Powder Research
to Promote Competitive Manufacture of Added-Value Food Ingredients

Strategic Document
for Research in Food Powders

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Project Overview

Background

This project is the result of a project funded by the EU Commission through an Accompanying Measure. The focus of the project is to highlight industry problems, knowledge barriers and research and development opportunities in relation to food powders. It will highlight the priority research needs for development of new and improved powder products and processes. It is envisaged that this will act as a necessary step in **fostering the potential for future research ideas and collaborative research**.

Objectives

The specific objectives to achieve were:

- to outline research and development needs and opportunities in terms of:
    - industrial problems with handling, processing and production of safe, high quality food powders that require further targeted research initiatives;
    - areas requiring further science and engineering knowledge so that this can be applied in the development of new and more efficient processes to produce added-value food powders that are safe and of high quality;
    - new and emerging food powder technologies requiring research and development.
- to promote the creation of a sustainable network of excellence in the area of food powders.

These objectives were achieved by:

- obtaining the views of many individuals actively working with powders.
- implementing a Workshop to create dialog on food powder production, handling and processing, whereby a number of people were invited to participate, who are actively involved in this area throughout the EU, from Industry, Research Centres and Universities;
- disseminating the findings among the scientific and industrial community.

Organisation

Co-ordinators

The principal partners who co-ordinated the implementation of the project were Dr. John Fitzpatrick from the Department of Process Engineering at University College Cork Ireland (UCC) and Dr. Lilia Ahrné from the Swedish Institute for Food and Biotechnology (SIK).

Management committee

The management committee consisted of the two co-ordinators and the following members:

Professor Fernanda Oliveira, Head of the Department of Process Engineering, UCC, Ireland
Professor Thomas Ohlsson, Head of Environmental and Process Engineering, SIK, Sweden

Scientific committee

The activities of the project addressed six different areas, and each area had a leader selected on the basis of experience and competence in the subject. The scientific committee consisted of the two co-ordinators and the area leaders listed below:

Area	Leader
Quality and safety Powder production	Dr. Peter Lillford formely of Unilever Research, U.K.
Powder mixing and agglomeration	Professor Karl Sommer Technical University Muenchen, Germany
Other added-value technologies	Professor Koen Dewettinck Ghent University, Belgium
Powder storage and transport	Richard Farnish Wolfson Centre for Bulk Solids Handling Technology, U.K.
Powder characterisation	Dr. Sivert Ose Tel-Tek, Norway

Implementation

The main steps in implementing the objectives of the project consisted of:

- Holding of a workshop on food powders
- Creation of strategic document for research on food powders
- Dissemination of the output from the project

Workshop

The objectives of the workshop were:

i) To assemble together a mix of individuals from industry, research centres and academia throughout Europe who were working with or had an interest in food powders. This gathering could act as a basis for a future network or for future collaborations.

ii) To address the major industrial problems, knowledge barriers and R&D challenges and opportunities in the production, handling and processing of food powders

47 participants from throughout the EU attended a two-day workshop held in Brussels in November 2002. Day one consisted of presentations by a mix of participants from industry, research centres and academia on the issues that they believed to be important. Day 2 was led by the area leaders and consisted of five "brainstorming" sessions on each of the five areas mentioned above.

Strategic document

The objectives of the strategic document were to outline the major industrial problems, knowledge barriers and R&D challenges and opportunities in the production, handling and processing of food powders. It is envisaged that this will act as a source of ideas for future projects and collaborations.

The creation of this document involved the development of a series of drafts. Draft 1 was developed from input by the project co-ordinators and area leaders. Draft 2 was developed from input from the workshop participants and many others, particularly those in the U.S. working with powders in general and food powders in particular. This draft acted as the starting point for the brainstorming sessions in day 2 of the workshop. Draft 3 was developed from the output from these brainstorming sessions. The final draft was developed from an appraisal of draft 3 by the participants and many others.

Dissemination

The major outputs of the project to disseminate to a wider audience are the strategic document, the workshop proceedings and information on the participants in the project. The major vehicle for dissemination is by the implementation of the website (www.foodpowders.net)

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Introduction

Food powders – Powder technology and ingredient functionality

The development of formulation engineering concepts in food manufacturing and the demand for diversity in food products has driven a substantial market increase for food ingredients. Most ingredients are supplied in powdered form and therefore powder technology is an increasingly important issue both to food ingredient manufacturers and food producers.

The major reason for production in powder form is simply to prolong the shelf-life of the ingredient by reducing water content, otherwise the ingredient will be degraded and broken down in its natural biological environment. Another important reason is simple transport economics as reducing the water content reduces the mass and thus cost of ingredient material to be transported. Overall, the major function of the powder form is to maintain the stability of the ingredient functionality until it is required for utilisation, which is usually in some sort of wet formulation. The major functionalities of food ingredients can be broadly classified as:

- physical / chemical: for example, gelation, emulsification, foaming, pH control.
- nutritional: for example, vitamins, nutraceuticals.
- organoleptic: for example, colour, taste, smell, texture

There are a multitude of food ingredients available with a whole variety of different functions, and there is huge scope for R&D into investigating new ingredients, and new and improved functionalities. ***As the role of the powder form is mainly to preserve this functionality over time and to deliver it when required, the focus of this work deals with the powder issues and not the different ingredient functionalities.*** In addition to maintaining the stability of ingredient functionality from production right through to final powder application, other powder issues are also important in delivering the powder. These include the ability to handle and transport ingredient powders, prevention of powder contamination with undesirable organisms or chemical components, dust problems, dust fire and explosion hazards, allergy problems, creation of desirable powder particle properties, and the ability to dissolve these powders when required.

Food powder handling and processing consists of a variety of operations including powder storage, transport, mixing, mixing with liquids, particle size control, particle separation, coating. It also concerns the properties of particles and powders and how this affects their bulk behaviour. An understanding of the properties and processing characteristics of these powders is an essential requirement in process design, process performance improvement and troubleshooting. There have been significant contributions from various researchers over the past hundred years in powder handling and processing technology. However, knowledge of powder processes is far behind that of liquid processes, and there remain a great many practical problems that current methods cannot address effectively.

There are a number of process technologies applied to food powders to impart properties to a powder that gives it added-value, in terms of improving the shelf-life of the stability of the ingredient, controlling its release, and improving the final application of the powder. These include particle coating and particle size control. Particle coating technology is now increasingly being considered by the food industry to produce a wide variety of encapsulated versions of powdered food ingredients and additives, such as preservatives, fortifiers, flavours and spices. The edible coatings serve to preserve the functionality of the ingredients over time and to control when and how the ingredients are released for their desired function. Superior product quality can be achieved by manipulating the particle size through size-reduction, agglomeration and sieving. For instance, agglomeration can improve mixture quality and reduce segregation, reduce dust formation problems, improve ingredient sinkability in liquids.

Another issue of critical importance in relation to food powders is powder safety. This involves prevention of contamination with undesirable organisms and chemical components in the raw materials, during production and right through to final application of the powder. There are plenty of methods and procedures available to eliminate most contamination risks, however this requires constant monitoring and strict implementation of procedures. In a production process that is designed to current Good Manufacturing Practices (cGMP), where for example, ledges are minimised, there is a reduced risk of dust layer formation and consequently a reduced risk of contamination and secondary explosion. In addition, with good segregation of product and personnel flows, there is a reduced risk of contamination.

Identification of problems, knowledge barriers and research challenges and opportunities

When looking at the processes involved in going from powder production to its final application, they can be broadly divided into the following two categories:

1. ***Processes that give powder its properties***, namely
    - Powder production processes
        - Drying
        - Comminution
        - Crystallisation/precipitation followed by drying
    - Mixing
    - Separation
    - Agglomeration/granulation
    - Coating/encapsulation

2. ***Handling and transport processes***, namely
    - Storage (e.g. silos, IBCs, bags, cans)
    - Transport (e.g. feeders and conveyers)
    - Packaging equipment

Category 1 processes have the dominant influence in creating the powder properties that influence the powder's final application. Category 2 processes may influence the powder properties by degrading them or by requiring certain properties to allow effective handling and transport.

To identify problems, knowledge barriers and research challenges and opportunities, it may be useful to look at these categories separately and to generically investigate how research possibilities may come about as a result:

Processes that give powder its properties

It may be useful to firstly look at the applications of the powder (how it is finally applied) and work backwards to the production of the powder. There are not many food powders that are directly consumed by the final consumer in powder form only. Most are incorporated as ingredients into some sort of wet formulation somewhere along the chain before being finally ingested by the consumer. As a result, ***an important area is research into the technologies and processes involved in addition and mixing of powders to produce these wet formulations.***

Allied to this, is the creation of powder properties that enable these processes to function and that enhance process performance. Examples of the roles of these properties are:

- Enhancement of wetting, dispersion and dissolution of the powder
- Protection of components until they are required for application.
- Prevention of dustiness
- Application of the powder with a specified mixture quality.

From this, ***a major area of research is the investigation of how powder properties influence their roles in forming wet formulations.*** Examples of properties include:

- Particle size and its distribution
- Granule structure
- Hyrdrophopic / hydrophilic behaviour, zeta potential and solubility
- Component stability and internal component protective structures inside powder particles
- Coating properties
- Mixture quality

Some of these properties may be difficult to define and measure, thus ***definition and measurement may become research areas that must be tackled before effective investigation of how the properties affect application.***

A further step back from application to powder production is the processes that create the desired powder properties. Thus, ***another major area of research involves the study of these processes, and investigating how raw material variables and process input variables affect the engineering of the desired powder properties.***

As mentioned already, a very important aspect of research for many food powders is component stability, all the way from powder production, through storage, handling and processing right through to final application of the powder.

Handling and transport processes

These processes are primary concerned with safe, consistent and reliable movement of powder in such a way that minimises the degradation of the powder properties. The principle generic research issues include:

- Understanding and solution to problems that inhibit safe, consistent and reliable movement of powder.
- Enhanced understanding of how powder properties and process conditions affect the operation of these processes and how this knowledge can be applied in improving process design and performance. This may also influence the design of process that give the powder its properties.
- Developing enhanced predictive models for application in process design and improvement of process performance.
- Eliminating or reducing the degradation of powder properties caused by these processes.
- Minimising or eliminating residual powder in systems where such residual leads to decay or off-flavours.

Holistic issues of importance

These are issues that are superimposed on what is considered above and include the following:

Health and food safety: These derive from potential sources of microbial and chemical contamination of food powders or how undesirable compositional change of the powder may occur from production to consumption.

Fire and explosion hazards: This is a real issue in the handling and processing food powders because most food powders are flammable and can produce explosions.

Energy efficiency: Most powder operations are not particularly energy efficient, thus there is plenty of research scope for improving energy efficiency or for new process developments that are intrinsically more energy efficient.

