Particle technology: the 4M business

PARTICLE TECHNOLOGY - THE 4M BUSINESS

A collection of papers

submitted by

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CONTENTS

1.1 PARTICLE TECHNOLOGY – THE 4M BUSINESS

I have never thought of Particle Technology as a separate discipline or training, rather have I seen it as an integral and vital part of the engineering discipline of Process Technology. This discipline is often called Chemical Engineering but the process industries encompass far more than chemicals, they include other industries such as pharmaceutics, minerals and food. It has been estimated that 70% of the final or intermediate products of these process industries are in particulate form.(1) They may be called a powder, paste, slurry, suspension, emulsion, aerosol or spray. The common feature is that there is a continuous and a disperse phase. The disperse phase is in the form of particles. Of course, the science of particulate materials has important applications in almost every branch of technology, for example in civil engineering, electronics and combustion engineering. The essential difference, in process engineering, is that the particulate nature of the materials is not just inherent; rather we deliberately design both the particulate product and the process to make it. Thus, two of the "M's" in this business are the ***Manipulating*** and ***Making*** of particles. The properties of a particulate material depend upon those of the constituent materials but also critically upon the disposition of the particulate phase. To manipulate the product, we create a mixture of sizes, shapes and species that will deliver the required functional properties. The consequent step, the making, is to design and operate the processes that will make that mixture. The tools that we use are ***Measuring*** and ***Modelling***. These tools are not exclusive to particle technology, they are the tools used by any process engineer. However, it is true that measurement plays a much greater role in particle technology than in some other branches of process engineering. The reason for this is that any model requires input data. In some cases, this may simply be values of constants or of properties, such as the density or viscosity of a liquid that can easily be measured or be found in a database. In Particle Technology, every material is comprised of a different population of sizes, shapes and other properties. It is inevitable that an individual characterization is always necessary.

This report summarizes the results of 40 years of endeavour, divided equally between Loughborough University of Technology and Delft University of Technology. In both universities I was the Group Leader of the Particle Technology Group and so most of my work has been done in cooperation with colleagues and with students. The result has been more than 50 Ph.D. theses and many more Master's theses. In Delft, every student is required to make a research project of about 9 months duration to complete the Master's degree. We have always strived to enable students to attend international conferences and so there are often conference papers and later a journal paper on the same subject. In such multiple author papers, my rule was that my name should be usually at the end, occasionally at the beginning, but not in the middle.

I have always taken a broad interest in the subject, specialised in Particle Technology but not within Particle Technology. Consequently, the publications cover a wide range of subjects. They have been divided arbitrarily into two groups. Those that concern primarily the objectives, Making and Manipulating, are grouped as ***Powder Processing***. Those that concern mainly the tools, Measuring and Modeling, are grouped as ***Particle and Powder Measurement***. In turn, each of these groups has been divided into sections. In the subsequent text these sections are described and are identified by being printed in red. Only within the sections are the publications listed chronologically. A distinction is made between a published article (P), a conference paper (C) and a review or plenary lecture (R). From the approximately 370 papers 42 have been selected and are reproduced here. They are readily identifiable within the list of publications because they are printed in red.

1.2 POWDER PROCESSING (Manipulating and Making)

During the last century, process technology developed from its early conception into a mature and sophisticated subject. A clear record of this development was given in 1996 by Professor Jacques Villemaux (2). He described the three paradigms that the profession has followed. The subject of Particle Technology has followed those same paradigms.

Process Engineering first developed as a collection of unit operations; individual processes that can be combined, usually sequentially, to achieve the total process. Some unit operations had little to do with Particle Technology, for example distillation. On the other hand, many unit operations were clearly particle processes. Making particles smaller from a bulk could be ***milling*** or ***spraying*** dependant on the phase of the material. Similarly, growing particles from the molecular level is ***crystallization*** or ***aerosol reaction***, also dependent on the phase. Combining small particles together into larger ones is ***agglomeration*** and combining several species is ***mixing***. Separating particles from a fluid is ***filtration*** or ***gas cleaning***, again dependent on the continuous phase. Many expert Process Technologists still specialize in one unit operation and organize their conferences and journals on this basis. In this collection of papers, those that fit the unit operation classification are grouped under these headings which are emphasized in red.

The second stage in the development of process engineering was to group the skills on a scientific rather than a technological basis; reactor engineering, transport phenomena, process control and others. Particle Technology was conceived by many, including myself, as such a comprehensive subject with certain common concepts and rules. The core of the subject is the relationship between the microscopic and macroscopic properties, to relate the particle distribution of the disperse phase to the resulting macroscopic behaviour. In the early days the subject was somewhat confined to models of spherical particles and of circular pores. This earned a reputation for Particle Technology of being more empirical than some other subjects that were more amenable to more exact analysis.

