NOVEL CONCEPTS FOR TEACHING PARTICLE TECHNOLOGY

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Particle technology is an interdisciplinary subject dealing with disperse systems, including all types of solid particles (aerosols, suspensions), liquid particles (droplets, emulsions), and gaseous particles (bubbles). The main focus of our current research and curriculum, however, is on solid particles.

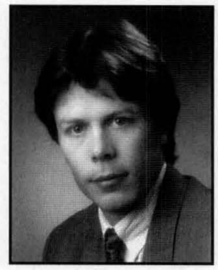
The goal of particle technology is producing and handling disperse materials under economical and ecological constraints. The materials are produced due to a surplus value of the product properties. Typical examples for these properties are the taste of chocolate, the color of pigments, the strength of concrete, or the electrical properties of semiconductors. Consequently, this is also a key point in our curriculum.

In order to prepare a young engineer for his possible tasks in industry and research, we have organized the curriculum to reflect the structure of the field (see Figure 1). The field can be structured generally in four levels. The first and most fundamental level covers the elementary processes, *i.e.,* the physical fundamentals. They include the statistical foundations of particle technology, multiphase flow, bulk mechanics and powder flow, interfacial phenomena, and the interactions of dispersed matter with electromagnetic radiation. On the second level, we apply the fundamentals to machines and unit operations. In our curriculum, we concentrate on separation processes, further strengthening students' capabilities in multiphase flow phenomena. The third level considers whole processes. Here, we teach the concept of product engineering, *i.e.*, how to tailor product properties. Consequently, we have a close link to the applications, which are actually very broad:

- Materials science (*e.g.*, all ceramics manufacturing is in fact applied particle technology)
- Life science (*e.g.,* proteins may be treated as small particles in some respects, drug delivery)
- Information technology (*e.g.,* quantum dots, clean room technology, chemical mechanical polishing)
- Environmental engineering (*e.g.*, particle separation)

How can the new areas be included in the curriculum without disregarding the conventional ones? In our opinion, the only answer is that teaching the fundamentals is even more important, but the examples given to the students should change.

Traditionally, chemical engineering has been taught in Germany using the unit-operations concept. In most universities, teaching particle technology has followed the concept of Hans Rumpf, who stressed the physical fundamentals in the basic course, which is followed by courses in agglomeration, solid-liquid separation, or particle characterization, to name just a few. Unfortunately, in the USA particle technology is taught extensively in only a few universities. Students learn how to design machines and processes that either keep the particle size constant (*i.e.*, separation, mixing) or change the particle size (*i.e.*, size reduction and size enlargement). In the past, only mechanical means to produce and handle par-



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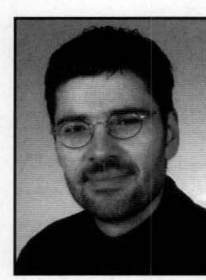

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ticles were considered; therefore, particles larger than approximately 1μm were mainly dealt with while the non-mechanical methods of particle synthesis (*e.g.*, crystallization, gas phase processes) that lead to submicron particles were neglected.

By introducing product properties, we address the overall goal of a chemical process, *i.e.*, the production of well-defined product properties under economical and ecological constraints. The concept of product engineering transcends educational traditions and recognizes the end value of dealing with process technology, *i.e.*, the product property. Although this point of view is not new, it is largely neglected in the curriculum. Rumpf[1] coined the expression "property function" for the end-product qualities as well as handling characteristics. The property function is defined as

Product property = F(disperse properties and microstructure, chemical composition)