Cost of manufacture: Especially for basic foods.

What follows?

As a result of the above considerations, the following six sections were created to gain a more focused insight into typical industrial issues and problems, knowledge barriers and research opportunities in areas that have importance to food powders in particular, and which also are relevant to powders in general:

- Quality and safety
- Powder production processes
- Mixing and agglomeration
- Other added-value technologies
- Powder storage and transport
- Characterisation of powders

Quality and safety considers some of the quality issues from powder production to final powder application along with safety issues in terms of food safety and fire/explosion safety. The next 3 sections deal with processes that give the powder its properties and also with wet formulation processes where powder is mixed into liquids. The next section deals with the storage and transport of powders, and finally the last section deals with powder properties and their measurement, which is of importance in all the previous 5 sections. This document represents the culmination of input from many individuals, a list of whom is given at the end of this document.

Quality and Safety

Quality of food powders

Powders are used mainly as components of wet formulations further processed in factory, as mixtures with other particulates in ambient stable meals, and adhering to other dried structures as colour and flavour components. This section explores some of the quality issues from powder production to final application of the powder, which is mainly in the form of a wet formulation.

Food powder quality may be defined in terms of:

- functionality of the powder when used, such as taste or gelation properties.
- physical properties of the powder, such as particle size distribution and flow properties.
- safety in terms of contaminants.

Industrial issues and problems

Food powders are usually considered as lower value, thus there is great difficulty in adding cost to powders, which has a huge inhibiting effect on innovation and problem solving in food powder production. Technology is limited because extra cost cannot be added in, and as a result, production cost is the driver that is stunting innovation. Many of the processes used today were designed for ingredients 10-50 years ago. There is a need for powder people, ingredient people and marketing people to add more value to powders so as to overcome this resistance to innovation. There is a particular need to market the functionality of powders, and consumers need to be convinced that powders have high functionality and quality. Consumers may be willing to pay more for powders if they can perceive the high functionality and quality of a powder. It should be noted that some food powder products, such as infant formulas, are considered high value.

Food ingredients companies can tailor make their ingredients such that they can give a large variety of functionality, however these ingredients must be used as prescribed by the ingredient company. This effectively ties the user to a specific process and a specific ingredient supplier. Considering the multitude of functionalities, it is important to firstly know what functionality is required and then to target appropriate cost effective ingredients that will give this functionality. It is also important to make the right measurements of functionality and of factors that may affect it.

Ease of powder handling in the factory and in the home, whether it be powder flowability, caking, stickiness, dustiness or reconstitutability are real issues. As more people eat out of home, catering is a rapidly growing business. Powdered ingredients are convenient for storage and stability, and since the consumer never sees the food assembly process, any prejudices concerning the lower quality associated with dried ingredients is removed. Caterers therefore like big packs of powder that they often leave open, and this can give rise to problems of caking, oxidation etc.

Food powder quality incorporates i) drying methods to maintain the “native” state of molecular ingredients, or selective denaturation for specific functional use ii) stability of the functionality of the ingredients in powder form and iii) the suitability of the powder properties for storage, handling and application. In the first case, degradation of the functionality of ingredient components may be problematic during powder production and may reduce solubility, dispersibility and hence subsequent functions of thickening, gelation and surface activity. In the second case, slow aggregation in the dried state can have similar effects, fragile particles are further abraded, oxidative reactions occur, and encapsulated entities can be released. In the third case, the powder properties may lead to problems with dust formation giving safety concerns to handlers, severe plant cleaning problems and even explosion hazards; dissolution and caking giving rise to lengthened process times and poor mixing. Where the product is itself distributed as a dry mix, then segregation and settling of components can occur.

In the specific case of the production of dairy powders, many studies have examined survival of micro-organisms, and in particular thermophilic spore-forming bacteria, however there is little currently known about the inactivation of indigenous milk enzymes during powder processing. Raw milk contains significant lipolytic and proteolytic enzyme activity, and the survival of these enzymes during evaporation and drying, and their stability during dry storage, is not well characterised. The primary requirement in this regard is for clear evaluation of the potential for enzymatic activity in reconstituted or reformulated products made from dairy powders.

Knowledge barriers and research opportunities

This section considers the research needs in terms of how powder production and storage/handling influence the quality attributes of food powders that affect component stability, powder handling characteristics, and production of wet formulations.

Stability of ingredient functionality

Due to the biological origin of food powders, a major concern is the stability of components right through from production to final application of the powder, that is, will the components maintain their desired functionality and/or nutritional quality when finally applied? This leads to the following research possibilities at the powder production stage, for example spray drying, and at subsequent stages during the life of the powder up until it is finally applied, which is usually in the form of a wet formulation:

Stability during powder production:

- Research into formulation technology prior to drying and the role of excipients in maintaining and enhancing component stability.
- Research into the mechanisms of small molecule stabilisation of biopolymers during the removal of water during drying.
- Research into improved and alternative drying, agglomeration and coating technologies that maintain and enhance the stability of components (e.g. low temperature drying).

Stability during storage, handling and further processing:

- Research into factors that affect the destabilisation of the functionality of ingredients in powder form during storage, handling and rehydration.
- Research into agglomeration, coating, encapsulation, and barrier technologies, to maintain component stability and to provide “smart” composite powders for triggered release and targeted delivery.

Powder handling characteristics

Flow characteristics:

The flowability of a powder is an important quality attribute for ease of handling, processing and final application. The chemical and physical state of the components in the powder will influence the cohesive nature, stickiness and caking characteristics of the powder, which will influence its flow characteristics. The powder production process and storage/handling conditions will influence the chemical and physical state of the components, thus this leads to the following research possibilities:

- Research into the fundamentals of how dehydration, in particular spray drying, and storage affect the components and their interactions that affect stickiness, crystallisation, and caking, which ultimately affect flowability. Biomaterials science, for example glass transition studies, are important in providing information of molecular interactions and existence of various phases and phase transitions. Once an understanding of how drying and storage influence the components and their interactions, there is then potential for optimizing drying and storage so as to produce powders with less problematic flow characteristics.
- Research into how composition, location of components and physical state of components coupled with storage conditions (temperature, time consolidation and moisture pick-up) affect powder flow characteristics.
- Research into the production of consistent powder particle size and shape and how this may influence powder flow and other handling characteristics.
- Research into moisture transport through bulk powders.

- Research into finding an effective, food grade, water-soluble and non-E–number anti-caking agent is required. The commonly used effective silica acid powder is not water-soluble and it has to be labelled using an E-number, which is in general not well perceived by the consumer.

Dust formation: The ease with which powders form dust clouds is an important quality attribute as dust formation can lead to health problems, fire/explosion hazards, and plant hygiene problems, as discussed in the next section on safety. As a result, there is a need for standardised tests that be used as an index of the ease with which a powder can form a dust cloud. There is also a need for improved strategies and their implementation for prevention of dust formation.

Segregation: Segregation is an important quality issue for food ingredient mixes, whereby the ingredients demix usually during handling and transport. This problem is particularly severe when there is a significant difference in particle size between the ingredients, for example in case where large particulates are mixed with finer powder ingredients. A difference in particle size causes different mobilities of the particles. Also different densities and shapes of the particles can cause segregation of mixed particles. Once again, there is a need for standardised tests that can be used as an index of segregation tendency. Two new tests for segregation are being developed by the American Society for Testing and Materials (ASTM). There is also a need for a better understanding of segregation mechanisms and strategies that can be used to overcome this problem. Adding of a liquid, such as an oil, to the mix will make the mix more cohesive and will tend to inhibit segregation, however the increased cohesion may greatly reduce flowability and may make the powder stickier and cause it to stick to equipment. Thus solving one problem may only produce others.

Production of wet formulations

The chemical and physical state of the components in the powder will influence the production of wet formulations. The powder production process and storage/handling conditions will influence the chemical and physical state of the components, thus this leads to the following research possibilities:

- Research into the fundamentals of how dehydration, in particular spray drying, and storage affect the components and their interactions that affect wetting, dispersion and dissolution rates in the formation of wet formulations.
- Research into how granule structure affects wetting, dispersion and dissolution rates in the formation of wet formulations.
- Research into the role of excipients in enhancing wetting, dispersion and dissolution rates.

Particle engineering

The above ideas lead to the concept of producing and preserving desirable powder particle structures, that can maintain or enhance stability and functionality, make the powder more friendly to handling and transport, and enhance its ability to form wet formulation while delivering the desired functionality. For example, fat encapsulation in a fat powder, preventing crystallisation in a sugar holding powder, getting the “right” components at the surface of the powder.

Safety of food powders

Industrial issues and problems

Food powder safety incorporates i) risk of biohazard to the user (whether in the factory or at home) ii) contamination of food powders and iii) fire/explosion hazards presented by transport and handling of food powders.

Food powders frequently contain proteinaceous material so that allergic reaction and sensitisation needs to be eliminated or minimised. As more active agents are used, personal hazard from enzyme action, microbial action or accidental dosage of ingredients such as antioxidants or carcinogenic agents must be eliminated.

Contamination of food ingredient and animal feed powders with pathogens, viruses, hormones, pharmaceuticals and other undesirable chemicals is of major concern to industry. This can occur along the whole supply chain from raw materials, through manufacture and in the distribution chain to the final consumer. There are a number of high profile incidents that can highlight the problems and research needs, for example, salmonella in infant formula; pharmaceutical byproducts being mixed into syrup that was mixed into an animal feed supplied to pigs. Occurrence is not frequent, however one high profile case can be very damaging to a company or an industrial sector. Most contamination hazards can be eliminated by i) routine monitoring of raw material and product quality, ii) heat treatment to eliminate pathogens, iii) implementation of HACCP to identify and eliminate contamination hazards within the factory, iv) use of hygienically designed equipment that prevent dead-spots where material can build up, v) proper implementation of wet or drying cleaning protocols.

Dust formation and the aerial spread of powders can be a source of contamination. This must be restricted since the majority stick to surfaces when damp, providing a hard to clean biofilm which may be a source of microbial contamination. One predominant factor that applies to food safety is that of contamination between fresh and aged materials, or between completely different product types. In the operation of bins and silos, an appreciation of flow patterns within the vessel can bring about considerable improvements in both diagnosing and eliminating cross contamination issues. The generation of aflatoxins as a result of inappropriate flow patterns is a prime example in cereal based applications.

Like most finely divided material, food powders can provide a fire and explosion hazard. Dust explosions and fires are pretty well covered and existing knowledge is sufficient for many products to cover most foreseeable industrial requirements. EU legislation (e.g. ATEX) would seem to have this area well covered in terms of legislation. Especially the new ATEX directive (ATEX 137-a, directive 1999/02/EC) that will become effective mid 2003 will have large effects as relevant industries will have to set up explosion safety documents. However, self-ignition of powders in drying installations and filter bag houses is still a severe hazard.

