Stefan Jan Kowalski
Editor

Drying of Porous Materials

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PREFACE

Preface

Stefan Jan Kowalski

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I am very pleased to act as Guest Editor for this Special Issue of the *International Journal Transport in Porous Media*, entitled **Drying of Porous Materials**. This Special Issue consists of selected papers presented at the XI Polish Drying Symposium, held in Poznań, a historic and beautiful city in Western Poland, on September 13–16, 2005. The Symposium, organized jointly by the Drying Section of the Committee of Chemical and Process Engineering of the Polish Academy of Sciences, the Polish Drying Association, Poznań University of Technology and August Cieszkowski Agricultural University of Poznań, attracted 94 participants, including foreign guests from 13 countries. The Polish Drying Symposium series was initiated in 1972 by Professor Czesław Stumiłło, the Honorable President of this Symposium.

The Symposium language was English, both for lectures and poster presentations. This allowed extended foreign participation and a fruitful exchange of ideas between Polish and international participants. Several prominent scientists were present, including, among others, A.S. Mujumdar, P. Perre, Y. Itaya, T. Kudra, G. Srzednicki, A.E. Djomeh, O. Yaldiz, T. Metzger from abroad and Cz. Strumiłło, Z. Pakowski, I. Zbiciński, S. Pabis, P.P. Lewicki, A. Kmiec from Poland. Altogether, 34 lectures and 7 excellent keynote lectures were presented and the poster session accommodated 43 posters.

The subject of the Symposium has been traditionally shared by agri/food (ca. 35%) and all other drying subjects. Among agri/food subjects, the drying of wood was strongly represented and a considerable number of papers covered drying process simulation and parameter identification. A brief survey of all presentations indicates that there is no national bias or specialty characterizing Polish drying research. Instead, it can be noticed that it encompasses a majority of topics represented at all drying conferences, including the well known IDS (International Drying Symposium).

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This indicates that Polish drying research closely follows global cutting edge research on subjects of drying, including such emerging areas as CFD (Computational Fluid Dynamics) application, drying of nanomaterials, microencapsulation, supercritical drying, etc.

The papers selected for inclusion in this special issue concern mostly drying of liquid-saturated porous materials, but not exclusively. The paper by A.S. Mujumdar "An Overview of Global R&D in Industrial Drying: Current Status and Future" presents a review of the current problems concerning research and development on drying, and particularly on industrial drying. Several papers deal with spray drying, or drying in a bubbling fluidized bed, whose modeling is quite similar to that encountered in the theory of the liquid-saturated porous media.

The Editor of TIPM kindly agreed to publish this special issue of the Journal, with several unpublished papers reflecting some aspects of the theory of saturated porous media applied to heat and mass transfer in drying, as well as an analysis of drying induced stresses. Out of 84 papers presented at the Symposium, the Scientific Committee and the specialists on porous materials, both from Poland and abroad, who acted as the reviewers, have selected 16 papers for this Special Issue. A number of original papers concerning drying, but not necessarily drying of porous materials, presented at the Symposium, will be published in a special issue of *Drying Technology–an International Journal* as well as in a regular issue of the journal *Chemical and Process Engineering*.

As the Guest Editor, I would like to take this opportunity to express my cordial thanks to Prof. Jerzy Weres, the co-chairman of the Symposium and his co-workers from the August Cieszkowski Agricultural University in Poznań, for their help in organizing the Symposium. I also address my sincere thanks to my co-workers from the Department of Process Engineering of the Institute of Technology and Chemical Engineering, Poznań University of Technology for their efforts and precious help in all aspects of the Symposium's organization.