The direct application of the equivalent sphere model is to those systems where the concentration of the particles is so low that there is no inter-particle interaction to consider. If the behaviour of a single particle can be described as a function of its size, then the behaviour of the whole cloud or suspension can be integrated from a knowledge of the particle size distribution. The requirement is to understand quantitatively the forces that are exerted on a single particle. Usually this includes the particle-fluid drag and any other applied force. For gas systems, the electrostatic force is particularly interesting and offers opportunities to develop new processes and new equipment. The papers that are particularly concerned with these principles have been divided into those two classes, ***forces*** and separately, ***electrostatics***.

As the concentration of the particles increases then their interaction with the fluid is coupled. The effective drag may be increased by two orders of magnitude which leads to complex inhomogeneities and instabilities. Experimental observations of these instabilities are described in those papers classified as ***fluidization*** and ***hydraulic transport***. In the last decade the readily available computers have become powerful enough to simultaneously track the position of many thousands of particles within such a process where the particles frequently collide but are still separate. This has led to the popularity of the Discrete Element Simulation (DES) techniques which are achieving success in simulating the observed instabilities although they do not yet fully iterate the particle-fluid coupling. However, such simulations also need basic input data, more scientific models of what happens at the particle-fluid interface on the molecular scale and at the particle-particle contact during a collision. In turn, a simulation of the behaviour of a sample of one million particles occupies appreciable computer time but this sample is small compared to the full-scale equipment. Maybe it was this realisation that stimulated the development of the third paradigm of Process Technology, the multi-scale paradigm.

Whatever the stimulation, the role and importance of Particle Technology is today much clearer than ever and will lead, I believe, to much more effective development of the subject. The third paradigm is illustrated in Figure 1a, which is taken from the article of Professor Villemaux in which he explains that any problem can be viewed with different length scales and different time scales. In the figure he shows the five length scales, nano- to mega-scale, which concern process engineers. When thinking in one scale the fundamental rules that must be used come from the smaller scale and the applications of the thinking are to the larger scale. In Figure 1b, the concept of length scales is adapted for Particle Technology. The particles, powder and equipment are essential length scales within the paradigm.

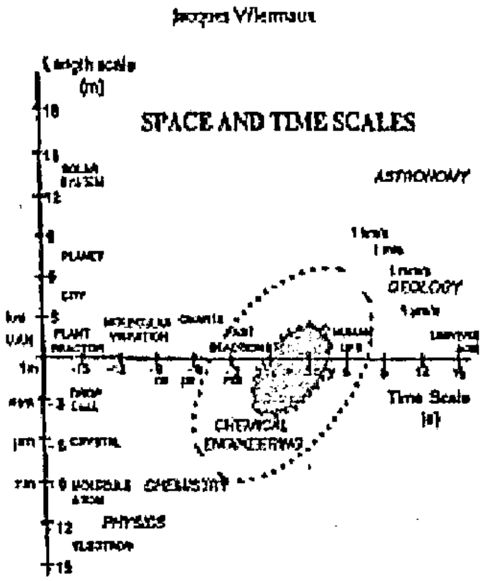

Figure 1.A

Length Scale	Model	Time Scale
Environment	Large Eddy	Decades
Process	Population Balance	Real Time
Equipment	Finite Element	Design
Powder	Discrete Element Simulation	Time
Particle	Equivalent Sphere	
Molecular	Molecular Simulation	Microseconds

Figure 1.B

Extrapolating further, at the smaller scale, the particle properties are dependent upon the chemistry, particularly the surface chemistry, and at the larger scale, the equipment is incorporated into total processes. Extrapolating even further, the processes all combine to contribute to the *environment* and, at the smaller scale, the chemistry can be interpreted by understanding the structure of the nucleus. Particle Technology can also be structured on the axis of time. The chemical reactions that occur in a particulate system may have a time scale of milliseconds. The mechanical processes occupy seconds and large-scale equipment may have a residence time of hours. Environmental effects may have a response time of decades.

The concept is not completely new, rather the capabilities have complelely changed. In striving to develop the subject as a science, it was always the intention to relate the particle properties to those of the powder and the powder properties to the design of the equipment. The individual particles obey the constitutive equations for that material and the fluid surrounding them obeys the Navier–Stokes equation. The limitation is that their behaviour does not average to a few effective constitutive equations for the powder. Any particular powder reacts to both the equipment and the operating conditions and takes up a different state. Thus, it is not possible to separate the material, equipment and operating variables in the classic way even if the particles do not change. Usually, the particle properties are also changing as a result of the process. The new paradigm is applicable because the computer now offers the possibility not only to simulate but also to iterate between the relevant length and time scales. The computer does not obviate the need for analytical thinking, it will never be powerful enough to achieve such iteration unless the problem is formulated in a consequent form. This capability is changing completely the previously totally empirical approach to an important subject like ***dust explosions*** where the turbulence, burning and radiative transfer are all occurring simultaneously and where these mechanisms are strongly coupled. This group of papers reflects the interest I have always had in process safety. It also reflects the changes that I see and the even greater changes that I forsee in process and product modelling. It is now also easy to understand that the unit operation paradigm is restrictive because there is rarely a single mechanism active in any piece of equipment and, if it is deliberately so designed, then that is a very restrictive design. The modern paradigm offers the opportunity to simulate a conceptual process, based on all of the mechanisms, before the geometry of the equipment is chosen. It is also possible to begin to develop procedures for product design whose aim is to match the use of the powder and of the process to make it.