Knowledge barriers and research opportunities

Health issues and dust formation

Allergic reaction: Allergic reaction usually arises as a result of exposure to dust, in particular dusts containing proteinaceous material, although it is probably true to say that most dusts have potential for causing allergy problems even if it is only in a small proportion of a population. Powders containing enzymes have produced major allergy problems in the past and are thus used as a marker for determining maximum acceptable levels for dust concentrations. The law requires continuous monitoring of staff for allergic response. Biohazard from active components requires continuous incorporation into powder design. Current guidelines are set by active enzyme powders, requiring stable encapsulation until their action in the product is required. As other bioactives are developed, including “nutraceutical” additives, some of which will be derived from transgenic material, powder design will require the development of materials and processes equal in sophistication to the pharmaceuticals industry.

Problems with fibrous powders: Another potential health problem associated with dusts is the inhalation of dust particles which possess a fibre shape. This can potentially lead to asbestosis type problems in the lungs.

Contamination of food powders

Dust formation: Dust formation will lead to the deposition of powder on surfaces which can sorb water from the air and support the growth of microbes, giving rise to a potential source of microbial contamination. As a result, there is a need for greater control of dust, and minimisation of dust retention on surfaces.

Sticky powders and cleaning: Sticky powders may stick to process equipment during processing producing crusts, for example in powder mixers. As a result, there is a need to periodically clean the equipment. Wet cleaning may not desirable as it may introduce an opportunity for microbial growth, however there is research potential of using wet cleaning followed by efficient drying. There is a requirement for improved dry cleaning techniques. In this case a sophisticated hygienic design is necessary. There is also a need for a good test for measuring the stickiness of powders, and for determining approaches for overcoming this problem of powders sticking to equipment and forming crusts.

Fire/explosion safety

ATEX directives: The new ATEX directives are a valuable contribution to improved fire and explosion safety, however industry will have to demonstrate compliance with this new legislation. It is expected that many companies will not have sufficient knowledge and expertise, and they may need assistance from research centres and consultants in order to comply with this legislation. In particular, they may not have the associated documentation in place, such as Material Safety Data Sheets and zoning drawings.

Self-ignition: Fires caused by self-ignition of powders in driers and filter bag houses are a real problem, as discussed in more detail in the Spray drying section. There is a need for a greater understanding of self-ignition mechanisms and their control, and for proper sensors to be used as early warning systems.

Powder Production Processes

Spray drying

Industrial issues and problems

Quality issues are of constant concern, in trying to gain a better understanding of how feed properties and drying conditions affect the quality of the dried powder. The main quality issues are component stability or maintenance of functionality during drying and how this will be affected during storage and handling until final application. Sugars, salts, proteins, fats, nucleotides etc. are usually present in food powder products. Due to these, drying behaviour is difficult to predict and often difficult to perform in large dryers. The flow properties of these products cause many problems, and little is known about modelling and controlling these flow properties. Sticking of product to the drying chamber during drying is a problem and leads to product losses and increase of cleaning and effluent costs. Adherence of product in the drying chamber can also lead to fires in drying chambers caused by the ignition of the product. Sticky behaviour during drying and hygroscopicity of these complex products are determined on a trial and error basis. Better understanding of the drying is needed.

Microencapsulation is one approach to maintain component stability, whereby the component of interest is first prepared in the form of an emulsion or suspension. This consists of hydrating and dissolving the coating material to a high solids loading, and adding it to the core material while mixing and homogenising the resulting blend. Upon formation of a fine emulsion or suspension, the mixture of core and coat material is atomised through a nozzle or rotary wheel into the drying chamber. Simultaneously, a heated air stream is supplied to the feed spray in a concurrent or countercurrent way, hereby contacting upon the atomised particles and evaporating the water. The spray drying process results in the production of microcapsules dispersed throughout a filler matrix making up the powder particle.

Drying is an energy intensive unit operation and there is always a need for strategies that can reduce this energy demand. These innovations and their implementation are usually driven when energy costs increase significantly.

Knowledge barriers and research opportunities

Product quality

Effect of drying conditions and feed properties: Drying conditions and feed properties are of critical importance as they have a key role to play in determining powder quality parameters, in particular the stability of ingredient functionality, how the powder handles during storage, transport and processing, and how it reconstitutes when forming wet formulations. Most of the research issues have already been highlighted in the previous section dealing with Quality of food powders.

Microencapsulation of food ingredients: There is a lack of fundamental knowledge to understand how the feed composition and the drying parameters influence the stability of the microcapsules and component within during drying and subsequently during handling and transport. This is once again done by trial and error.

Reduction of cost and optimisation

Control of concentrate leaving the evaporator: Control of solids content or viscosity of the concentrate leaving the evaporator can lead to energy cost reductions. If the solids content is too low, then more energy is required in drying, and if it is the viscosity of the concentrate is too high, this will disrupt the atomisation process and the drying process. In addition, if the solids content of the feed entering the dryer is kept more constant, then the drier can operate at a target final moisture content close to that desired, resulting is less overdrying which saves energy and improves quality. The technology is available to implement this but it is not widely used by industry. Greater uptake by industry would result in cost reduction.

Computational fluid dynamics (CFD) modelling of spray drying: CFD modelling can give an insight into the air flow, particle trajectories, and temperature and humidity distributions in the dryer. This information can be used in selecting air flowrates and patterns that can reduce energy requirements and improve product quality. This technology has been developed and needs greater penetration into industry. CFD software packages that are more user-friendly are under development.

Stickiness, fouling and self-ignition

Stickiness and fouling: How to predict likelihood of product sticking onto the drying chamber and how to prevent this from occurring? Stickiness of carbohydrate containing products is a problem that can be solved by different design of drying equipment.

Self-ignition: Product that sticks onto the drying chamber may self-ignite over time. The product may be experiencing temperatures below its minimum ignition temperature, however the temperature and moisture content may be high enough to favour other exothermal reactions, such as Maillard reactions, that may cause the product to heat up over time until it reaches a temperature that can sustain combustion reactions. At this stage, it will start to smoulder and then it can start a fire or a dust explosion. This self-ignition scenario can also occur in other equipment, such as filter bag houses. There is a need for a greater understanding of these self-ignition mechanisms and how to prevent their occurrence. There is also a need for in-line sensors that can detect volatiles coming from these reactions and give early warning of self-ignition. Sensors for measuring carbon-monoxide have been developed and are already industrially implemented in the dairy industry but sensors for measuring other volatiles where CO is not given off are required.

On-line / in-line measurement and control

From the above considerations, there is a need for the implementation and further development of user-friendly sensors that can effectively monitor the concentrate leaving the evaporator, moisture content of powder leaving the dryer, and volatiles being produced from self-ignition reactions

Dehydration of large food particulates

Industrial issues and problems

Larger dried food particulates, such as dried chicken, carrot or mushroom pieces, are often added to many food powder mixes. These represent the high added-value components of the mix. The consumer's perception of the quality of the reconstituted mix will often depend on the textural and sensory perception of these particulates. This is often poor as modern dehydration technology is not good at preserving textural and sensory properties of larger food particulates. As a result, the product is considered to be of inferior quality and value.

Knowledge barriers and research opportunities

The major research challenge is a challenge that has been around for awhile, that is, how to do a better job at dehydrating biological material so that once it is rehydrated, it will regain its original textural and sensory properties. A new research approach to this old problem is to learn from nature. Many natural systems, such as plants and microbes, can become dehydrated during unfavourable conditions, and can regain their fresh living form when "reconstituted" or when water becomes available. The challenge is to understand how nature does this and to investigate if this can be incorporated into future dehydration technologies.

Comminution

Industrial issues and problems

Eventhough comminution is a common operation in the food industry for reducing particle size, there is little detailed predictive modelling of the performance of comminution equipment. It is also a well-known fact that less that 5% of the input energy in many crushing and grinding operations is used in breaking particles, the rest is dissipated as frictional heating.

Knowledge barriers and research opportunities

Greater understanding and predictive modelling capability: Research is needed to investigate how powder mechanical properties, breakage mechanisms and milling parameters affect the change in the particle size distribution during milling. At the same time, there is a need for defining and measuring particle properties that can be used for predicting the mill performance. Potential methods to solve these problems are population balances with breakage kinetic models, possible combined with discrete element modelling of comminution processes to obtain kinetic co-efficients. There is also potential for applying computational fluid dynamics for air-based milling operations.

Development of more energy efficient mills: Grinding and crushing operations commonly used in the size reduction of food materials are very energy inefficient. Thus there is plenty of scope for developing size reduction mechanisms and equipment with enhanced energy efficiency.

Powder Mixing and Agglomeration

Mixing of powders and liquids

Industrial issues and problems

Mixing of powders and liquids can be classified into 2 categories. The first category is where powder is mixed with the liquid based material to form a wet formulation, usually as a dispersion or solution. These processes are of major importance as they represent the final application of most food powders. The rate-limiting step is often the initial step of wetting the powder with the liquid, and this becomes more problematic as solids concentration increases in solution or dispersion. Energy requirements may increase exponentially at higher solids concentrations, and thus mixing system design to minimise energy requirement can be very important.

The second category is where the liquid, which contains an ingredient, wets the surface of the powder particle and, in so doing, attaches the ingredient onto the surface of the powder particle. This is basically a coating operation to produce a mix. It is usually done by contacting a fine spray of liquid droplets onto the particles. In this category, obtaining a uniform "coating" of the liquid ingredient may prove challenging especially as liquid/powder ratio decreases. Specification and position of spray nozzles is challenging. With liquid addition, the material may become stickier and stick onto the equipment, giving rise to crust development within the equipment which is undesirable. Agglomeration may also occur, which maybe desirable or undesirable and controlling it is another challenge.

Knowledge barriers and research opportunities

Mixing of powders into liquids to form solutions and dispersions

Wetting rates: There are many types of commercial mixers for mixing powder in liquid with different wetting mechanism, for example, sinking by surface addition of powder and venturi mechanisms. There is plenty of scope for investigating and comparing different wetting mechanisms and how they behave as more powder is added to a given amount of liquid, for example, how mixer system design affects wetting rate and specific energy requirement. This research can lead to designs with improved wetting rates and reduced energy requirement. It may also lead to new and superior wetting mechanisms. Another important dimension to improving wetting rates lies in modifying the physical and chemical properties of the powder.

Dispersion of a small proportion of liquid throughout a powder: A good example of this is liquid conching in chocolate manufacture whereby molten cocoa butter has to be distributed throughout a fine powder. This is a long energy intensive process. There is scope for research into finding more efficient ways of liquid / particle contact, and in establishing a "thermodynamic" minimum energy requirement for doing a given job. A deep understanding of the influencing parameter of the suspension rheology is necessary.