Disperse properties are particle-size distribution, particle shape, particle morphology, and particle-surface characteristics. As an example, Figure 2 shows the product quality of a pigment (in this case the color strength per unit mass of pigments) that improves with decreasing particle diameter. The yield stress of the powder, as an important handling property, also increases with smaller particles, indicating prohibitive high resistance against powder flow. Obviously, there exists an optimum where both product and handling quality are acceptable. One solution to this problem may be to optimize powder formulation allowing both high product quality and acceptable handling properties. Of course, there are many other end-product qualities, such as taste (*e.g.*, of chocolate), strength (*e.g.*, of concrete), activity (*e.g.*, of a catalyst or a drug), or the band gap (*e.g.*, of a nanocrystalline semiconductor). Typical handling characteristics are flowability, dust development, filtration resistance, risk of explosion, and abrasiveness, to name only a few. Polke and Krekel[2] introduced the term "process function" to relate the disperse properties of the product to the production process and the educts

Disperse properties = F(process parameters, educts)

Process parameters include the types of machines and unit operations as well as their interconnection, the operational parameters. The art of chemical engineering in this context involves designing the best process for producing the correct dispersed properties, leading to the desired product quality with a minimum of costs, including environmental costs. This way, the product would achieve the highest profit since it is the most competitive. Our point of view includes both the economical aspects and a global perspective of environmental responsibility.

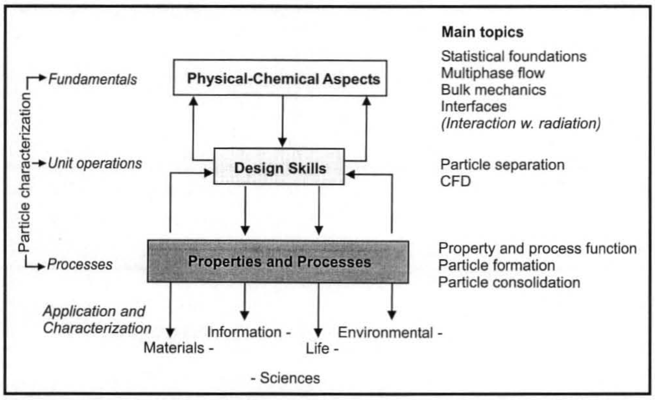

Figure 1. *Structure of particle technology curriculum and courses offered at Munich University of Technology.*