This report also includes papers where the particles were collected from an unknown process and where we were required to make a forensic study; to try retrospectively to infer the processes that had formed the particles. These sections on ***moondust*** and ***underground gasification*** are less open to verification but afforded ample opportunity for imagination. The application of forensic particle analysis is not confined to criminal activity, every particle tells a story.

During the early part of this work we called the subject Particle Science and Technology. Gradually it became Particle Technology. It has not been necessary to discover many new laws of science; the basic knowledge was more than adequate compared to our abilities to apply it to complex particulate systems. That situation still appertains although the gap is narrowing as the ability to model improves. There are signs that the science on which the models are based may not be adequate. Specifically, there are limitations to the classic concepts in the fields of light scattering and of surface forces. Nevertheless, this report concerns the past and so it is structured in the technological format, the "4M's".

1.3 PARTICLE AND POWDER MEASUREMENT (Measuring and Modelling)

The behavioural properties of a particulate material depend upon the physical and chemical properties of each phase and then upon the sub-division of the disperse phase into a population of particles of different size and shape. Thus, in the classic view it is the particle size distribution that distinguishes one sample from another of the same material. In this concept, the size of a particle may be expressed as one scalar number that is the diameter of a spherical particle, which is equivalent with respect to some common behaviour. If the properties of a spherical particle can be related to its diameter, then an equivalent sphere can be defined. The most direct equivalence is geometrical, for example the sphere of equivalent volume or the sphere of equivalent surface. The early measuring techniques which determine directly some geometrical feature of the particle were sieving and microscope counting, both of which make some determination on a projected area of the particle. However, in developing measuring techniques it was more convenient to define a behavioural equivalent. If there exists an analytical solution relating the behaviour of a spherical particle to its diameter, then that behaviour can be utilized as a measurement method. Such analytical solutions have existed for more than 100 years and there are two that are the basis of most particle measurement techniques. They are Stokes' Law and Mie theory.

Stokes' Law relates the viscous drag between a spherical particle and a fluid to its diameter. The method is necessarily slow but is still used for some applications. As the particles become smaller, there is a competition between the gravitational settling and the Brownian motion of the particles. One solution is to enhance the settling velocity as in ***centrifugal sizing*** techniques. Alternatively, the Brownian motion can be measured using ***photon correlation spectroscopy***. The particle size is then determined by assuming that the Stokes-Einstein equation applies.

Mie theory relates the angular distribution of the intensity of light scattered by a spherical particle to its diameter and to its refractive index. Early aerosol counting devices used a white light source and they required careful calibration to determine the size of the particle. In measuring particles suspended in a liquid, the early electronic counting device was the ***Coulter Counter***. In this device, the particles are counted as they pass through an orifice by interrupting an electrical current that is also passing through the orifice. With the right design, the response is proportional to particle volume. The instrument is still the most accurate of the laboratory-based instruments.

Since Stokes' and Mie derived their equations tens of thousands of papers have been written about ***particle size(general)*** size measurement. Any phenomenon that is dependent upon particle size has been used to measure it. There is currently, for example, much interest in the use of acoustic techniques to measure particle size. However, the majority of instruments that are widely used and are sold commercially are based on the same few principles. They are mechanical separation, sedimentation, optical techniques and electric field. The reason for this is clear. Any method of measurement should give a response to particle size which is preferably linear and is at least monotonic. The equivalent sphere concept ensures that the response is linear with size as long as the method is used within the range of applicability of the appropriate equation.