Mixing of powder with liquid by surface wetting of powder with fine liquid droplets

Design and modelling of contact processes between particles and liquid droplets:
There is a need for improved understanding and modelling of contact processes between powder particles and liquid droplets so as to aid in the design of processes that can give a more even distribution of liquid throughout the mass of powder particles. This requirement applies equally to granulation processes, coating processes and even the conching process mentioned above. There is also a need to investigate the fundamentals of liquid / powder particle contact, as this may suggest new more effective and efficient methods for liquid / powder contact that could result in new mixers, granulators, coaters and conches.

Stickiness, crusting and cleaning: The contacting of a small fraction of liquid with powder may result in making the powder stickier. As a result, there is a need for a test that can measure stickiness and that can be used in assessing whether or not the sticking of powder to equipment is going to be a problem. If a powder sticks to equipment, it may gradually build up as a crust, which will require periodic cleaning. Food powder processors are reluctant to use regular wet cleaning in a dry powder plant because it may lead to microbial growth if not properly dried, thus dry cleaning is preferred. From this, there is scope for research and development into improving dry cleaning operations.

Dry powder mixing

Industrial issues and problems

Dry powder mixing is a very common operation in the food industry. Ingredients may be mixed and packed for sale, or individual ingredients may be purchased and mixed by a processor prior to inclusion in the manufacture of a food material. Industry issues include the following: "Which mixer is most suitable for the mixing job in order to attain the required mixture quality?". "How to define mixture quality, how to measure it, and is there an "easy way" of doing this?". "What is the minimum mixing time required to do the job and what is the minimum energy requirement?". "What is the tendency of the mixture to segregate and how can this be overcome?". "Can any powder properties be measured that would give an insight into mixer performance?".

Off-line or in-line sampling is necessary to measure the mixing quality. The answer to the questions "What is the right sample size?", "How many samples have to be taken?", and "Where have the samples to be taken?" are of critical importance. Some may argue that in most powder mixing processes the mixing time and the energy consumption are not of relevant importance. Much more important are the questions "Are there any dead zones in the mixer?" or "Is there a tendency of demixing?". This is strongly influenced by different mobilities of the mixed components, which depend on the powder properties. Therefore it can be often stated: "If the powders are mixable, then every kind of mixer can be used, the choice of the right mixer becomes important when the mixing of the powders is problematic!"

Knowledge barriers and research opportunities

Sampling

Mixture quality is the main quality parameter of dry powder mixing, thus its definition and measurement are crucial. Sampling of the mixture (sample size and representative sampling of the mix) has a critical role to play in the determination of mixture quality. With regard to the physical implementation of taking samples, there is a need for improvement in powder sampling techniques. There is a need for development of powder samplers that can take different size samples with minimum disturbance of the powder mix. Some good work has already been done on novel samplers but it needs commercialisation. This is an area where industrial practice lags far behind available technology.

Segregation

Segregation or de-mixing is a major problem. Segregation can even be a problem in mixers, whereby overmixing can actually result in segregation. More commonly, the major segregation problems occur after mixing. This may occur during discharge or during transport and handling. The problem mainly occurs when there are differences in the mobility of the particles caused by different sizes, densities or shapes. The bigger the mobility difference, the greater the problem. This is a major problem with food mixes that contain bigger dried particulates mixed with powders, which may easily segregate during transport and handling after mixing. As a result, there is a need for measuring segregation tendency to give an index of the problem, a greater understanding of segregation mechanisms, and procedures for trying to overcome these problems.

Mixer selection and performance prediction: a knowledge-based approach

Expert systems could be developed for traditional mixers, whereby the knowledge of experts in mixing could be harnessed in a software package to predict the performance of a given mixer based on powder properties and mixture quality requirements. The system could also select which mixer, if any, is most suitable for a given job, and make comments with regard to the segregation tendency of the mix.

New Mixers

Traditional mixers, such as tumblers, ribbon, plough-share mixers have been around for a long time. There is a need to further investigate the fundamentals of the mixing of powder particles, which may suggest new more effective and efficient methods for their mixing. This could result in new mixer designs with shorter mixing times and reduced energy requirement to achieve a specified mixing job. For example:

Development of truly chaotic mixers: Traditional mixers have a periodic motion in which particles are pushed in given directions. In a truly chaotic design, the direction of particle movement would be random and this could lead to reduced mixing times and energy requirement.

Continuous mixing

The result after batch mixing is often good, however the subsequent process stages of emptying, transport, storage and packing offers a substantial chance of segregation and this may result in demixing. Continuous mixing offers advantages over batch mixing and requires considerably less space. Continuous mixing can reduce storage requirement in silos, segregation can be limited because the product can be taken directly to the next processing stage, lower potential risk (e. g. explosion) caused by a smaller hold up, and less cleaning requirement in continuous production. However, there are downsides to the technology as well, mainly the requirement of more elaborate feeders and control systems. Continuous mixers can do a good mixing job, but their effectiveness depends on being able to precisely control the feed rates of the ingredients to be mixed. Nowadays the control of feed rates is not such a big problem as there are now very good volumetric feeders. In the past, a lot of work has been done to improve the long-term dosing constancy and this problem is solved satisfactorily. In addition, the short-term dosing constancy of volumetric feeders can be improved tremendously by using star or rotating star attachments for the standard dosing tube. With experiments and calculations it can be shown that the average residence time of the particles in the mixer related to the period length of the entering mass flow fluctuation is the main influencing parameter of the mixing quality. For this reason more work has to be done to examine the parameters influencing the average residence time. The in-line monitoring of the mixing quality, especially for sticky products, is a big problem. As a result, there is a need for research on control systems and in-line monitoring of mixing quality.

Modelling

Design models for mixing: Predictive modelling using measured powder properties useful in process design is currently not a reality. In comparison to distillation, dry powder mixing is at the pre-McCabe-Thiele analysis stage. Thus, there is plenty of scope for basic research into developing models to predict mixture quality obtained in a mixer using powders with known powder properties.

Discrete element modelling (DEM): DEM has good long-term potential, bit it is currently (and will be for a long time) limited by computational resources and the connected need to use simplified models to describe interactions between complicated real powder particles. Besides the fact that many are still dubious whether DEM will ever be a useful quantitative and predictive tool, considerable progress has been made in the last number of years to describe the complexity of real powder systems, including novel models for segregation and mixing. Nevertheless, there is a considerable challenge for comprehensive contributions from DEM.

Segregation kinetics: Despite almost one hundred years of research, little is known about this, and it represents a barrier for the development of more effective technologies for powder mixing. Stochastic models as well as DEM simulations allow a limited insight into the local segregation dynamics, but in order to describe industrial devices, these local, “microscopic” results have to be generalized to macroscopic models in the framework of a multi-phase continuum theory. Progress has been made in the last years using kinetic theory for rather rapid flows, paralleled by DEM simulations and verified by low-gravity experiments.

Mixing of cohesive powders

Mixing of cohesive powders is made difficult because of the large inter-particle forces in the powder, combined with the reduced flowability. A high amount of additional energy is necessary. But cohesive powders have the advantage that they don't segregate when they are mixed. The influence of cohesion makes modelling even more difficult, and some researchers have only started to attack this problem using DEM.

Agglomeration / Granulation

Industrial issues and problems

The major problems include understanding and predicting how process and raw material variables affect granule properties (in particular, its size and structure); how granule properties, especially granule structure, affect its functionality; how to produce granules with the desired functionality. Up to now, progress has been made by trial and error, and this is time-consuming. Scale-up of granulators has not been resolved despite lots of effort in the past.

Knowledge barriers and research opportunities

Structure / functionality of granules

Definition and measurement of granule structure: A granulated material is characterised by its composition, particle size distribution, shape and structure. The structure of a granule is characterised by the 3-D spatial arrangement of its components, or by describing the pore network and where the components spatially lie in the non-pore mass. To investigate how granule structure affects the function of a granule, it is necessary to define and measure the structure of a granule. Porosity measurements have been used as an index of structure, however the pore size distribution, pore location and components lining the pores may prove critical for functions such as wetting and dissolution. No simple methods are available to quantify pore size distribution. Thus, there is scope for research that can quantify granule structure.

Granule structure / function relationships: The major functions of granulation of food ingredients are: prevention of dust formation problems; improvement of powder flowability; prevention of segregation by production of granules from a mixture of ingredient particles; improvement of instant or dissolution properties. The first two are primarily achieved by increased particle size, however the structure of the granule will also have an influence. For example, more compact granules are stronger and less likely to produce dust by breakage during handling; this will also maintain their superior flow properties as less fines are generated. On the other hand, structure may have a primary role in affecting functionality. For example, a more porous structure is required to improve dissolution. The size and structure of this pore network and the components lining the surface of the pore network will have a major impact on the wetting and dissolution properties of the granule. There is plenty of scope for investigating how the granulation process affects the structure of the granules and how this affects their functionality.

Production of granules with "tailor-made" functionality: The main idea for research here is to investigate the production of primary powder particles and granules with granule properties that give superior functionality. For example, the production of primary particles whose surface composition is suitable for dissolution which, when granulated, have a pore structure that is suitable for wetting the powder. This research is concerned with how powder production processes influence particle structure and how granulation influences granule structure. For example, different processes may produce different structures and varying the process variables will also influence structure. In addition, the composition of the components will have a major influence on the structure of the primary particles.

Improved design methodology and new granulators

The mechanisms by which modern granulation equipment operates could be considered to be old technology. Granulation process design is very much based on experience, empirically based, and trial and error. This approach works reasonable well and results in fairly reliable processes. However, there is a lot more scope for research into the fundamental science behind granulation. The result could be the improvement of existing equipment to produce well-designed agglomerates or the design of totally new granulators with superior performance and energy efficiency. Much of the basic science deals with particle / liquid contact, which also applies to coating, mixing and conching operations, as mentioned previously.

Structured granulation: Traditional granulation processes are random with regard to building granules. Are there other granulation mechanisms, which are more structured in determining which particle goes where?

Modelling

Predictive modelling of granulation processes: The present state of predictive modelling of granulation processes is similar to powder mixing, that is, it is in its infancy. Granulation modelling is more complex as it strives to predict how powder and liquid properties and granulator process variables affect granule particle size distribution and structure. Presently, the modelling focuses mainly on the modelling of particle size distribution during granulation. The use of population balances and development of kinetic models to describe particle breakage and growth is one approach used, and DEM is another. This is an active area of research within chemical and mechanical engineering, with direct application to food powders. While granule particle size is an important quality parameter, granule structure is often as important, and this represents an exciting area of research.