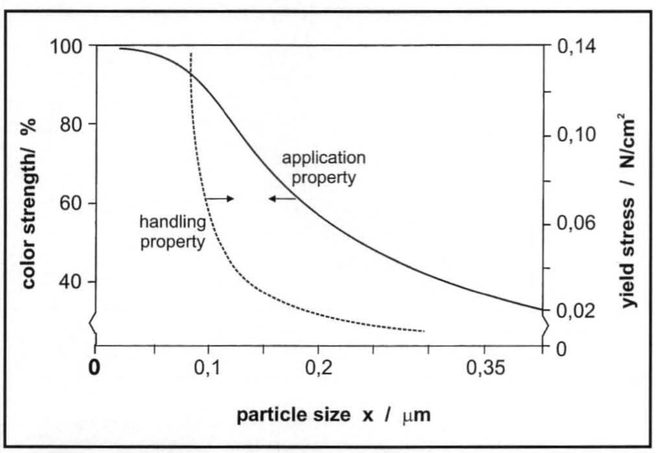

Figure 2. *Property functions of a typical pigment.*

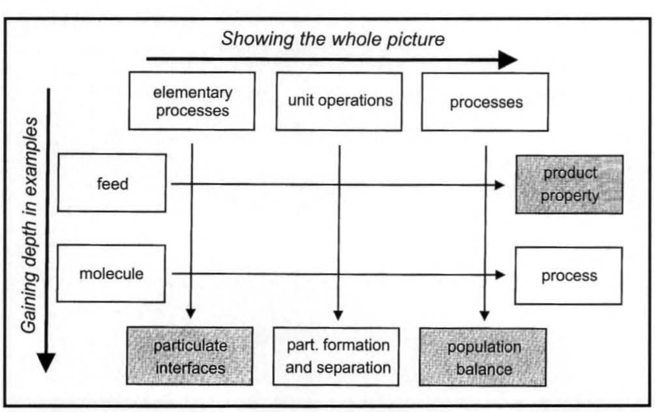

Figure 3. *Teaching concept and new topics (gray).*

EDUCATION IN PARTICLE TECHNOLOGY AT TU MUNICH

Teaching Concept and New Topics

The particle technology courses are a part of the chemical engineering and process engineering ("Verfahrenstechnik" in German) curricula at the Munich University of Technology. On one hand, the traditional education of chemical engineers prepares students for well-known applications such as the design of cyclones or heat exchangers, but many of the traditional applications have reached the point where their economic success is decreasing. On the other hand, new opportunities are evolving in areas that are less familiar to engineers, *e.g.*, information technology or various aspects of materials science. The question is: How can the new areas be included in the curriculum without disregarding the conventional ones? In our opinion, the only answer is that teaching the fundamentals is even more important, but the examples given to the students should change.[3,4]

In Figure 3, our approach is shown schematically. We explain the whole picture to the students by showing them the progression from molecular precursors to the whole process, which actually covers many orders of magnitude in both geometrical dimensions and time scale. In other words, we pave the way from feed materials to end-product properties—this is the horizontal line. In the vertical, depth is gained by explaining certain aspects in a detailed way. By reflecting the first three levels of Figure 1, we stress particulate interfaces (fundamental level) since we believe that this aspect has not been sufficiently covered in the past. Moreover, with the advent of nanotechnology, interfacial aspects have become increasingly important. The second level, comprising unit operations, is handled in a more-or-less traditional way, although new aspects such as CFD modeling are included. On the process level, disperse systems have to be treated mathematically by means of population balance equations, which have so far not been covered in traditional particle technology curricula.

Courses

The courses are organized into three levels. The first and most fundamental level comprises a two-semester course in "Fundamentals of Particle Technology" (see Figure 4). In this course, the important foundations (ranging from statistics, motion of particles in fluids, fracture mechanics, to dimensional analysis) and their implication in mechanical process engineering are covered. In addition, new elements such as population balances (which are increasingly used in industry) and interfacial phenomena are introduced. The latter comprise the fundamentals of interactions between molecules and particles, characterization of particulate interfaces and aspects of nanoparticle technology (*e.g.*, coagulation and stabilization of colloidal suspensions).

The second level stresses unit operations. Here, we concentrate on "Particle Separation" (see Figure 5). This course is principally organized in the traditional way, focusing on separation of particles from gases as well as solid-liquid separation. Different unit operations in gas-solid separation are introduced systematically by focusing on common principles, *i.e.*, on transport mechanisms of particles to the collecting surfaces of the respective separators. In this way, various unit operations are treated very efficiently, which allows for introduction of new, modern methods such as CFD and its use for optimizing such apparatuses. We also offer a complementary course

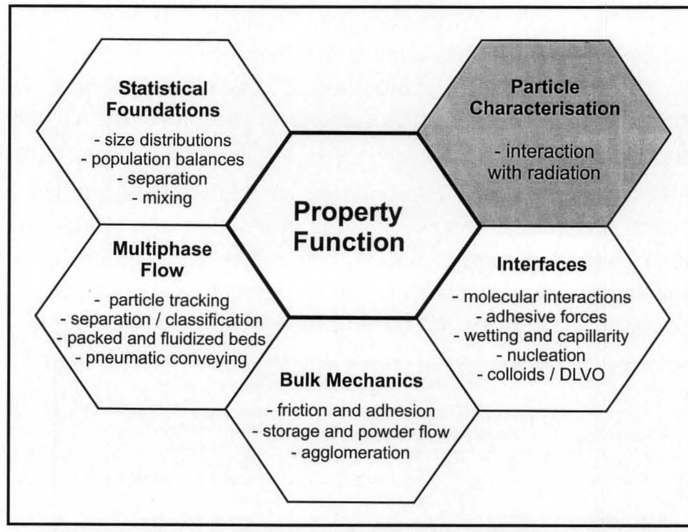

Figure 4. *Fundamentals of Particle Technology course (particle characterization included in separate course).*