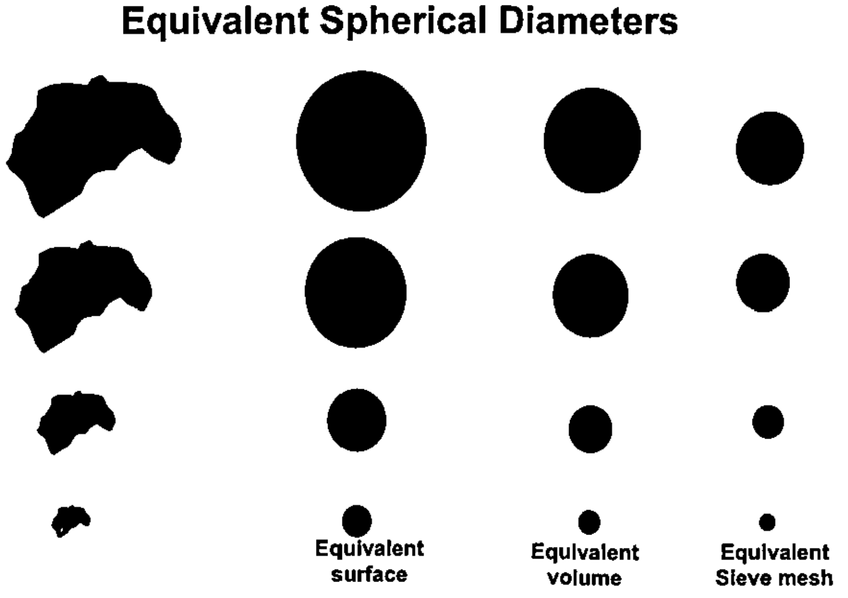

Figure 2

As modern photo-detectors have become available, the ***optical techniques*** are no longer confined to be counters of single particles. Collectively, they are by far the most widely used because of their speed and flexibility. The laser provides a monochromatic source and thus the signal received from a population of particles can be de-convoluted. These techniques are often called ***laser diffraction*** but they are not confined to that regime of scattering. Similarly, when the scattered light is focused, the image is no longer dependent only on human interpretation and many features of particle size and shape can be recorded by ***image analysis techniques***.

When the intensity of the laser is increased, the particle does not simply passively scatter the light but is itself ablated. This phenomenon has endless possible applications. This report includes papers where the ablated fragments are passed directly to a ***mass spectrometer***. In this way, the particles can be identified not only by size but also by species. More recent interest has been to apply this technique to biological aerosols, inert particles that are carrying a biological passenger.

The electrical technique has also been revised in a different form. ***Tomography*** is an essential tool in medicine but has come late to process engineering. The reason is that the speed of x-ray tomography is still too low to be used for process monitoring. However, various forms of electrical tomography, such as resistive and capacitive, are being developed to measure particle concentration and velocity. They have not yet been applied to single particles but that will come.

A particle size instrument may be judged on the basis of reproducibility, sensitivity and accuracy. The first requirement is to ensure that the ***sampling*** is representative. Most modern instruments are then reproducible when used carefully and their sensitivity can be adjusted according to the application. With regard to accuracy, it is a little disturbing that they do not all give the same result with the same sample, even when they are different versions of the same technique. This is the reason for the importance of ***standards***. And I am currently Chairman of the appropriate ISO committee. Standards are not intended to restrict development, rather to make it clear that any two methods can be calibrated to coincide if they are operating in a linear regime. I have constantly advocated the view that the equivalent volume diameter should be considered to be the basic size of any particle and that its ratio to any other equivalent sphere constitutes an arbitrary shape factor. Figure3 illustrates, for example, the relationship between the sieve diameter and the volume diameter of a sample of irregular particles.

