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Review of Optimized Technologies for Cryogenic Grinding

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*Abstract:-***The production of finest powders of viscoelastic and plastic materials is often very energy consumptive and therefore expensive or even not possible at ambient temperatures. At low temperatures, many materials become brittle so that they can be grinded more effectively. To achieve these temperatures, the materials are presently cooled with liquid nitrogen (LN_2), which is followed by high operation costs. Cryogenic grinding is a proven Technology that is extremely effective, especially for plastics and rubbers, according to Frank Burmester, an engineer with industrial gas supplier Air Products in Germany. But as he pointed out: "Unfortunately, all too often it's put in a box marked 'too expensive'". Now a new independent pilot plant and consultancy service dedicated to cryogenic grinding is set to change engineers' perceptions of this method of size reduction Based at Oberhausen in the Ruhr area of Germany, the facility is run by Fraunhofer Umsicht, a research institution specialising in environmental, safety and energy technology that forms part of Germany's Fraunhofer Gesellschaft. The 2 0 0 kg/h pilot plant, which is equipped with six different mills, was started up on 10 November."This plant is unique – no university or company in the world has such a wonderful facility for cryogenic grinding," said Burmester. Air Products is supporting the project along with several manufacturers of grinding equipment, and Burmester has been closely involved. Notable features, he says, are the use of mechanical refrigeration alongside liquid nitrogen, and a control system based on a neural network. At Fraunhofer UMSICHT, a low-temperature fine-grinding plant in technical scale was erected for research. Investigations for optimisation of cooling equipment resulted in the development of an innovative technology based on cooling technology.With this technology, the usage of LN_2 could be dramatically reduced.The contribution presents some results of our research in the fields mentioned above. A discussion of the new developments compared to the established techniques will complete the presentation.**

Keywords- **cryogenic grinding; lN_2-consumption; cooling of granulate materials; alternative technology; cooling equipment**

1-INTRODUCTION

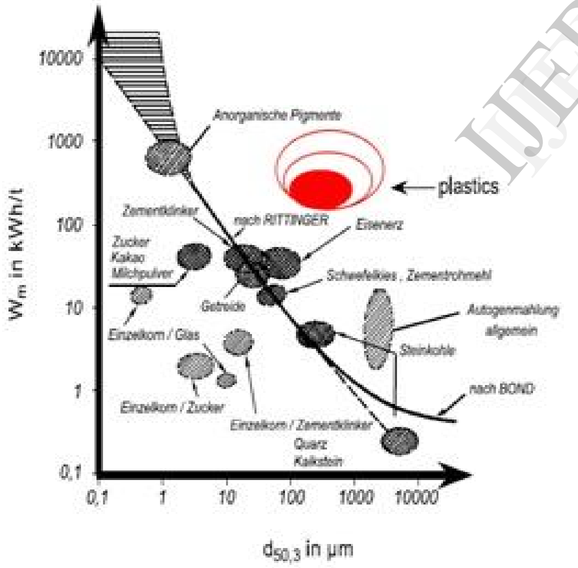
Historically, cryogenic grinding solutions have been used for hard-to-grind or specialist materials, particularly tough materials like plastics and rubbers, and to date have not been widely used in the production of pharmaceuticals and nutraceuticals.However, increased demand for ultra-fine grinding technologies and, in particular, the need to control particle size and maximise yields and throughputs, is encouraging many pharmaceutical processors to review their technological options. We can provide full systems or Component parts, including flow controls, control panels, cooling conveyor and tunnel freezers. Our systems use liquid nitrogen to cool and control the temperature of your product or mill so you can grind more efficiently in an inert atmosphere. They can help you. Increase production rates, improve product quality, achieve finer particle size and more uniform particle distribution, facilitate difficult material separation and prevent explosion. Our cryogenic specialists can help you determine which system is best for your operation based on your current system, the material you process and your goals. Generally the term cryogenics refers to the science of very low temperatures. Though, this is not specifically defined and can be referred to the temperatures lower than 120°K, the boiling point of air (Timmerhaus and Reed 2007) or 100°K (Karassik et al. 2008). Typical cryogens are usually in the form of liquid gases and can be defined as liquid nitrogen (LN2), oxygen, helium (LHe), methane, ethane and argon. However, in machining, sometimes temperatures higher than 100°K are also considered by some authors as cryogenics e.g. cryogenic machining using liquid and/or solid carbon dioxide. The efforts on liquefying permanent gases goes back to the mid-18th century and the development of the first two thermodynamic laws, followed by liquefaction of oxygen (1877), nitrogen, hydrogen and finally helium in 1908 (Kalia 2009, Timmerhaus and Reed2007, Dhokia 2009). The word "cryogenic" was first used by Heike Kamerlingh Onnes in 1894 as an adjective in the title of his paper "On the cryogenic laboratory at Leiden and on the production of very low temperatures" (Timmerhaus and Reed 2007).The early industrial usage of cryogenic technology was limited to the use of liquid oxygen particularly in oxygen-acetylene welding and oxygen furnaces for steel production. The first usage of liquid oxygen for rockets fuels was reported in 1926 in combination with gasoline,followed by the development of alcohol-oxygen fuelled German V-2 rocket during Second World War (Timmerhaus and Reed 2007, Edwards 2003). The studies continued in the United States which led to the development of the Redstone rocket which was first launched in 1953. The successful launch of liquid parahydrogen-oxygen fuelled rockets and the development of thermonuclear bomb and further expansions of the space programmes in the United States led to rapid growth in gas liquefaction industries in the 1950's (Timmerhaus and Reed 2007).