On-line / in-line monitoring and control

Like with many other powder processes, this is very much in its infancy and there is much scope for progress. The main quality parameters of granulation are granule particle size and structure. Measurement of particle size for on-line implementation is well development, while structure is not, however a barrier to the implementation of on-line particle size measurement is cost.

Other Added-Value Technologies

Microencapsulation of food ingredients

As mentioned in a previous section, spray drying can produce encapsulated entities dispersed throughout the matrix making up the powder particle. Microencapsulation also refers to a physical process in which thin films or polymer coats are applied to small solid particles, hereby offering the possibility to preserve a substance in a finely divided state, to release it on demand, protect it from adsorbing water or reacting with oxygen. Many techniques can be used to microencapsulate food ingredients in this way. The technique selection depends on economics, core sensitivity, desired final microcapsule size, physical/chemical properties of both core and coating, the release mechanisms, etc. Microencapsulation methods for food powders and particulates include fluidised bed coating, pan coating, co-acervation, spray cooling and chilling, and extrusion. In the development of any encapsulation process, it must not be treated as an isolated process but as part of an overall process starting with ingredient production followed by processes, including encapsulation, right through to liberation and utilisation of the ingredient. Furthermore, a selection has to be made between batch, semi-continuous and continuous encapsulation processes, resulting in a difficult choice for process designers. Cost is often the main barrier to the implementation of encapsulation, and oftentimes, multiple benefits are required to justify the cost of encapsulation. In addition, there is potential for looking at alternative mechanisms of liquid / solid contact that could result in coating equipment that is more cost effective. With the advent of nanoparticle technology, there may be some future potential to exploring dry coating of particles with nanoparticles.

Microencapsulation by fluidised bed coating

Industrial issues and problems

Fluidised bed coating of food powder ingredients has numerous potential applications, such as maintaining component stability, controlled release and protection from water and oxygen, however cost is a major barrier to its application and it is only feasible for high value ingredients that can be fluidised. Continuous operation does offer opportunities to reduce cost.

The current process consists of manufacturing batch by batch a uniform product quality and morphology. The process is characterised by a vast number of input variables. These variables constitute process variables, core material properties and coating material characteristics. One of the major issues is to predict how these input variables will affect coating characteristics, more specifically, coating uniformity and coating thickness. Furthermore, better understanding of the relationship between coating properties and functionality of the coated solids, such as dissolution profiles, is needed. For instance, when using inlet air of relatively low temperature, the effect of changing environmental variables such as temperature and relative humidity may become quite pronounced, resulting in a change in drying capacity, implying changes in film density and porosity, hence changes in release profile. This undesirable “weather effect” can be overcome by dehumidification of the inlet air or by humidification through additional spraying. 98 % of all fluid bed coaters do not need full air conditioning, but cooling only. The cost for inlet air dehumidificaton is about 2 % of the total equipment costs.

Application of a film to a solid is indeed very complex. A pre-set coating thickness is not obtained during a single pass through the coating zone, but relies on many such passes to produce complete surface coverage. During the process, droplet formation, contact, spreading, coalescence and evaporation are occurring almost simultaneously during the process. Certain encapsulation processes will tend to produce low yields of encapsulated product. For instance, in fluidised bed coating, side-effects such as spray drying of the coating solution and particle agglomeration can result in unexpected low yields. In most cases, selection of input variables to produce high quality coated solids will conflict with selected input variables for optimal yield.

There are presently more than 60 European companies which use fluid bed spray coating for the manufacture of controlled release products, which includes a number of food companies. Within the pharmaceutical industry, yields are approaching almost 99 % and there is a number of models available for quite some time. As a consequence, some may argue that there is no major need for better fundamental understanding, but there is a need for different industry sectors to share and better avail of the existing know-how. Interdisciplinary project teams could improve the situation.

Knowledge barriers and research opportunities

Continuous operation: Continuous operation offers opportunities for cost reduction, thus further research into developing this technology could reduce the cost barrier for implementing fluidised-bed coating.

Microcapsule morphology and performance: From a manufacturing point of view, four criteria provide the means of 'tuning' microcapsule performance and release behaviour: morphology, average particle size, particle size distribution and wall thickness (or core/coat ratio). This leads to some important criteria to be considered in microencapsulation processes. Firstly, their aim should be clearly defined. The active ingredient should not deteriorate during microencapsulation while its concentration should be optimized with respect to performance and cost. Core release should be studied and optimized against application parameters (dissolution, pH, temperature, pressure, etc.). Finally, the cost of the polymer coat and the overall microencapsulation process should be justified in terms of improved performance.

Particle size and coating performance: When coating substrates smaller than 100 µm, agglomeration is almost unavoidable because of the nozzle limitations and the tackiness of most coating substances. Another challenge formulators face, is determining how much coating may be necessary to achieve desired finished product performance. As particle size decreases, the amount of coating required to achieve a coating layer of for instance 10 µm, becomes very high. The most stringent raw material requirements are found when sustained release is envisaged. Therefore the use of very thin films (< 5 µm) in development work should be avoided. If, however, performance does not rely on film thickness, but is triggered by other mechanisms, such as pH change, the restrictions on substrate morphology are somewhat reduced.

Improved process understanding: Despite widespread use of microencapsulated ingredients in the manufacture of food products, details of the coating processes are not fully understood. In particular, the 'fine tuning' of microcapsules for optimum performance requires a thorough understanding on the polymer processes involved in microencapsulation. Both real-time measurements and efficient predictive modelling capability will contribute to improved coating process understanding, allowing better process control to be developed. There is a clear need for a better fundamental understanding of phenomena such as film formation and spreading, stickiness and structure changes during processing.

Real-time measurements in process control: Currently several methods have been established to assess particle properties such as particle size, particle shape, coating uniformity and coating functionality. However, these methods require extensive manipulations and can only be performed on the raw and encapsulated product. However, in order to ensure constant output quality in both continuous and batch encapsulation processes, real-time measurements of process parameters is necessary. In real-time measurements, a difference has to be made between *in-line* measurements, where the sample interface is located in the process stream and *on-line* measurements, where the sample is transferred to the analyser automatically. Furthermore, *in-line* measurements can be *invasive* or *non-invasive*, whereby the latter is preferred.

However, new measurement methods, such as laser diffraction or optically based methods, offer the possibility to assess a variety of parameters and consequently, they generate enormous amounts of data. The challenge will be to identify the most relevant parameters in real-time measurements. A variety of data processing techniques can hereby be used, such as neural networks, fuzzy logic or principal component analysis.

The most important advantage of the real-time measurement techniques is that the generated measurement results can be used immediately in process control. The generated data can be used in feed-back and feed-forward based control algorithms and models to ensure constant coated product quality. This methodology could provide the means for a huge process control improvement, compared with one of the first approaches in controlling the thermodynamic operation point of fluidised bed coating processes, consisting of reducing the high number of process variables. The two instruments to manage this are the actual temperature difference within the product and the actual process air volume. The control of the former could be improved by on-line temperature measurements over the whole product bed instead of measuring one product bed temperature. Additionally, the definition of the process air volume (= evaporation capacity) is a weak point, probably because reliable air volume monitoring systems are rather expensive. Secondly, one has to accept that the process air volume through the fluidised bed unit cannot be perfectly controlled by the defined setting of the air control flap only, as the permanently changing pressure difference across the machine (dependent on the relevant filter loads, product humidity, bulk density or eventual clogging of the bottom screen) also results in a permanently varying air volume.

Computational Fluid Dynamics (CFD): The capability of computationally simulating a complex physical process as fluidised bed coating, is maturing, paced by the continual and exponential increase in computer power. Together with the development of high-performance numerical methods, leading to accurate approximate solutions to the governing conservation laws (mass, momentum and energy), this results in the computational means for simulation of coating processes. The gas-solid flow field is usually calculated with an Eulerian granular multiphase (EGM) model, whereby both gas and particles are presented as interpenetrating continua. On the contrary, the atomizer gas-liquid flow field is calculated using a Lagrangian discrete phase model whereby the droplet trajectories are computed individually. The coupling between these two flow fields is an important factor in CFD modelling of fluidised bed coating.

However, several barriers exist to the effective use of CFD. Primary is the requirement for significant expertise on the user's part to avoid the many pitfalls that can compromise solution validity. On the mathematics modelling side, the intrinsic physics, transformation, thermodynamic and heat transfer processes are complicated and completely coupled. To execute a CFD model requires a priori specification of all this to close the mathematical model. Also the singular importance of physics-accurate boundary condition specification should be emphasized. Finally, the validation of CFD models requires the availability of high quality experimental data.

Nanotechnology and nanoparticles

A subject which is gaining more and more popularity and is definitely the new 'buzzword' in industry is nanotechnology. Unique material properties can be expected as the particle size approaches that of molecules and because of this, nanotechnology will become a very important growth area for research.

Industrial issues and problems

Recent times have seen a significant increase in demand for ultra-fine particles, based on nano-particles, for a wide range of manufacturing processes, ranging from the production of pharmaceutical products to the manufacture of electronic components and devices, including also the production of added-value food components. With respect to the latter, knowledge transfer from industrial processes already known and applied in pharmaceuticals and other high-tech products (such as catalysts, microelectronic parts and composite materials) towards the large scale production of special components for foods is a great challenge for the future in food technology and engineering.

As a result, nanoparticle technology represents a most promising field for added-value high-technologies in the food sector. The main potential industrial applications of nanotechnology and nano- (or sub-micron) particles in foods are as follows: producing food components for controlled release of flavours, stabilisation of vitamins and enzymes in food products or animal feeds during storage or processing, taste masking of nutritional supplement etc. Several dozen companies are already engaged in producing nanosized or nanostructured products throughout the world, however only a few of them are situated in Europe, and even less are there dealing with producing food components.

Knowledge barriers and research opportunities

Understandably, nanotechnology represents new major research challenges and opportunities, which will require new and highly skilled techniques and a wide variety of expertise. The application of nanotechnology for foods, even the R&D in this sector, is generally in its infancy now. Therefore, knowledge barriers are quite significant in this field, and it needs a great effort from leading research groups working in developing new solids food processing technologies. There are several university groups and institutes in Europe, who are engaged to this kind of work, but more concentrated activity and co-operation is needed. Research topics include: best available technology to produce micron and sub micron particles from food powders in relation to quality, capacity and consumption of energy, crystallisation on nano-substrates, ultra-fine emulsion crystallisation, agglomeration control in solid generation, spray freeze drying, smart particles with improved surface properties through micro- or nano-coating, developing unique processes producing unusual properties on components of food products, new methods of conveying and mixing (blending powders) of very low sizes or nano-particles with micro-particles. Bulk handling of nanoparticles will be an issue due to extremely strong particle-particle interactions. New technologies must be developed in this regard, e.g. fluidisation, filtration, storage and conveying, micro-granulation etc. It is also expected that nanoparticles in food industries occur in the form of suspensions, which is little understood in terms of stability and transport properties such as viscosity.