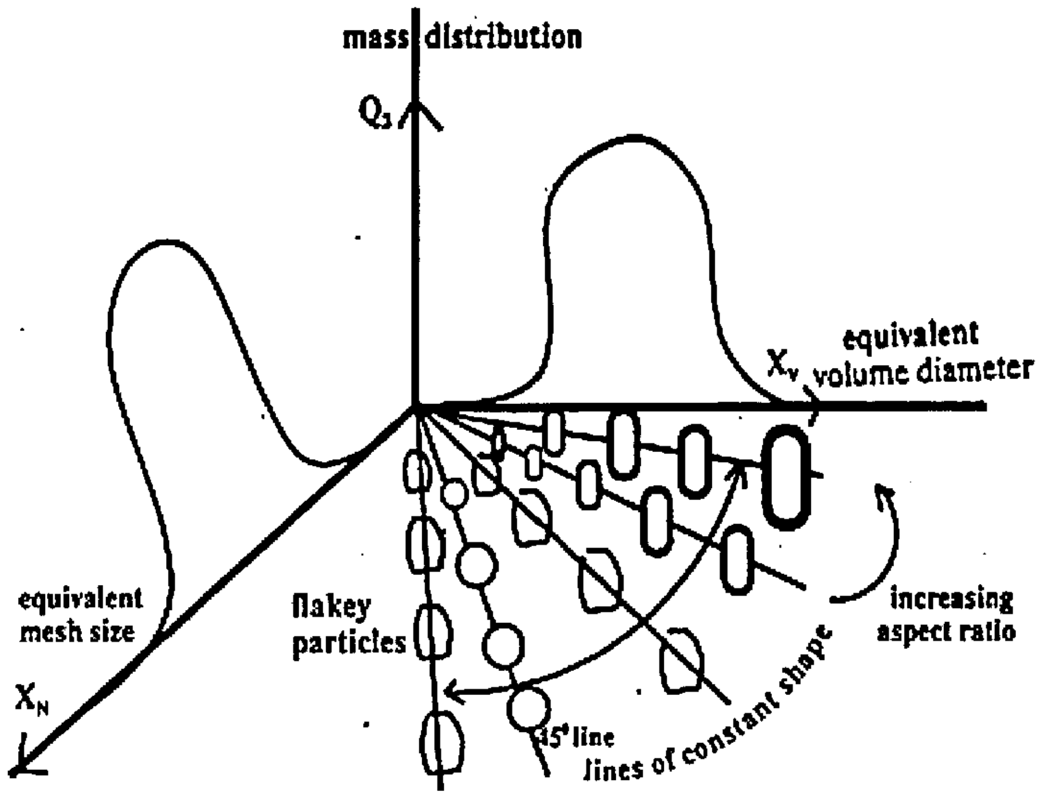

Figure 3

Within the paradigm of particle, powder and equipment the first choice to be made is the whether to characterise the particle and to model the powder or to characterise the powder directly and thus to model the equipment. The particle size distribution of a powder is usually considered sufficient to distinguish one sample from another and for dilute systems may be used to model the equipment directly. This is increasingly possible as the particle measuring techniques are moved from the laboratory and are applied on-line in the plant. A model of the process can then also be created and adjusted on-line. However, some particle properties do not depend only upon their size and shape and must also be measured. An important example of such a property is that of *particle strength*, the reaction of the particle to applied mechanical forces. The strength of a particle is dependent primarily upon its weaknesses, the small imperfections and flaws that exist in every particle due to its previous history. Such a parameter must be defined and measured separately. For more concentrated systems the particle shape is at least as important as the size and in packed particle systems it may be dominant. For these systems the equivalent sphere model is inadequate and, it may be necessary to make a direct measurement of the bulk properties of the powder. Some of these properties are borrowed directly from solids mechanics, for example the conductivity of a packed bed of particles. Other properties depend upon the pore space between the particles, for example the permeability to fluid flow of a bed of particles. The most difficult case is when the particles move due to an applied stress. The subject of *powder flow* is quite distinct from both fluid and solid mechanics although it borrows many ideas from the subject of soil mechanics. When the particles shear in a packed state the phenomenon of dilatancy is dominant and this, in turn, is dependent upon the anisotropy of the particle array. In this collection of papers, the idea is proposed that it is necessary to split each particle into smaller units in order to model such complex arrays, each particle being considered to be a bundle of chords or of cones.

Forty years ago the measurement techniques available were modest and consequently the models and design procedures we used were confined by what could be measured. Today, if the parameter can be defined then it can be measured. Thus, the challenges, which this subject, Particle Technology, poses, have never been more amenable to realistic solutions. The best is yet to come! Nevertheless, the time has also come for me to submit this report.

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PUBLICATIONS POWDER PROCESSING

PUBLICATIONS

P: Published Articles
C: Conference Papers
R: Review and Plenary Lecure
Selected paper copied on page [ ]

POWDER PROCESSING

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"Regularized Modified Newton-Raphson Technique Applied to Electrical Impendance Tomography",
C.J. Grootveld, A. Segal, B. Scarlett;
Journal of Imaging Systems and Technology, Vol.9, pp. 60-65, 1998. 1998 P

"Development of Displacement Current Tomography System",
M. Machida, B. Scarlett;
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M. Machida, B. Scarlett;
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"A Fast active Differentiator Capacitance Transducer for Electrical Capacitance Tomography",
W.K. Harteveld, P.A. van Halderen, R.F. Mudde, C.M. van den Bleek, H.E.A. van den Akker, B. Scarlett;
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M. Machida, B. Scarlett;
Proceedings 1st World Congress on Industrial ProcessTomography, Buxton, Greater Manchester, April 14-17, pp. 560-562, 1999. 1999 C

"Imaging Reconstruction of an Electrical Capacitance Tomography System Using an Artificial Neural Network",
T.D. Sun, R.F. Mudde, J.C. Schouten, C.M. van den Bleek, B. Scarlett;
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"The production of nanoparticles by Electro Hydrodynamic Atomisation",
J.C.M. Marijnissen, B. Dudout, B. Scarlett;
ESF Symposium ESF-NANO 1999 Vapour-Phase Synthesis and Processing of Nano-Particle Materials, December 1999, Gerhard-Mercator-University, Duisburg, Germany. 1999 C

