natural gas leak occurred at the compressor station of the wastewater treatment plant. The methane concentration of 10–20%$_{vol}$. was measured. The mixture was not initiated.

7.3.2. Fire protection

Fire protection in milk dryers is provided by a system that is a combination of various elements. The purpose of this system is to prevent the spread of fire in the technology and to warn the operator. The basic elements of a protective system include:

- Control unit
- Temperature detectors
- Carbon monoxide detectors
- Extinguishing system

Increased temperature in selected parts of the technology may signify a spontaneous heating of the milk powder sediment. For this reason, technology is equipped with temperature detectors. Beever and Crowhurst (1989) state that sensitive temperature detectors should be placed at the outlet of the spray drier, and any associated fluid bed driers, and also in exhaust filters and cyclones. The temperature sensor is also placed in storage silos. This sensor is connected to the control room; if the set limit is exceeded, an alarm is triggered to alert the operator of an emergency situation, or the deluge system is directly started. However, the activation of the deluge system is costly and can degrade the product inside the dryer. For this reason, the activation of deluge system by thermocouples using two out of three (marked 2oo3) voting logic is advisable (Feltoe, 2018).

According to the information from the authors' database, it is evident that, if the fire extinguishing system was started, in most cases the fire was effectively extinguished. However, in one case, the fire extinguishing system was not able to completely suppress the fire; probably due to the low pressure in the system. The installation of auxiliary pumps, the installation of an air compressor for the pneumatic control of the fire water valves, and the connection of these devices to the emergency power supply were chosen as measures against the recurrence of this situation.

The self-heating of the milk powder layer is accompanied by the formation of carbon monoxide. The installation of carbon monoxide (CO) detectors is another technical measure. Detectors are placed where there is a risk of dust explosion. As Feltoe (2018) states, one of these places is the area around the spray nozzles. There may be deposits, and spontaneous heating can occur. If the sediment is released, it can create a dust cloud in the drying tower and cause an explosion or fire. Carbon monoxide is released during the self-heating of the milk powder layer. Carbon monoxide sensors measure the difference of CO concentration at the inlet and outlet. Table 5 shows the responses to various CO values as stated by Feltoe (2018).

Table 5
Response to measured values of CO (Feltoe, 2018).

Difference of CO concentration in the air [ppm]	Response
0.5	Alarm
1.0	Controlled shutdown
2.0	Deluge

7.3.3. Explosion protection

In the case of safety features failure, the technology is equipped with explosion protection systems. Explosion isolation, explosion suppression or venting system are used to mitigate the dust explosion in a spray dryer.

Studies of Tamanini (1996) and Miranda et al. (2014) deal with the issues of the venting system in milk dryers. Miranda et al. (2014) compare the design of the venting system according to EN 14491 (2006) and NFPA 68(2007). NFPA 68, 2007EN 14491 (2013) and NFPA 68 (2018)NFPA 68, 2018 are currently in force.

A design of installation resistant to the explosion pressure is also the possibility. However, this measure is not widely used in practice because of high financial costs and design difficulties. The installation should be designed in such a way so that it was not damaged despite the effective explosion pressure relief.

This may occur due to a recoil during the explosion pressure relief. In this case, a deflection of the structure may occur.

7.3.4. Environmental protection

It is a matter of course to ensure the storage of liquid hazardous chemicals against leakage into the environment. Storage tanks of larger volumes can be secured, for example, by a bund, if necessary with the drainage of liquid outside the bund into the collection sump. Storage tanks of small volumes can be secured using steel or plastic containers. It is advisable to provide bunds (or collection containers) with liquid leak detectors for early warning of the operator. The detectors can be autonomous or connected to the technology control room.

In the chemical industry, the issue of the effect of extinguishing water on the environment is also mentioned. In the case of milk drying technology, the appropriate method of drainage of extinguishing water from the extinguishing system, its subsequent retention (e.g. in a retention tank) and disposal (e.g. in the waste water treatment plant) must be kept in mind.

7.4. Organizational measures

Organizational measures to ensure the safe operation of the facility consist primarily in determining the correct procedure for the operation of the facility and its operators and in the permanent requirement to comply with this procedure. Therefore, the organizational measure consists mainly of the following activities:

7.4.1. Plant operation documentation

In particular, the operating instructions should ensure that all risk situations are covered at all stages of the plant life. The operating manual should contain the following: Prestart-up checklist, Start-up procedure, Normal running, Normal shutdown, Emergency shutdown (Mujumdar, 2006). This documentation should be regularly verified and kept up to date. The operating instructions or other operating documentation should also describe special works that pose a significant risk (e.g. hot works).