Other important research areas include investigation of the role of interfacial aspects with liquid phases in adhesion, dispersion, nucleation, stabilisation; easily deliverable particles for health care, clustering and release of nanoparticles; dispersability in air, in water or other fluids, e.g. in viscous fluids or solid matrix; impact of the release of nanoparticles on the environment; functional surfaces of nanoparticles; and new instrumentation for in-line and off-line measurements of fine particle properties (sizes, volumes, surfaces, morphological parameters, thermal and/or adsorption properties as indicators of size or morphological parameters, surface structure and composition, etc).

The most promising techniques where more concentrated research and development activities should be fulfilled in the near future in food powder processing are: dry coating of micron and sub-micron sized particles, micro-encapsulation by spray drying, spray-freeze drying and spray-freezing, nanocrystallization of food components, spray granulation of mixes of nano- and microparticles. Functionality studies include: controlled release of flavours, vitamins or other valuable components, quality improvement and conservation of valuable components by nano-encapsulation or matrix embedding of nanoparticles, action mechanism of nanosized or nanostructured particles, production of large solid flavour particles with no loss of high notes by agglomeration or/and coating, production possibilities of "interactive beverages or foods" which could change their colour or flavour at will, production of unique formulations from plant and animal materials.

Powder Storage and Transport

Flow out of hoppers and silos

Industrial issues and problems

A wide range of industrial problems can be traced back to the flow patterns that develop within storage and dispensing equipment. Mass flow is the flow pattern of choice for consistent reliable flow, however funnel flow is most prevalent in industry. The major problems that occur are flow inconsistencies and stoppages, caking and lumping during storage (due to moisture migration, plastic flow, mechanical or electro-static phenomena), and segregation of materials (de-blending). Ratholing is very undesirable when dealing with food powders because material can potentially be trapped in the silo for prolnged periods of time. Likewise, a silo operating in funnel flow that is never completely emptied before filling will also have the same problem.

Many of these issues are associated with a lack of understanding of the implications of the flow patterns that develop within hoppers and silos. The occurrence of any one of these problems can result in substantial impact on the bottom line profitability for a plant. In many cases more than one type of problem may be evident. These types of problems are not isolated to any particular type of product, company size or other defining characteristic, but are well documented as affecting virtually all plants that handle dry powder ingredients irrespective of company size (i.e. from SME's to "blue chip" producers). Flowability is not perceived to add value to the product so little time and investment is put into preventing and solving flow problems. The use of equipment featuring geometry inappropriate to the material to be stored or the use of discharge feeders that are inappropriately configured is common, and this reflects the lack of knowledge of this topic on the part of both manufacturers and equipment suppliers. This is a world-wide wide problem.

Design techniques and approaches to eliminate most of these flow issues have been in the public domain for over four decades. A lack of understanding in industry regarding what parameters of particulate characteristics are most relevant to flow, has led to a range of "tests" being developed to assess powder flow. Invariably the techniques employed by persons that are not well versed in the subject are crude and have little bearing on packed bed flow performance. An ongoing requirement for industry is for a simple, repeatable, relevant and cheap test procedure by which materials can be indexed against one another.

The flow properties at low loads for example in small bins and customer dosing systems, are of high potential for food powders and are not well known until now.

Knowledge barriers and research opportunities

More education

A considerable barrier to improvements in product quality and plant performance is the lack of understanding of what is already available in terms of the technology that has been developed over the last 40 years to characterize flow properties and design for reliable flow. Whilst most mechanical, process or chemical engineers will have completed modules dealing with fluid flow, virtually none will be aware of the nuances of powder handling (which is considerably more complex and subtle). The inclusion of a basic introduction to powder flow issues at both undergraduate and graduate level could serve to alleviate many very basic errors made when specifying equipment in-plant. Similarly, a greater awareness within industry that existing operational inefficiencies that are accepted as the "norm" could actually be eliminated or minimised, could result in a greater uptake of the limited number of industrially orientated short courses that are on offer, in order to educate existing engineers. There may also be potential for a European or even world-wide distance learning programme dealing with the storage and transport of powders.

Obtaining more reliable discharge

Utilisation of existing knowledge: As already mentioned above, standard shear testing techniques are already available to help in the design of reliable mass-flow hoppers. Proper implementation of these techniques by those who are designing and specifying hoppers and silos could greatly reduce industrial powder flow problems. The main barriers to the implementation of standard shear testing techniques are a lack of awareness of its existence, the testing is demanding and time-consuming, and it is perceived as an extra cost, however if it prevents future flow problems, then it is very good value.

Simpler flow property measurement: Another major barrier has been the difficulty in measuring powder flow properties using shear testing techniques. It requires trained and experienced personnel to conduct the measurements and the tests can be time-consuming. In addition, there are not many laboratories that can do this work. Over the last decade, progress has been made in achieving more automation so that less skilled personnel can undertake measurements and obtain accurate results. For example, a semi-automatic ring shear tester has been available for some time now, and very recently a new fully automatic ring shear tester has become available. Due to the complex nature of powder flowability, it can be argued that it is unrealistic to believe that a simple quick automated test can be developed to measure powder flow properties that can be applied in design.

There are many empirical tests for assessing flowability, but there is a need to select or develop a standard test that is cheap and simple to use by plant managers and operators and can give an indication of whether or not a powder is likely to have flow problems when exiting a given fixed silo.

Effect of particle properties and storage conditions on flow behaviour: Relating measured particle properties to bulk behaviour is usually just a guesstimate and is often wrong. In fact, if particle properties or storage/processing conditions change, the advice is usually to measure flow properties for the new state. Thus, this is a huge area for basic research to try and obtain a better understanding of how powder particle properties and storage/processing conditions affect and interact to affect flow properties. In fact, many important properties are not measured or not even properly defined. For example, there is very little research into how particle shape affects flowability; in fact, defining and measuring shape is problematic. The whole area of measurement of the surface forces that act between powder particles and how this is affected by consolidation is still very much in its infancy. Basic research into the measurement of interparticle Van der Waals forces, capillary forces and electrostatic effects and how these influence flow properties is required. To further complicate things, changes in storage conditions, such as moisture sorption or change in temperature may influence the surface force interaction. In addition, some physical/chemical changes may be occurring over time, such as crystallisation. There appears to be a need for collaboration between powder people who know about powders and physicists and chemists who know something about surface force measurements. Another key interaction in the flow of powders out of hoppers and silos is wall friction. Similar research to above could be performed to investigate surface attraction forces between the powder and the wall surface. Further discussion on the measurement of surfaces forces is continued in the section dealing with food powder properties and characterisation.

Food powder caking: Susceptibility to caking is important for proper design and operation as this can lead to flow stoppages and unreliable flow. Thus, there is a need for tests that can predict the susceptibility of food powders to caking. Glass transition measurements using DSC can give some insight into the existence of unstable amorphous components (e.g. sugars) that will readily crystallise under the right storage conditions and cause caking problems.

Use of inserts: A considerable amount of silos and storage containers have funnel flow. This is especially undesirable when it relates to food powders. Inserts offer a way to change the flow pattern to mass flow, however there is still many uncertainties relating to the design and placement of these inserts. Some insert techniques have been subjected to analysis and research (inverted cone type and cone-in-cone), while other designs have received virtually no research attention.

Flow promotion devices: Care must be taken when using flow promotion devices, because if they are used incorrectly or for the wrong powder, they may have no effect at all or may even make the problem worse. A considerable literature exists describing various types of devices, mainly written by vendors, however there is little useful guidance provided to select and implement a reliable discharger and how this is related to powder properties. There is a lot of scope for research into determining how powder properties influence the performance of these devices. There is a need for a rough guide on how to select and operate common flow promotion devices based on powder properties and hopper parameters, and to determine whether or not a device is suitable for a given powder.

Effect of electrostatic charging on flowability: Powders may accumulate electrostatic charges and enter a silo as charged particles. Bipolar charging, where particles have both positive and negative charges, may lead to opposite charge attraction leading to greater cohesion. On the other hand, unipolar charging will lead to repulsion between the particles which may increase bulk density and may leading to flooding upon discharge. Research is required to investigate how electrostatic charging affects flowability, and on the factors that influence discharge over time in hoppers and silos, as this problem is more likely to affect freshly filled silos.

Modelling

More accurate prediction of critical rathole diameter: Funnel flow is undesirable, but ratholing is highly undesirable when dealing with food powders, as powder effectively remains trapped in the silo. There are methods for estimating the critical rathole diameter based on measured flow properties, however the estimation is not very accurate, thus there is a need for more accurate predictions. There is an associated need to exploit flow geometry and insert technology to eliminate this phenomenon.

Discrete element modelling (DEM): The advantage of DEM is that the force interactions between all the particles and their surrounding, and the movement of every particle over time is known. However, besides many qualitative insights into the powder flow behaviour, only in the last few years the first quantitative comparisons between DEM and experiments have become available. This is an active frontier of basic research and in time, will help in solving real problems. Assume a silo with billions of particles in it. Instead of trying to solve the limiting problem of computing time by brute force, a more promising approach is to model so-called representative elementary volumes only (with several thousands of particles), which represent typical flow situations at the corresponding positions in the silo. Doing this and applying a micro-macro transition, one can obtain from DEM the flow fields and constitutive relations, needed in FEM models, as discussed below.

Finite Element Modelling (FEM): Several groups have worked extensively with the use of FEM-methods to predict flow and stresses in silos, and obtained promising results. However many of the same problems that relate to DEM, also relates to FEM-models. More specific, the major problem with FEM models is the continuum theory with all its assumptions FEM is based upon. Especially the constitutive relations for cohesive, frictional powders, possibly with a wide variation in sizes and shapes, are mostly still unknown. There is also a problem due to the fact that the parameters of such models are typically not available experimentally. Non-local elasto-plastic theories, or hypoplastic constitutive models can involve even the rotational degrees of freedom of the particles, and astonishing quantitative agreement can be found between laboratory experiments and FEM models in the literature. However, such approaches are typically too advanced for a simple and everyday use, so that further developments are needed to facilitate the use of research results.

Pneumatic conveying

Industrial issues and problems

Pneumatic conveying systems are commonly used for powder transport because the powder can be conveniently transported like a fluid in an enclosed pipe throughout large distances. The main problems are unreliability of operation, degradation of product, wear of lines, dust releases, and poor modelling capability of pneumatic conveying systems, which means that the design is based on guesstimates. Unreliability is caused by inappropriate velocities, poor routing and bends. Product degradation is a serious problem and is caused by high velocities and unsuitable bend geometries. Wear of lines is usually not a major problem with food powders as they are usually not hard enough to cause abrasion.