"Using Regularization Methods for Image Reconstruction of Electrical Capacitance Tomography",
L. Peng, H.G. Merkus, B. Scarlett;
Part.Part.Syst.Charact. Wiley-VCH, 17, pp. 96-104, 2000, ISSN: 0934-0866. 2000 P

CURRICULUM VITAE

OF

BRIAN SCARLETT

CHRONOLOGY

a)	Technical Assistant United Kingdom Atomic Energy Authority - Chapelcross Works	: 1959 - 1961
b)	Research Associate Nottingham College of Technology	: 1961 - 1963
c)	Lecturer in Chemical Engineering Loughborough, University of Technology	: 1963 - 1969
d)	British Steel Corporation Research Fellow, Carnegie Mellon University, Pittsburgh, USA	: 1970 - 1971
e)	Senior Lecturer in Chemical Engineering Loughborough, University of Technology	: 1969 - 1982
f)	Professor of Particle Technology Delft, University of Technology	: 1983 - 2001
g)	Research Professor Engineering Research Center for Particle Science & Technology University of Florida	: 2001- present

PRESENT APPOINTMENTS

1. Series Editor of Kluwer books on Powder Technology.

2.	Editor	:	"Particle & Particle System Characterisation", Wiley-VCH, USA.
3.	Editorial Boards	:	"Chemical Engineering & Technology". "Advanced Powder Technology". "KONA". (Chairman, European Branch)
4.	Chairman	:	ISO Committe TC/24; Methods of Particle Sizing other than Sieving.
5.	Visiting Professor	:	University of Leeds, U.K.

MEMBERSHIPS

1. Fellow Royal Academy of Engineering. (F.R.Eng.)
2. Fellow Institution of Chemical Engineers. (F.Inst.Chem.Eng. C.Eng.)
3. Fellow Institute of Physics. (F.Inst.P. C.Phys.)
4. Member - Royal Dutch Institute of Engineers (KIVI).

PREVIOUS APPOINTMENTS

1. Chairman of Water Management Committee, (1978 - 1983)
   Severn Trent Water Authority.

2. Chairman of British Standards Committee on
   Methods of Particle Sizing other than Sieving.

3. Secretary - Particle Technology Subject Group.
   Institution of Chemical Engineers.

4. Chairman - Particle Size Group.
   The Royal Society of Chemistry.

5. Member of B.C.R. (EU) Committees:-
   Working Group on Particulate Materials.
   Specialist Group on Particle Size Reference Materials.
   Specialist Group on Atmospheric Dusts.

6. Member of Physics and Engineering Advisory Committee.
   Ministry of Defence.

7. British Council Fellow.
   University of Belgrade (August 1976).

8. District Councillor (1973-1983).
   Charnwood District Council.

9. External Examiner - Cork Regional College of Technology.
   - Bradford University.

10. Member Process Engineering Committee - EPSRC.

11. European Adviser – International Fine Particle Research Institute.

12. Consultant - Dupont de Nemours.
    - Gist-Brocades.
    - Genencor.

13. Member Adviesraad TNO-Prins Maurits Laboratorium.

14. Member Particle Characterisation.
    Working Party European Federation of Chemical Engineering.

15. Agglomeration Working Party.
    European Federation of Chemical Engineering.

SOME PREVIOUS RESEARCH CONTRACTS

		Sponsor
1.	Cross Flow Filtration of Sea Water for North Sea Oil Well Injection	SERC
2.	Propogation of a Mechanical Impulse through a Granular Medium	SERC
3.	Development of an Instrument to Monitor Cleanliness of Medical Gases	Ministry of Health
4.	Electrostatic Precipitation	SERC
5.	Electrostatic Powder Coating	SERC
6.	Aerated Flow of Powders	IFPRI
7.	Particle Attrition	IFPRI
8.	(a) Particle Size Reference Materials (b) Powder Flow Reference Materials (c) Standard Sand for Cement Testing	EU (BCR)
9.	High Temperature Gas Cleaning (with Professor K.R.G. Hein)	EU (Joule)
10.	Particle Production during underground gasification	EU
11.	Dust Explosions	SON
12.	Production of Si_3N_4 for ceramics (with Prof. J. Schoonman)	IOP Keramiek & EU (BRITE)
13.	Automation of a Ball Mill Process for Paint	IOP Verf Dispersion
14.	Laser Aerosol Reactor for the Production of Si_3N_4	OSPT
15.	Automation of Continuous Crystalliser(UNIAK) (with Prof. van Rosmalen and Prof.O.H. Bosgra)	STW + 6 Companies
16.	Development of an on-line aerosol mass spectrometer	TNO
17.	Automation of a Jet Milling Process	WEDCO
18.	Electrostatic Spraying of Fine Particles	STW
19.	Thermophoresis Forces Measured in Microgravity	ESA