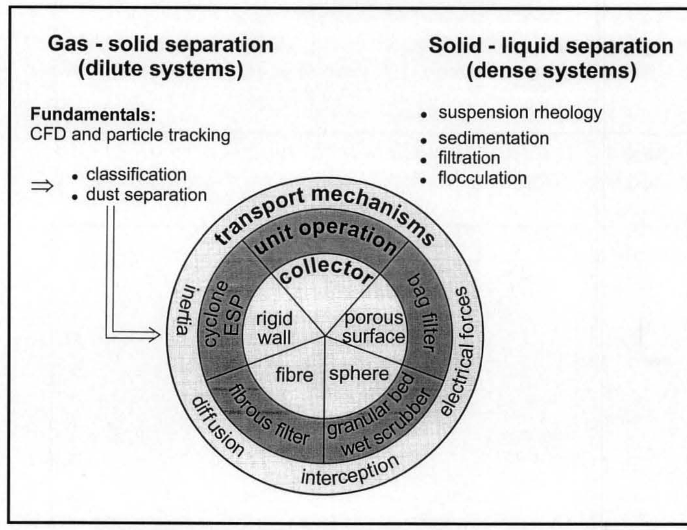

Figure 5. *Particle Separation course.*

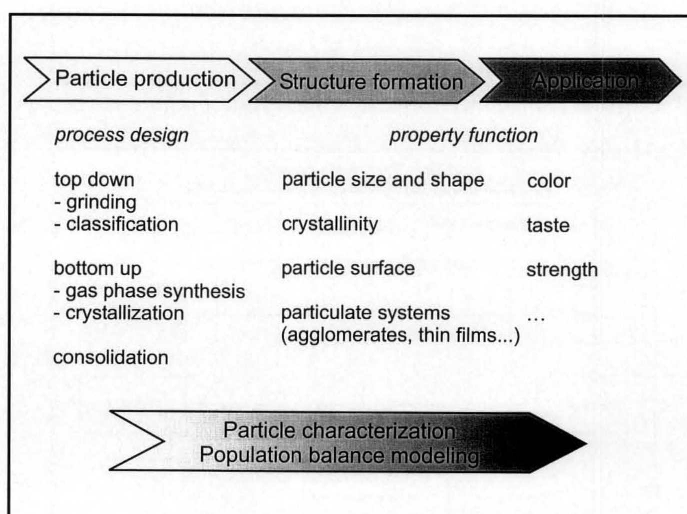

Figure 6. *Product Engineering course.*

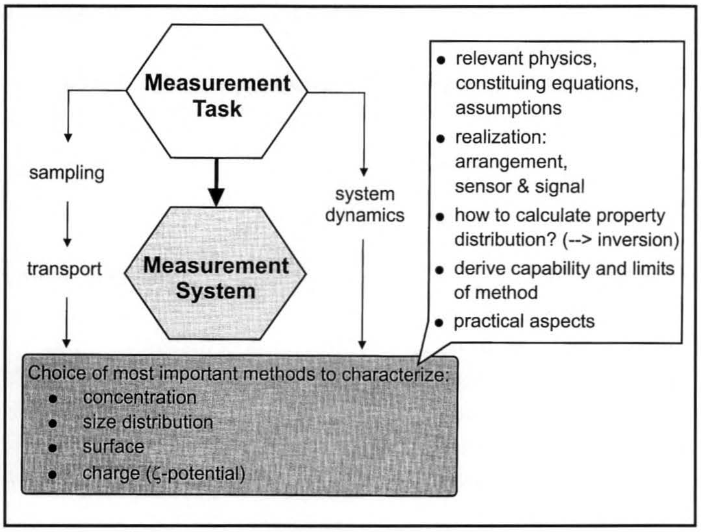

Figure 7. *Particle Characterization course.*

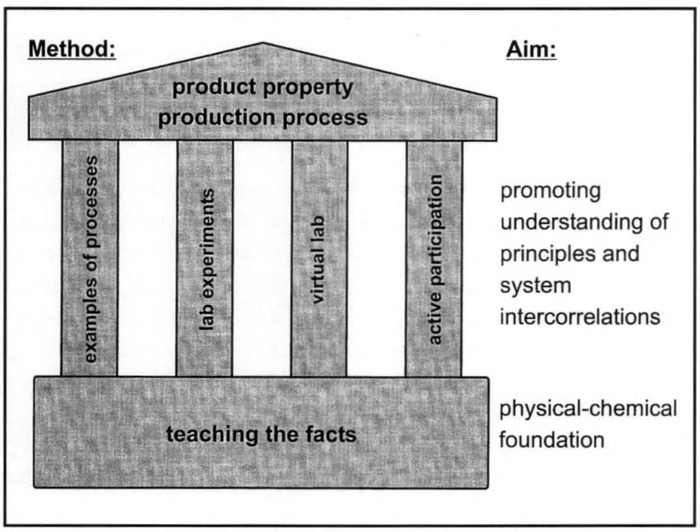

Figure 8. *Methodological approach.*

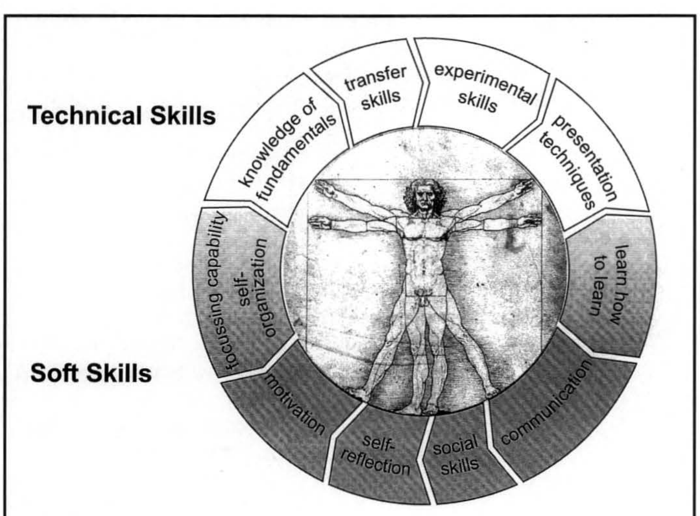

Figure 9. *Integrated approach of university education.*

dealing with "Downstream Processing of Biotechnological Products" that focuses primarily on different unit operations for separation, disintegration, and purification of bioproducts as well as their interactions in the whole production process. In several aspects, bioproducts such as proteins can be regarded as nanoparticles, although the limits of this point of view should be kept in mind.

A completely new course is being offered in product engineering (see Figure 6). The key question is how to produce the physical properties that define the product property, from the point of view of both handling and application. Examples for property functions are presented together with various methods for producing the particles (*e.g.*, comminution and classification, gas phase synthesis of nanoparticles, crystallization, and precipitation). Handling and formulation topics round out this course. The students learn key concepts for formation of structured solids, product design, and powder processing systems. In this context, the systems engineering approach is important. There is also a course in particle characterization that teaches the main principles in characterizing particle properties, *e.g.*, concentration, size, shape, surface, and zeta potential (see Figure 7). The purpose of this course is to enable the students to choose an appropriate setup for arbitrary particle characterization tasks. This is accomplished by emphasizing the basic aspects of a measuring technique (*e.g.*, physical principle, signal recording, conditioning, and evaluation) as well as a complete measurement system (including sampling, transport, and preconditioning). These principles are explained in conjunction with a choice of the most important measurement techniques.

Whereas Fundamentals of Particle Technology I and II are mandatory for all chemical engineering students, Particle Separation is one of a group of three courses (together with Process and Plant Design and Design of Thermal Processes) from which the students must choose two. The remaining courses are elective.