7.4.2. Marking of hazardous areas

In accordance with the risk assessment, hazardous areas should be marked at the workplace and dangerous activities that must not be performed at the workplace should be specified. Also, in these zones, only equipment and work aids that correspond to these zones may be used.

7.4.3. Protective work equipment

Operators must be equipped with protective equipment in accordance with the risk assessment, such as non-sparking protective clothing. The operator must be informed of how these aids are used and their use must be monitored.

7.4.4. Training and education

Mujumdar (2006) states, for this area, the following organizational measures: apply the general policy in a breakdown case or adequate training of management and employees. It is also possible to mention the creation of a plan for dealing with emergency situations of a general nature for all employees moving in the building and a special document for facility operators. In the case of more complex activities, it is necessary to use staff practical training, which consolidates the correct procedures better than a mere educational training. Employees' knowledge should be checked regularly.

7.4.5. Checking the correct work activities of employees

Managers must regularly check the correct activities of employees, specifically the risky activities, e.g. performing hot works such as welding, cutting, or soldering (Mujumdar, 2006).

7.4.6. Maintenance

A properly set up maintenance system is one of the preventive organizational measures. Maintenance should include both ensuring the good condition of the production equipment and also the functionality of the safety features. Maintenance must be carried out at fixed intervals. As a part of maintenance is also cleaning, particular attention should be paid to the parts of technology where deposits of powder may occur, e.g. filters.

With some parts of the installation, it is not possible to avoid dust sticking to walls, especially in drying towers. If it is not possible to install the technical measures mentioned above, Beever and Crowhurst (1989) recommend adjusting the working intervals in such a way that the device is cleaned before the critical layer is formed. However, some installations have a growth rate of the layer thickness very high. In this case, working intervals would be too short, which could have a negative impact on the economy of operation and life of the installation. This can be solved by various alternative methods; but it is necessary to mention that sometimes they are not appropriate. A manual removal of a layer of sediment during operation can be considered as an example of an inappropriate method.

8. Conclusions

Milk drying installations are not installations where an accident can cause so much extensive damage to life, environment, or property as in the chemical industry. This is obvious also from the authors' database of accidents, where, fortunately, any fatal injury associated with fire or explosion was registered. In most cases, damage to the installation or the product occurred. This entails financial losses resulting from the interruption of operation; these losses may be especially high when important parts of the installation are damaged. If the company is not economically strong, bankruptcy may occur. Thus, it is at least appropriate that, in this area, increased attention should be paid to process safety.

An important outcome of this study is the analysis of historical data on accidents. The basic prerequisite for the analysis of accidents was the creation of their database. The scattered information was thus aggregated and further evaluated. The information presented in the paper can help in the creation of safety instructions for accident prevention in industrial spray drying. The collected historical information about accidents shows that it is most often associated with:

- spontaneous ignition of milk powder, which is gradually deposited in a layer (in filters, drying towers, unloader hoppers, etc.),
- extraordinary shutdown and start-up of technology,
- unusually heated surfaces (e.g. conveyor bearings, overheated drives, etc.),
- static discharge,
- the presence of glowing particles,
- hot works,
- damage to the product line (e.g. due to a material defect).

Therefore, it is appropriate to focus on these areas when setting safety guidelines, procedures and other preventive measures. Some of the areas listed are still being discussed in other industries, such as the issue of hot works, a hazard of heated surfaces or the issue of starting and stopping the operations.

The prevention of accidents caused by hot works has long been enshrined in the national regulations of the individual countries of the European Union. However, accidents caused by hot works are constantly occurring. Nevertheless, since the human factor plays an important role here, they will continue to occur. In order to reduce the risk, consistency in inspection activities and the use of advanced technologies, e.g. thermal imaging systems, are necessary. Manual thermal imaging systems are already financially affordable and can also be used to inspect machinery for maintenance to ensure that some surfaces are not heated and that there is no risk of ignition.

The area of self-ignition of milk powder is specific for milk spray dryer technologies. The conditions for the formation of processes leading to the self-ignition of milk powder and preventive measures against the formation of dust layers are given in Chapters 4 and 7.

Ideal, but unattainable, is a state where layers would not form in any part of the technology. It is clear from the description of historical events that the self-ignition of a layer of milk dust can generally occur when changing the product, changing the process settings or due to an insufficiently performed maintenance. However, in some spray dryers, layers are formed even during a common operation.

Therefore, further research in this area should be directed to the design of devices that are less prone to the formation of milk powder layers and hence to a safer operation. Research can also lead to the development of new predictive tools to prevent accidents. For example, a study by Malafronte et al. (2015) seems to be promising in this area.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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