2- THEORY OF CRYOGENIC GRINDING

In the following, the theoretical background of cryogenic grinding and a new technology based on alternative cooling equipment are presented. With the alternative technology, the operation costs during cold grinding will be drastically reduced. At the end, experimental results show effects of the variation of different running parameters.

3-MATERIAL PROPERTIES:

In addition to the target particle size, the specific comminution work is substantially affected by the material properties. This work is 10 to hundred times higher for the comminution of plastic than for minerals see figure



SPECIFIC WORK OF COMMINUTION OF DIFFERENT MATERIALS DEPENDING ON THE PARTICLE SIZE (Rumpf, 1975)

4-HEAT TRANSFER AT A PARTICLE

The heat transfer at particles with a different diameter should be taken into consideration before a calculation of the theoretical lowest demand on lN2 may be performed, temperature field within a particle is the joining of the energy due to the multiply stress of particles that is necessary to achieve the desired particle size. The base of a calculation of a changing balance with the basic law of heat transfer from Fourier Petersen, 1983:

$$\rho \dot{c} p(\partial \vartheta/\partial t)= \Delta\lambda\ \Delta\vartheta \text{.......} \quad \textbf{Eqn (1)}$$

The temperature compensation of a particle could be calculated by knowing the material values ability of heat transfer k, density q, heat capacity cp, and the particle start temperature under the following conditions Schfnert, 1975:

- The observed particle has the shape of a sphere.
- The material values are independent on place and temperature.
- The particle has a homogeneous temperature Ta at the beginning of the calculation.
- The ambient temperature and the heat transfer coefficient between particle and the surrounding area are well known.

If the calculation of a one-dimensional radial heat flow in spherical coordinates is examined, the Eq. (1) is simplified as follow

$$\frac{\partial \vartheta}{\partial t} = \frac{\lambda}{\rho c_p r^2} \frac{\partial}{\partial r}\left(r^2 \frac{\partial}{\partial r}\right) \qquad (2)$$

A temperature shift of the ambient temperature from Ta to Tl at the time t=0 is designed to be a boundary condition for the calculation. By transforming the Eq. (2) to a dimensionless form with the following dimensionless variables, the calculation of the cooling becomes identical to the heating of the particles: standardized temperature:

particles: standardised temperature:

$$\Theta = \frac{T - T_\infty}{T_a - T_\infty} \qquad (3)$$

standardised distance to the symmetric centre:

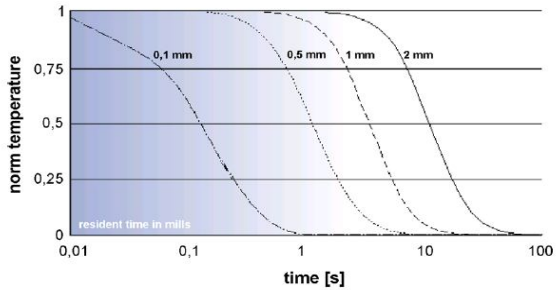
$$\zeta = \frac{r}{R} \qquad (4)$$

dimensionless time (Fourier number):

$$\tau = \frac{\lambda t}{\rho c_p R^2} \qquad (5)$$

This results with the Eq. (2) in dimensionless form in standardized temperature function Ø (r,t) Petersen,1983:

5-NORMAL TEMPRATURE Vs TIME CURVE



TEMPERATURE IN THE CENTER OF A PARTICLE WITH DIFFERENT DIAMETERS

6-CALCULATION OF LN2 CONSUMPTION

The heat to be discharged at cryogenic grinding is composed of heat, which has been introduced by the product (Q˙ feed) and the heat introduced by the drive capacity of the mill (Q˙ mill), provided that the grinding air flow required for the operation of the mill is met by the condensing nitrogen alone.