Knowledge barriers and research opportunities

Design methods in dense phase pneumatic conveying: The development of a technique to enable determination of conveying line performance and pressure drop from relatively small batches of materials remains a highly desirable goal. Similarly an improved approach to "scale up" should be implemented. Achieving both of these objectives would enable a far more economical design procedure to be available for either dense or lean phase pneumatic conveying systems. Modelling dense flow using modelling techniques, such as combined continuum and discrete models (CCDM), may show some future promise.

Monitoring and control: There is a need for non-intrusive in-line measurement of solids mass flowrate and flow pattern for monitoring and control.

Product degradation: Research has been undertaken at a fundamental level with regards to relationships between product degradation and conveying velocity, suspension density and bend radius for a range of food grade powders (rice, sugar, etc.). Further work in this area for a comprehensive range of food grade particulates would serve to enable informed purchasing decisions to be made with regards to conveying line configurations and components. Analysis of the effects of pipe misalignment on pressure drop and particle attrition is also an area where investigative research is required.

Electrostatic charging during pneumatic conveying: Electro-static charging of particles in conveying lines is an increasing problem, as a result of the increasing trend in industry to use very fine, dry particles in processes. Issues of charge decay times and resulting "flushing" of material from storage vessels is a frequent manifestation of this type of problem. The development of affordable techniques for facilitating charge decay would be of considerable use in many industries. Electrostatic charging will inevitably happen during handling of powders. The problems associated with charging are twofold: Unipolar charging which generates to high charge levels, leading to possible hazardous discharges and bipolar charging where powder tends to clog process equipment etc. The basic understanding of why powders charge is on hand, however the understanding about why one batch charge so differently from another is not here yet. This offers a large and very challenging research area, where knowledge about the chain all from process operations to the micro-scale characterisation of powders are needed to obtain the full knowledge about the problem.

Mechanical powder transport technologies

Industrial issues and problems

Many types of mechanical conveying systems are applied within the food processing industries, each of which has its particular appropriate application. Generally, mechanical handling systems (i.e. belts, screws, en-masse conveyors, etc.) are considered robust and reliable. Problems usually occur in instances where a handling system that is incompatible with the material being handled has been installed (usually on the basis of lowest capital cost!), although the issue of material build-up within handling equipment is also quite prevalent in industry (particularly so in the case of sticky or cohesive powders). Chutes (which for the purposes of this document have been grouped as transport) can also give rise to flow irregularities and stoppages in much the same way as silos and hoppers, insofar as the use of inappropriate geometry or wall finishes.

Knowledge barriers and research opportunities

One of the main reasons why plants experience problems with mechanical conveying systems is through the misapplication of equipment. As with all aspects of powder handling this recurrent theme can only be resolved through improved education of end users and suppliers. However, where correctly applied this type of equipment is fairly robust and efficient.

Vibratory conveying is one field that has been identified as offering scope for improvement (although it should be borne in mind that this type of conveying is best suited to coarser granular materials), in particular: flow patterns, operating regimes, flow rate as a function of powder properties and vibration parameters, scale-up issues, prevention of caking using the vibro-method, agglomeration due to vibration etc.

As mentioned previously, chutes can also be categorised alongside vessels and as such the comments in the storage section can be applied with regards to chute applications. In particular the following areas have be identified: flow pattern, operating regimes, flow rate as a function of particle physical and mechanical properties and chute inclination, and scale-up etc.

Characterisation of Powders

Characterisation of powder properties is the measurement and determination of defined powder properties. Powder characterisation is a necessity because of its application in quality assurance, process design, troubleshooting and research. Food powders are powders first and foremost, thus most powder property measurements are of relevance to food powders. Reliable and accurate determination of powder properties is essential to all aspects of powder production.

Industrial issues and problems

In powder systems, there is a vast amount of properties and technologies to measure these properties. Particle properties include size distribution, shape, particle density, composition and internal structure. Bulk properties include flowability, bulk density, mixture quality, segregation tendency, dustiness and rheology. There are also many properties that exist at the interface between particles and between particles and fluid, such as force interactions.

In industrial processes, particle properties directly influence bulk properties, processing behaviour and product quality. Fluctuations in raw material composition, feed rate and process variables will impact on particle properties, which can lead to off-spec. product and equipment downtime. Particle and bulk property measurement is important for a number of reasons. Firstly, these properties are often quality parameters, such as particle size or mixture quality. Secondly, the measurement of key properties can describe what is happening in a process. Thirdly, property measurement is critical for conducting research, to understand how process variables affect these properties and how they in turn affect product quality and process performance. Fourthly, property measurement is critical for good process design whether this is qualitative or quantitative design.

A major source of problems in industry is the problematic day where suddenly things are not working as they should! Common questions include “what has happened to the process or what has changed, can we do any measurements to describe what has happened or what has changed?”. Identification and measurement of key powder properties can give an indication of what is happening in a process when problems occur, and may give an indication of possible sources of the problem. This approach makes good sense, however a problem in industry lies in determining what measurement techniques are available, appropriate and cost effective, which one to select, how to operate it properly, and how to apply the measured values in troubleshooting and solving problems.

Furthermore, measurement of key properties can provide feedback to control industrial processes. An extension of this is the implementation of on-line or in-line measurement in process control, however this is only in its infancy as applied to powders. The benefits of its implementation derive from real-time measurements of key properties that can be applied in better process control resulting in more consistent product quality, improved productivity and cost savings. Many measurement techniques, whether they be of-line or on-line, need to be calibrated in order to output correct results, thus routine calibration needs to be considered and implemented.

Knowledge barriers and research opportunities

From the technical sections above, there is much scope for further developments in powder characterisation.

Sampling

The importance of correct sampling should never be forgotten. If the sample fed to an analysis instrument is non-representative, the result is inevitably wrong. This result may then lead to a faulty product leaving the producer, or other decisions taken that interrupt production. Samples taken with a scoop from the top of a powder heap is often highly inhomogeneous and not suited for measurement. Good sampling techniques should be implemented in the factories. Even when the sampling is correctly done, there exist a number of opportunities for improved measurements.

Standardisation of measurement techniques

There is a large amount of powder properties and property measurement techniques available to measure them, however many properties do not have precise standardised measurement techniques, which makes it difficult to compare results obtained by different individuals. In addition, there are many industry specific standards for defining and measuring properties. Particle size measurement has possibly the greatest standardisation, however many properties do not have a standard method for their definition and measurement. Many powder properties, especially bulk properties, such as flowability, have a myriad of techniques used to measure them. There is a need to short-list or select techniques with the most promise for application of their measured values, and to standardise them. Ideally, it would be nice to have a register of standardised techniques for characterising powder properties (some work is in progress in the American Society for Testing and Materials). This would make it a lot easier to select and use measurement techniques.

Education and training

More education in powder technology, powder properties and their measurement will help individuals gain a greater awareness of measurement techniques and of how to select and apply them. Some measurement techniques, such a shear cell tests for measuring flowability, are difficult to implement, and thus training and maybe even certification should be required of operators.

Property measurements

There is plenty of scope for further developments in powder property definition and measurement.
Oftentimes, one of the difficulties in powder characterisation is property definition, and once the property is defined, then tests can be developed to determine values for the defined property. Some further possible developments are outlined below for some important powder properties:

Particle size: Measurement of particle size distribution is well developed with a multitude of commercial equipment available using a variety of different measuring principles that can measure particle size down into the nanoscale domain. It is a good example of a routine property measurement tool that has become very automated and easy to use. Even with this, there remain a number of challenges, including how particle shape influences the size distribution, and measuring particle size in concentrated systems.

Particle shape: Although particle size analysis is now a common analytical tool, particle shape analysis is still a relatively new technique needing further development. As a result, there is very little research into describing how particle shape affects bulk properties or processing behaviour.

Particle surface properties: In many powder processes, particles are required to move over each other, and their surface force interaction acts as a resistance to flow. The types of forces involved include van der Waals, capillary and electrostatic. In order to study how interparticle forces, coupled with particle size and shape, affect particle flowability, it is necessary to be able to measure these forces. There are some techniques, such as atomic force microscopy, which have potential for contributing to these measurements, however this is a basic research area requiring much work. With these tools, it would be possible to predict how a powder may flow, or how composition influences flowability, or investigate how compaction, moisture content, temperature etc. affect these forces and the powder's flow behaviour. Particle surface composition may be different from average composition as a result of migration of components during drying.

Particle structure: Particle structure refers to the spatial arrangement of components within the particle. Particle structure, whether it be a spray-dried or granulated particle, may have a significant and even tailor-made influence on particle functionality. In order to investigate how raw materials and processing affect structure and how this in-turn affects particle functionality, there is firstly a need for research into the quantitative definition and measurement of particle structure.

Particle strength: Particle strength influences the performance of processes where particle break-down is occurring. In comminution processes, breakdown is desirable, while it is undesirable in handling and transport processes. Quantitative description of breakage models and measurements of particle strength can give an indication of ease of particle breakage, which can be applied in process design.

Properties of nanoparticles: Measurement of properties of nanoparticles is prone to many of the same problems as larger particles, though the small size of these particles makes the problems associated with the measurement even more difficult.

Segregation tendency: Segregation is a big problem in industry and there is a need for standardised techniques for assessing and classifying the segregation tendency of a mixture.

Dustiness: Dust formation is a big problem in industry and there is a need for standardised techniques for assessing and classifying the dust formation potential of powders.

Stickiness: Powders sticking onto surfaces is a big problem in industry and there is a need for standardised techniques for assessing and classifying the stickiness of powders, especially onto surfaces.

Simpler and more automated testing

Many methods are adequate but are operator dependent and require trained operators. The challenge is greater automation and less operator dependence, and reduction in measurement time. For example:

Flowability: Simpler more automated techniques for measuring flowability are needed, as this is one of the areas that cause most process problems. Over the last decade, much progress has been made in trying to achieve this, and there is a great need to transfer the use of this technology into industrial application.

Mixture Quality: Simpler more automated techniques for measuring mixture quality are also needed. Infra-red measurement techniques offer some interesting possibilities for the food powders. However, most of the techniques can only check a surface layer, and segregation/mixture quality in the depth/bulk can not be easily determined.

In-line and on-line process control

On-line and in-line process control is only in its infancy as applied to powders, but the benefits of its implementation can result in improved product quality and productivity. Some of the requirements for the realisation of in-line and on-line process control are outlined below.