20.	Development of a Biaxial Cell for Stress and Strain Controlled Deformation of a Powder Sample	SON
21.	Granule Strength	GENENCOR
22.	Ignition Sources for Dust Explosions	STW
23.	Control of Granulation Processes	DSM

Ph.D. THESES SUPERVISED AS MAIN SUPERVISER

1968	M.K. Bo	Fundamentals of Flow through Packed Beds
1968	L.R. Beardall	Liquid Film Flow and Solid-Liquid Separation on a rotating, inclined surface
1969	M.J. Blogg	Size Segregation of Solid Particles in Liquid Fluidised Beds
1969	I.E. Eastham	The Stresses in Granular Material due to Applied Vibration
1969	A.C. Todd	The behaviour of a bed of particles under the influence of shear stress
1972	B. Barber	Stress Distribution in particulate systems
1973	C.S. Parkin	The production of droplets from liquid jets by capillary and electrodynamic instabilities
1973	A. Grimley	The hydrodynamic behaviour of settling suspensions flowing in a horizontal circular pipeline
1975	G.E. Fletcher	Factors affecting the atomisation of saturated liquids
1976	S.K. Cowlam	Particle interaction in dilute, slowly sedimenting suspensions
1977	D.H. Harris	Photoelastic analysis of stress generated by powder beds
1981	A. Caldwell	Propogation of an impulse through a granular medium
1988	E.F. Hobbel	Cohesion and Interparticle Forces
1990	W. Boender	De verspreiding van deeltjes in een turbulente stroming
1992	G.M.H. Meesters	Mechanisms of Droplet Formation
1992	C.A.P. Zevenhoven	Particle Charging and Granular Bed Filtration for High Temperature Application
1992	J.G. Bernard	Experimental Investigation and Numerical Modelling of Cyclones for Application at High Temperatures
1992	A. Boxman	Particle Size Measurement for the Control of Industrial Crystallizers
1993	S. Drescher	Technologische Anwendung der Partikelformanalyse

1993	F.E. Kruis	Particle Formation in a Laser-heated Aerosol Reactor – Application to Silicon and Silicon Nitride Synthesis
1993	P.G.J. van der Wel	Ignition and Propagation of Dust Explosions
1994	WJB van den Bergh	Simulation of the Dynamic Mixing Performance of an Orbiting Screw Mixer. Influence of Particle Breakage on the Wall Friction Coefficient of Brittle Particulate Solids
1995	J.H. Gerla	Modelling, Measurement and Manipulation of Crystallizers, the role of classifiers and hydrodynamics
1995	P.H.W. Vercoulen	Electrostatic Processing of Particles *"A tool in particle technology"*
1995	A.M. Mollinger	Particle Entrainment -Measurement of the fluctuating lift force -
1995	O. Kievit	Development of a laser mass spectrometer for aerosols
1995	C.M.G. Heffels	On-line particle size and shape characterization by narrow angle light scattering
1996	M.A. van Drunen	Measurement and modeling of cluster formation
1996	M. van der Kraan	Techniques for the measurement of the flow properties of cohesive powders
1996	H. Grootveld	Measuring & Modeling of concentrated settling suspensions using Electrical Impedance Tomography
1997	M. Weiss	An On-line Mass Spectrometer for Aerosols: Development, Characterization and Applications
1997	I.L. Tuinman	The Production of Si_3N_4 Powders in a Laser-Driven Aerosol Reactor
1997	H.J.C. Gommeren	Study of a closed circuit jet mill plant using online particle size measurements
1998	W. Oostra	An experimental approach into the phenomenon of thermophoresis
1998	R.P.A. Hartman	Electrohydrodynamic Atomization in the Cone-Jet mode. From physical modeling to powder production
1998	A.W. Willemse	Optical measuring techniques for particulate systems at the fringes of concentration 'Paints and aerosols'
1998	F.T. Kühn	Electrical Capacitance Tomography - Development and Application to Fluidised Beds

1999	D.M.A. Camelot	The Bipolar Coagulation Process for Powder Production. An application of the ElectroHydroDynamic Atomization of liquids.
2000	A.D. Dahoe	Dust Explosions: A Study of Flame Propagation.
2000	W.J. Beekman	Measurement of the mechanical strength of particles and Granules.
2001	P.A.L. Wauters	Modelling and Mechanisms of Granulation.
2001	D. Verkoeijen	The Measurement and Modeling of Granulation Processes - a Turbo View
2001	Z. Ma	Measurement of Particle Size and Shape by Laser Light Scattering.
2001	R.J.M. Janssen	Structure and Shear Incohesive Powder.