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{feed}} + \dot{Q}_{\text{mill}}$$

Eqn (6)

The calculation of the heat to be discharged from the grinding material is as follows:

$$\dot{Q}_{\text{feed}} = \dot{m}_{\text{feed}} c_{\text{p,feed}} (T_{\text{in}} - T_{\text{out}})$$

Eqn (7)

Tin is considered to be the inlet temperature of the material, and Tout the temperature at the outlet of the mill. It is necessarily provided that with cryogenic grinding, nearly all drive capacity of a mill is transformed to heat by different processes (particle deformation, internal friction of the particle collective, friction of the particles at processing surfaces,etc.).To simplify, the capacity of the mill was assumed to be proportional to the grinding mass flow so that the energy to be discharged may be described by the following relation:

$$\dot{Q}_{\text{mill}} = P_{\text{mill}} = P_0 + (P_{\text{max}} - P_0)\frac{\dot{m}_{\text{feed}}}{\dot{m}_{\text{max}}}$$

Eqn (8)

The idle performance is represented by P0, Pmax indicates the maximum performance of the motor at maximum mass flow, mmax, and m˙ feed is the present mass flow. The performance data are dependent on the mill used. The cooling performance of the liquid nitrogen comprises the condensation and the sensible heat.

$$\dot{Q}_{\text{lN}_2} = \dot{m}_{\text{lN}_2}\left[\Delta H_V + c_{P,\text{lN}_2}(T_{\text{out}} - T_{\text{lN}_2})\right]$$

Eqn (9)

As a result of combining the Eqs. (6)–(9), the theoretical minimum amount of liquid nitrogen required for the cryogenic grinding related to the mass flow of the grinding material is yielded.

$$\frac{\dot{m}_{\text{lN}_2}}{\dot{m}_{\text{feed}}} = \frac{c_{\text{p,feed}}(T_{\text{in}} - T_{\text{out}}) + \left[\frac{P_0}{\dot{m}_{\text{feed}}} + P_{\text{spec.}}\right]}{\Delta H_V + c_{P,\text{lN}_2}(T_{\text{out}} - T_{\text{lN}_2})}$$

Eqn (10)

In Eq. (10), only three parameters are determined (Condensation enthalpy, heat capacity, and temperature of the liquid nitrogen). Other parameters are to be set according to the material used (such as Pspec, the specific grinding work, cp, feed, and the plant configuration) and may therefore vary in wide ranges. In practice, those plant configurations are usual that allow a refeeding of part of the grinding air into the mill. Considerations including these circumstances and rule out losses merely lead to an increased mass flow by the mill. The energy balance however remains unchanged, because the reefed grinding air has the same introduction and outlet temperature.

7-NEW TECHNOLOGY DEVELOPED BY FRAUNHOFER UMSICHT

The theoretical consumption of LN2 was calculated. Measurements at production plants showed that the real consumption is sometimes much higher than the theoretical calculated consumption. To relate the theoretical to the practical consumption, the efficiency factor glN2 is defined as-

$$\eta_{\text{lN}_2} = \frac{\dot{m}_{\text{theo}}}{\dot{m}_{\text{real}}} 100[\%]$$

At a cryogenic grinding plant in the chemical industry, this efficiency factor varies from 25% to 75%. That shows that there is a demand of optimisation.

8-OPTIMISED PROCESS DESIGN

In addition to increasing the efficient factor by optimizing the operation of conventional plants, Fraunhofer UMSICHT has developed an innovative technology which allows avoiding the use of LN2 partially or completely, depending on the material. This technique is based on the employment of a refrigeration plant. This plant has a cooling power of 40 kWth which is equal to 360 kglN2/h . The heat is transported by a cooling medium, which is still liquid at temperatures below _1008C. This allows to cool the grinding material and the grinding air separately in special heat exchangers down to a temperature of about _608C. For many materials, this temperature is sufficient to become brittle. Should this temperature be not sufficient, the material may be exposed to further cooling in a cryoscrew with lN2.