Sensors: There are not many measuring techniques that can be used on-line or in-line for powders. Techniques do exist for particle size measurement, moisture content, and composition, and there are techniques that can give an indication of shape, electrostatic charging and flow/transport conditions. This equipment is often highly costly and not reliable enough. There is a need for the development of better on- and in-line measurement methods to improve the control of the processes, and this is a field where the development can move quickly. There exist a number of new and cheaper technologies that can become more commonplace in the years to come. Examples of sensors that may prove useful are acoustic, ultrasonic, NIR, tomography techniques and microsensors for force/pressure measurement. Some methods are indirect and others may only perform surface measurements.

Data analysis technology: The problem for powder technologists may not be in finding sensors but in making more use of the data they produce. This is the role of data analysis and this is the activity of filtering raw sensor data, analysing it and relating it to some key property or properties. Examples of data analysis include chemometric analysis, neural networks and image analysis. This analysis has a pivotal role to play in trying to gain as much useful information as possible out of the sensor data for utilisation in process monitoring and control. An example of current work is acoustic monitoring of pneumatic conveying lines accompanied by chemometric analysis to determine mass flowrate and particle size in line. These analyses could be further applied to multi sensor systems to obtain more useful information for process control.

Trouble shooting industrial problems - contribution of property measurements

There is plenty of scope in powder processing for the identification and measurement of key properties that can be used to describe how a process is performing and for detecting the onset of problems. These measurements could help in researching the effect of fluctuations in raw materials and process variables, which could act as the basis for process control. This work would also help initiate or further develop the role of on-line measurement in process control of powder processes. Chemometric analysis methods provide one solution to detecting when the process might go wrong.

Other Issues of Importance

Reducing energy requirement in powder processing operations

Industrial issues and problems

In industrial particle production and processing, drying is possibly the most energy intensive unit operation, which can and should be optimised. It occurs too often that, for the sake of the operator's convenience, the product is overdried to a moisture content well below that required for shelf-life stability. There are solutions available to overcome this, but are scarcely implemented. In addition, there are many powder handling and processing operations using large amounts of energy, and most are not optimised with regard to energy usage. One example of this is the use of air in pneumatic conveying. Many systems operate at too high airflows something that not only gives higher energy consumption, but also results in more breakage of the particles, and thus reduced quality. Another example is size reduction, where large amounts of energy are needed for the (intended) crushing/and milling of particles.

Knowledge barriers and research opportunities

The main knowledge barrier is the major lack of mathematical modelling capability to describe how energy is being used in many powder processes, which is in stark contrast to operations like distillation where the modelling tools exist to optimise energy usage. There are some exceptions, such as spray drying, where models do exist to optimise energy usage, however these are scarcely used by industry. From this, there is a lot of scope for development of more energy efficient powder processes for doing a given job. This would have a significant affect on making these processes more sustainable by reducing their energy requirement.

Automation

In practise, many of the food powder operations still involve a lot of manual handling. Perhaps it is worth noting that there may be research opportunities in the automation of some of these areas. Exposure of the process to manual input invariably leads to increased risk of contamination as well as dusty work areas.

Packaging technology

This is an important operation in the handling and processing of powders with much scope for R&D.

Utilisation of particle segregation for powder separation

This is based on the idea of withdrawal of particles from a segregated band/core. The withdrawal may result in further segregation and modify the segregation dynamics – this has attracted little attention.

Conclusions and Recommendations

There are a number of important issues that are recurring throughout the above sections. Food powders are powders first and foremost, thus many of these issues are relevant to powders in general, while some are of particular interest to food powders. These are summarised as follows:

Of particular interest to food powders:

Maintaining or stabilising the functionality of ingredients
This is a critical theme for food powder ingredients as many of them will be added to form wet formulations and they will be expected to perform. For example, will the egg white have the same functional performance when dried, handled and rehydrated as it did before it was dried? So, research into maintaining the stability of ingredient functionality during formulation prior to drying, drying, handling, processing and rehydration is key to food powder ingredients. In addition, an important aspect of innovation is research into processes that can protect food ingredients, such as encapsulation.

Contamination
Contamination of a food powder with undesirable bio-life forms and chemical components is a major concern due to direct impact on human and animal health. As a consequence, one high profile case can cause major damage to an individual company and a whole industrial sector. There is a lot of knowledge and methods available that when implemented properly can eliminate most contamination hazards. Problems still exist with dust formation leading to powder settling on equipment, which may provide a growth environment for microbes when contact with moisture exists. In addition, there are problems with sticky powders that may form crusts in equipment over time.

Dust prevention and control
Dust generation can lead to a number of problems for food powders. These can be summarised as follows: i) health problems, in particular allergy problems; ii) contamination and plant hygiene issues due to dust settling and sticking onto equipment; and iii) fire / explosion hazards. As a result, improvement in dust measurement, prevention and control is a major issue when dealing with food powders.

The value of powders
Food powders are usually perceived to have a low quality and thus low value. As a result, low cost production drives powder production and thus there is little investment available to stimulate innovation and change, so the technology tends to stagnate and change little over time. From this, there is a need for investment in powder science and technology in the food industry to help solve recurring problems, improve process efficiency and engineer added-value properties into food powders. Solving problems and improving efficiency will reduce cost and added-value properties will increase the value of food powders. Some of this cost saving and additional revenue can then be ploughed back in to continue the cycle of product and process innovation. Simultaneously, there is a challenge for scientists and engineers to continue to demonstrate that powder education and R&D in the food industry is worth the investment.

Powder storage and transport operations are perceived not to add value to the powder, thus there is little investment into dealing with and solving storage and transport problems. Processors appear to simply live with the problems and do not appear to realise that solving these problems can save a lot of headache and more importantly, bottom-line cost. A major underlying problem is education insofar as many working in the food industry do not have an adequate knowledge of powder science and technology to be able to apply it effectively in the food industry.

Particle engineering
This involves the engineering of food powder ingredient particles that can maintain ingredient stability and functionality, that do not present dust formation problems, that do not present difficult handling and

transport problems, and can be readily rehydrated to deliver their required functional performance in a wet formulation. The major limitation to this type of approach is the low value of food powders and the low cost driven nature of food powder product that stunts this type of innovation. On the other hand, particle engineering is the key to a higher added value of food powders, e.g. by producing products with excellent instant properties.

***Of interest to powders in general, including food powders*:**

Education

Most of the industry people dealing with food powders come from a food science and technology background or an engineering background. Powder science and technology is seldom taught in engineering courses or food science and technology courses. The subject is too important in the practical life of an engineer or scientist for this to be omitted from curricula. Thus, there is a need for incorporation of powders into existing undergraduate and postgraduate education. The world of particle and powder technology should be as important as fluids.

The educational scenario is more complex for practicing engineers and scientists. For those wishing to obtain a greater knowledge of powders, there are a number of short courses available conducted mainly by industry consultants and some academic institutions. The question is: Is this sufficient? or is there a need for more educational opportunities? There may be potential for a European or even world-wide distance learning programme dealing with aspects of powder science and technology. Allied to this is the problem that many practising engineers and scientist do not realise their deficiency in powders or are simply not aware of the educational opportunities or are not given the time and support to pursue them. This can only be overcome by promoting a greater awareness of the importance of particle and powder science and technology, which is definitely making progress with time.

Transfer of existing knowledge into application in industry

Much more attention should be paid to transfer of existing knowledge from universities, research centres and consultancies into industry. In most cases, knowledge transfer, mainly in the form of innovative equipment and system design, is introduced to industry via powder equipment suppliers. Consequently, there is potential for greater synergy between these suppliers and centres of research.

Non-multinational companies/SMEs, in particular, can use much more knowledge to escape from the trial and error approach. There is an enormous amount of wasted time and effort because the same mistakes and problems appear time and time again throughout the process industries. There is a lot of wisdom scattered about that can be applied to solve many of these problems and prevent many of these mistakes. However, the limiting steps are education and knowledge transfer, although the situation is gradually improving with time and with more and more individuals promoting the importance of particle/powder science and technology. Workshops should be organised and software should be developed and distributed at low cost. Two examples of available knowledge that are not widely applied are i) methods for achieving reliable flow from hoppers and silos, and ii) optimisation and control of spray driers to reduce energy consumption, enhance quality and prevent fires.

Standardisation of powder property definition and measurement

In the world of particles and powders, there are many properties and there is a multitude of property definitions and measuring techniques, which may even vary from one industry to another. There is a need to standardise the definition and measurement of these properties. This will help streamline definitions and measurement techniques to those that are most applicable. It will help in obtaining greater reproducibility and also enable greater comparison of work undertaken by different groups.

Fundamental science, modelling and design

Description and modelling of the fundamental mechanisms that can be applied in the design of most powder processes is still very much at an early stage. It is comparable to the pre McCabe-Thiele era in distillation technology. This is particularly true for many common operations like dry powder mixing, mixing of powders and liquids, granulation and coating. Many of them have similar mechanisms taking place, such as particle motion and particle/liquid contact, thus there is potential for cross-fertilisation. There is much scope for progress in this area. Modelling techniques, such as DEM and CFD, are trying to model particle/particle and particle/fluid motions and interactions, however it may take many years before these techniques are useful for design involving real powders, and some are dubious whether they will ever be useful for real cohesive powders. The first step in the modelling of spray-drying has already been taken.

In addition, there is potential for looking at alternative mechanisms that may result in more effective ways of doing things that could lead to the development of new equipment based on these new concepts. For example, the concepts behind most present-day dry mixers have been around for decades. Maybe, there are alternative approaches, such as the application of chaos in mixing that could lead to more effective mixing with less energy requirement. Similar comments could be made for other processes, such as granulation, whereby a greater understanding of the fundamental science may lead to alternative approaches to granulation process design.

On-line and in-line monitoring and control

This is very much in its infancy as applied to powder processes, and as a result, there is a lot of scope for work in this area. The advantages of improved monitoring and control are early warning of problems, reduced costs and more consistent product quality. Presently, there are a number of sensors that have potential for use on- or in-line, however there is scope for the development of on-/in-line versions of existing sensors and totally new sensors. The major challenges for the application of existing sensors are either one or a combination of the following: i) reducing sensor cost; ii) improvement of sensor robustness for real-time operation in a powder environment, and iii) development of data analysis technology that can filter the sensor output and convert it into useful information for control. There is also potential for utilising multiple sensors coupled with appropriate data analysis for implementation in control.

Nanoparticle technology

Nanotechnology is gaining more and more popularity throughout industry. As a result, nanoparticle technology represents a new promising field of application to food powders, although current research and development is very much in its infancy.

Energy efficiency

Most powder processes, and in particular drying and comminution, are not very energy efficient. A major reason for this is a lack of fundamental understanding, modelling capability and industrial awareness that could be applied in optimisation. An improvement in the fundamental science, modelling and application to design coupled with improved on- and in-line monitoring (e.g. model predictive control) will give opportunities to improve energy efficiency while ensuring product quality.

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