Ph.D. THESES SUPERVISED AS CO-SUPERVISER

1967	M.J. Groves	Studies of the influence of physical properties, in particular particle size, on the flow behaviour of emulsions.
1972	D.N. Skinner	The coating of steel strip with aluminium powder by roll compaction.
1973	D.F. Booker	The flow of a Newtonian liquid on rotating inclined surfaces with application to atomisation.
1974	W.D. Hill	Boundary enhanced sedimentation due to settling convection.
1991	R. Bauer	Laser Chemical Vapour Precipitation of Ceramic Powders.

MASTERS THESES SUPERVISED

1984	Dalen van. A.G.	Onderzoek naar de werking van een Coball-Mill; October 1984, 82 pag.
1984	Derks, P.A.H.	Aerated flow of alumina powders; March 1984,
1984	Franken, M.C.	Attrition of cylindrical alumina particles; March 1984.
1984	Hoeksma, J.K.	Attritie van cylindervormige alumina deeltjes; November 1984.
1985	Haarst, van R.A.J.	Onderzoek naar de slijtage van een niet cohesief materiaal en de daarbij optredende wandwrijvings eigenschappen; June 1985, 107 pages.
1985	Rijke, de J.M.	Procesmatige en economische aspecten van bierfiltratie met behulp van kiezelgoer; January 1985.
1986	Bruinsma, C.J.	Hydrodynamica van een multi-stage fluide bedkolom; August 1986.
1986	Erftemeijer, L.P.	Light Scattering Techniques for On-Line Measurements of Volume Distributions; June 1986.
1987	Berendrecht, M.P.	De fluidisatie eigenschappen en het stromingsgedrag van gefluidiseerde poeders getest met een speciaal ontworpen couette viscometer; October 1987, 112 pages.
1987	Bernard, J.G.	Hot Gas Clean-up; - Granular Bed Filtration - Coulter Counter Analysis - Cyclone Efficiency; August 1987, 105 pages.

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1988	Eijkenboom, A.F.	Het onderzoek naar de stromingseigenschappen van calciumcarbonaat met de Jenike Shear Cel en de Rotating Shear Tester; April 1988, 109 pages.
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1988	Glass, H.J.	Analysis of Gas-Solids Flow in Fast Fluidized Beds and in Standpipes; April 1988, 105 pages.
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1988	Lannoy, de M.R.J.	Simulatie van het slijtageproces van niet-cohesief korrelvormig materiaal langs de wand in opslagbunkers; November 1988.
1988	Lans, van der W.C.	Model van het Materiaaltransport en Menggedrag van een Nautamenger; August 1988, 99 pages.
1988	Mackay, N.D.	Implementation of advanced methods for measuring particle size distributions using a light scattering technique; December 1988, 71 pages.

1988	Remijnse, D.J.	Model Verification and Optimization of an industrial biochemical waste water treatment plant; April 1988, 141 pages.
1988	Rijnhart, B.M.	De invloed van de deeltjesdiameter op stofexplosie-eigenschappen; November 1988, 61 pages.
1988	Spuyman, H.	Onderzoek naar het bepalen van de wandwrijvingshoek van een niet Cohesief korrelvormig materiaal bij verschillende normaalspanningen en wanghellingshoeken; August 1988, 71 pages.
1988	Veldhuizen F.J.E.	Onderzoek naar het meng- en stromingsgedrag in een vaste stofmenger met behulp van radioactief tracer; August 1988, 88 pages.
1988	Vliet, van M.	Het adhesiegedrag van koperdeeltjes; January 1988, 100 pages.
1988	Zevenhoven, C.A.P.	Electrostatical Enhancement of Granular Bed Filtration; January 1988, 64 pages.
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1989	Brons, J.F.J.	Electrostatically Enhanced Granular Filtration: - Choosing Materials - Filter Modelling; July 1989, 97 pages.
1989	Clasener, F.A.	Fractioneel Cycloonrendement. Een vergelijking tussen model en meting; January 1989, 135 pages.
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1990 Veen, van J.P.W. BOOOEM!! Explosies in twee verschillende stofexplosievaten. Een vergelijkend onderzoek;
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1990 Vercoulen, P.H.W. The development of a new aerosol generator, based on the Taylor cone;
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1990 Woerden, van M.J. The automation of uniform droplet production: Tailor-made droplets;
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1991 Bartels, E.J. Verdunningseenheden voor kristalslurries ten behoeve van het UNIAK project;
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1991 Paassen, van S. Ontsteking van Stofexplosies door Laserstraling;
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1991 Prins, R.B.A. Fines removal in DTB-crystallizers;
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1992 Bloembergen, F.O. Ultrasonic spectrometry an analysis technique for measurement and control of industrial processes;
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1992 Haket, A.J.W. Development of a computer program for forward light scattering particle size distribution measurements;
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1992	Haks, H.D.A.	Some Aspects of Hydrodynamic Modelling of a 970 L DTB-Crystallizer; August 1992, 65 pages.
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Improvement of the particle strength of enzymegranules;
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