9-COMPARISON BETWEEN CONVENTIONAL AND ALTERNATIVE COOLING TECHNIQUE

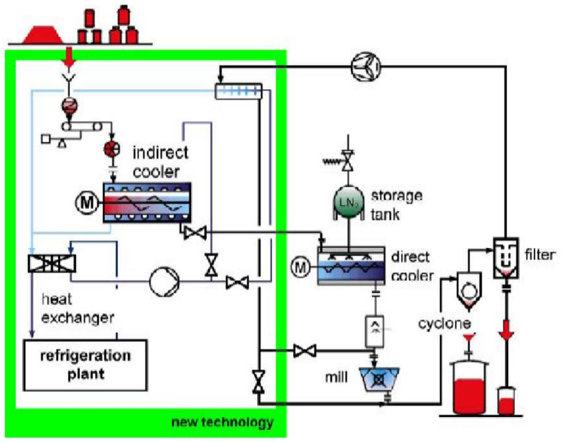
The supply of cold at a temperature of –196ºC is not necessary for many plastic materials. In many cases, temperature levels noticeably above –80°C are sufficient to make plastics brittle. Characteristic for a process of cold generation is the performance coefficient sselmann, 1957:

$$\varepsilon = \frac{Q_0}{W}$$

Q_0 Represents the cold quantity, and W the required mechanical capacity. To be able to compare different cold process to another, these processes have to be related to a reference process. This can be done by the Carnot process, including the performance coefficient ε_c:

$$\frac{1}{\varepsilon_C} = \frac{W_{ideal}}{Q_o} = \frac{T}{T_0} - 1$$

T here is the absolute temperature at which the exhaust heat may be discharged to the ambience/environment and $T_{\circ}$ the temperature at which the cold is generated.



PROCESS DESIGN OF THE CRYOGENICGRINDING FACILITY AT FhI UMSICHT

Fig. 8 shows clearly that a cold amount of thermal Energy (Qth) may be generated at a temperature level of –80°C utilizing one-sixth of energy input compared to a temperature level of –196 °C. The connection between the performance coefficients of the Carnot process ε^C and the parameter of the real process ε is formed by the efficiency factor η Nesselmann, 1957:

$$\eta = \frac{\varepsilon}{\varepsilon_C}$$

This efficiency factor depends on the used cold generation process. The Fig. 9 shows the factor of four different processes (r cold steamT, rPhilipsT, rThomson–JouleT, and radiabatic isothermalT). Plan and cycle in different diagrams of these processes are shown in Fig. 10. With respect to the temperature range between _80 and 0 8C, the cold steam process is the efficient process.In comparison to the use of LN2, the reduced energy input of the alternative cold technology is reflected in lower operation cost. However, the increased investment input for the acquisition of a cold generation plant comprising the necessary equipment has to be considered on the other hand. As a consequence, a plant based on the alternative technology will be cost-efficient only after a certain operation time .Fig. 11 displays the contrasting operational cost/running cost of a plant with conventional and a plant with alternative cold as a function of the amount of hours of operation during a year (h/a) under the frame conditions listed in the box. This plant configuration would yield a break-even point of 2676 h/a, indicating the threshold for a cost-efficient application of the alternative technology. For plants with lower operating hours, the conventional technology is more efficient. The example presented refers to a plant in which the entire cold requirement is met by the alternative technology. For the case that the temperature at which the cold is generated is not sufficient, a combination of conventional and alternative cold technology may be applied. First, the material has to be precooled down to approximately –50°C, and subsequently continued to be cooled with lN2 down to the required temperature. The saving of LN2 may be calculated by a simple energy balance:

$$\frac{\Delta \dot{m}_{IN_2}}{\dot{m}_{material}} = \frac{c_p \Delta T}{c_{p,IN_2}(T_{out} - T_{IN_2}) + \Delta H_{V,IN_2}}$$

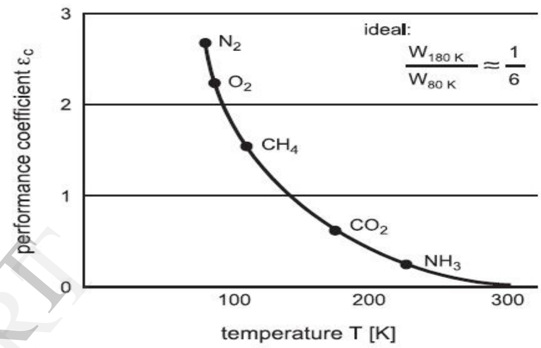


FIG8: PERFORMANCE COEFFICIENT AT DIFFERENT SUPPLY TEMPERATURE

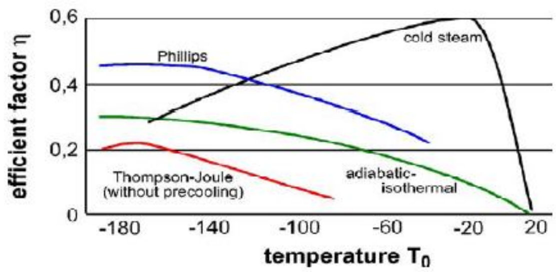


FIG9: EFFICIENCY FACTOR OF DIFFERENT PROCESS (NESSELMANN 1957)