Methodology and Didactics

The course in particle technology follows several guidelines:

- The key item is the product property approach, *i.e.*, particles have physical properties such as particle size distribution, particle shape, or particle morphology that are closely related to product properties.
- Although it is difficult to describe complete process chains, we enhance the student's awareness of the complete process.

From a methodological point of view, we believe that teaching should follow a double-tracked approach. On one hand, the teacher should stress the important physical foundations, since excellent skills in the fundamental principles will be essential for the students throughout their studies and their professional lives. This implies that a large number of facts have to be taught, thus assigning an important role to the teacher. On the other hand, to promote the students' understanding of the underlying principles as well as to sharpen their view of the complete process, active learning appears to be a key issue.[3,5,6] We try to support this active learning in different ways (see Figure 8).

Lab and virtual experiments are conducted so that students can apply and transfer their acquired knowledge and get involved with more realistic problems. This is accomplished by a mandatory lab course (one semester) as well as lab components that are integrated into the courses described above. The lab experiments include a wide field of exemplary tasks that include, for example, dust separation in cyclones, filtration, mixing, and particle characterization by laser diffraction as well as the investigation of the stability of colloidal suspensions by dynamic light scattering. Furthermore, a completely new virtual lab is currently being established in the course Product Engineering, with computer simulations of disperse systems (*e.g.*, crystallization, comminution) based on population balances using commercial software (*e.g.*, LabView and Parsival).

We also encourage the students to take an active role throughout the courses wherever it is appropriate, for example, in the particle characterization course. After introducing the basic principles and the important characteristics of a measurement systems (*e.g.*, assessed equivalent particle size, signal recording, conditioning and evaluation, necessary sample preparation, etc.) as well as discussing their application to the most important measurement techniques, the students are arranged in small groups. Each group is then assigned the task of analyzing one measurement technique that is so far unknown to them. They also have to prepare a presentation of their results that will relay the most important facts to their fellow students. The groups are supposed to work autonomously, with the teacher playing a more passive role and only giving guidelines or help when asked. In this way, several goals can be achieved.

- The students work and access information autonomously, *e.g.*, from literature in a foreign language.
- The group work necessitates that students find their roles in a group and work together productively.[7]
- Finally, the students are given the chance to prepare and give a presentation. Even listening and assessing the presentation of other groups increases their ability in this respect. This is a capability that is not practiced enough.[8]

By actively preparing a small part of the course, the students not only acquire valuable technical knowledge, but they also get a chance to increase their "soft skills." Personal development is often neglected in a university education. Students should concentrate on both their technical skills and their personal growth (see Figure 9). This includes an ability for self-organization and focusing on defined targets, intrinsic motivation to reach goals, and an ability to communicate results. On a deeper level, internal self-reflection is indispensable for accepting personal strengths and weaknesses as well as those of others. This is a precondition for all social skills.

CONCLUSIONS

Particle technology is a much wider field than many people realize since it also comprises biochemical, chemical, and thermal processes dealing with particles. Hence, it is not only of the utmost importance in the chemical industry, where about 60-70% of all products are fabricated in dispersed form, but also for a number of other fields, such as materials science and information technology. Product properties and the subsequently developed product engineering approach is at the center of our considerations. With a continuously growing number of applications for dispersed systems, we feel a need to stress the fundamental aspects even more. With the generally observed trend toward finer particle sizes, new topics such as particle interactions and population dynamics have been included in order to prepare our students for newly developing areas such as nanotechnology. The technical courses are complemented by various activities to strengthen the soft skills of the students.

Recently, suggestions have been made by Cussler, *et al.*,[9] on how to change chemical engineering curriculae. Considering the shift in industrial practice from large-scale processes producing commodities toward more specialized product design, we feel that particle technology and particle design methods deserve a prominent place in the curriculum.

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