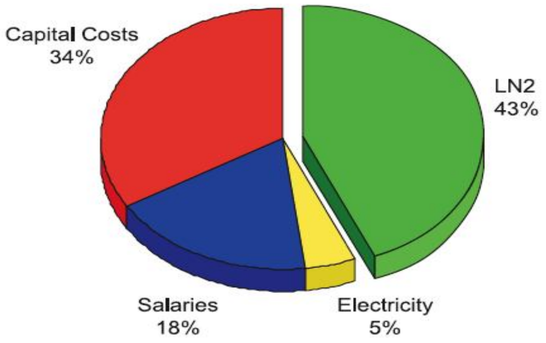
$\Delta \dot{m}$ LN2 represents the saved nitrogen, and DT the Temperature difference resulting from the pre cooling. For a starting temperature of Tout of the gaseous nitrogen to –100 °C and a pre cooling temperature of –50 °C, a saving of approximately 0.5 kgLN2/kg material is yielded only for cooling the material, which material properties are listed in the table of Fig. 5. By generating the cold with the alternative technology, a mass flow of 12 kg/h LN2 per kWth can be substituted. Decisive in this context is the temperature at which the cold should be available.

10-ECONOMIC ASPECT OF CRYOGENIC GRINDING

The utilization of liquid nitrogen (LN2) has undoubtedly numerous advantages in application such as:

- Readily available,
- Easy handling,
- Low technical input,
- Easy control,
- Good heat transition, and
- Inert atmosphere.

11-COST STRUCTURE OF CRYOGENIC GRINDING WITH LN2



12-CONCLUSION

Researchers have tried to control the heat generated at the grinding zone by using various coolants and the lubricants. Liquid coolants have been the conventional choice. They have good cooling and lubricating effects and lead to the improvement in the surface quality. However, their accessibility to the grinding zone and their environmental implication restrict their use. Researchers have also used solid lubricants to enhance the surface quality of the work materials [7]. Cryogenics (especially liquid nitrogen) as coolants do not have any adverse environmental effects.Cryogenic coolant can be directly applied to the grinding zone at high pressure. Cryogenics as the coolants have been used on steels and researchers have observed substantial improvement in the surface quality of the steels along with the reduced grinding forces [8]. Cryogenic coolants serve both as the coolants and as lubricants because along with liquid nitrogen some mist is also formed which surrounds the liquid jet and acts as the lubricating buffer layer in the grinding zone. Ceramics being highly brittle, having very low fracture toughness and poor thermal conductivity cannot be ground with cryogenic coolants. Thermal stresses produced during grinding of ceramics using cryogenic coolants may lead to the thermal shock and eventually surface and sub-surface cracks. Hence ceramics are generally ground without using the coolants. But with the advent of new ceramic matrix composites materials, having better thermal conductivity and fracture toughness, it is now possible to make use of coolants including cryogenics during grinding of such ceramics**.** This research paper experimentally investigates the effect of cryogenic coolant on the grindability aspects of composite ceramic (AlSiTi).Use of cryogenic coolants may lead to better surface quality,reduced grinding forces and higher machining rate.

13-ACKNOWLEDGEMENT

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LIST OF SYMBOLS

α	Heat transfer coefficient (W/m^{2}K)
ε	Performance coefficient (−)
η	Efficiency factor (−)
λ	Material values ability of heat transfer (W/mK)
ρ	Density (kg/m^3)
τ	Dimensionless time (Fourier number; −)
ξ	Standardised distance to the symmetric centre (−)
A	Eigenvalue (−)
c_p	Heat capacity (kJ/kgK)
$\dot{m}$	Mass flow (kg/h)
P_0	Idle performance of the mill (W)
P_{max}	Maximum performance of the mill motor (W)
$\dot{Q}$	Transferred heat (W)
Q_0	Cold quantity (W)
r	Distance to the symmetric centre of a particle (m)
R	Particle radius (m)
t	Time (s)
T	Temperature (K)
W	Mechanical capacity (W)
ΔH	Enthalpy of evaporation (kJ/kg)
ϑ	Particle temperature (K)
Θ	Standardised temperature (−)

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