Financial support for the Symposium from the following sponsors is gratefully acknowledged:

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ORIGINAL PAPER

An overview of innovation in industrial drying: current status and R&D needs

Arun S. Mujumdar

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Abstract Over the past three decades there has been nearly exponential growth in drying R&D on a global scale. Although thermal drying had always been the workhorse of almost all major industrial sectors, the need for and opportunities in basic as well as industrial research became clear only after the energy crisis of the early 1970s. Although the price of oil did drop subsequently the awareness of the significance of improving the drying operation to save energy, improve product quality as well as reduce environmental effect remained and indeed has flourished over recent years. New drying technologies, better operational strategies and control of industrial dryers, as well as improved and more reliable scale-up methodologies have contributed to better cost-effectiveness and better quality dried products. Yet there is no universally or even widely applicable drying theory on the horizon. Most mathematical models of drying remain product-equipment specific for a variety of reasons. In this paper, we examine the role of innovation in drying in various industrial sectors, e.g. paper, wood, foods, agriculture, waste management, etc. Progress made over the past three decades and the challenges ahead are outlined. Some areas in need of further research are identified. Examples of intensification of innovation in dryer designs via mathematical modeling are discussed. Finally, the need for closer interaction between academia and industry is stressed as the key to successful drying R&D in the coming decade.

Keywords Innovation · Intensification of innovation · Mathematical models · Energy aspects · Environmental impact · Novel dryers · Research and development needs

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1 Introduction

Thermal drying has been recognized as an important unit operation as it is energy-intensive and has a decisive effect on the quality of most products that are dried commercially. Escalating energy costs, demand for eco-friendly and sustainable technologies as well as the rising consumer demand for higher quality products, have given fresh incentives to industry and academia to devote great effort to drying R&D. Fortunately, this area does not demand a massive perfusion of R&D funds to come up with valuable insights and innovations, with only a few exceptions. Indeed, there is already a sustainable level of R&D support—both in terms of human and financial resources—around the world. Emerging economies of the world, such as China, Brazil, India, etc, have picked up the slack caused by the fully developed economies of the west moving towards nanotechnologies. Overall, the global R&D effort has been rising despite precipitous drops in North America and Europe. With 12–25% of the national industrial energy consumption attributable to industrial drying in developed countries, it is only a matter of time before high energy costs will stimulate further R&D in drying.

The fact that tens of thousands of products need to be dried in over a 100 variants of dryers provides major and ample opportunities for innovation. In this paper, we start with the definition of innovation and how it may be intensified. This is followed by a discussion of some new technologies in comparison with the traditional ones, which still dominate the market. The need for industry–academia interaction and a pro-active role of industry—the ultimate beneficiary of all R&D regardless of its origin—is stressed.

2 Need for and role of R&D

Researchers in academia as well as industry along with granting agencies consistently agree on the need for more R&D funds. They argue that R&D funds should be rightfully considered as investment rather than expenditure. In either case, it is necessary to account for the outlays on R&D in terms of its economic and/or social benefits. It is essential to look critically at the cost/benefit ratio for R&D funds in general and provide appropriate justification for such expenditures or investments. This is more readily—not necessarily easily or reliably—achieved in the business or industrial world. When public funds are used for R&D—a major source for most nations—it is a much more difficult task.

There is much scholarly literature on the economic returns on publicly funded basic research (e.g. A.J. Salter and Ben R. Martin, Research Policy, Vol. 30, 2001, pp. 509–532). As these authors point out, research output may be information or knowledge that can be used to economic advantage; they postulate that much of the publicly funded R&D output is of informational nature and the knowledge created is "non-rival" and "non-excludable". Non-rival knowledge is defined as that which others can use "without detracting from the knowledge of the producers". Non-excludable implies that no one can be stopped from using this knowledge—even competitors have free access to it although they did not pay for it directly. This is also the nature of information and knowledge disseminated by journals such as Drying Technology.

Utilization of "free" informational knowledge requires significant investment to understand and use it to advantage. Thus, scientific knowledge is really not available "freely" but only to those who have the necessary expertise to access it. An OECD

Report (1996) states: "Knowledge and information abound; it is the capacity to use it that is scarce". Information is available to all, but only those with the right capabilities can convert it to knowledge and use it to innovate.

I postulate that the rate of technological innovation depends directly on the rate of generation of informational knowledge and the effectiveness of its utilization; the latter is a measure of the ability to assimilate or exploit the knowledge. Efficient dissemination of knowledge is important but it is equally important to develop the ability to utilize it. Academic institutions are responsible for developing such ability. If they can also make a valuable contribution to the generation of new knowledge, then they are very effective in enhancing the rate of innovation, which drives the economic growth of nations.

Talking about sustainable development is in vogue these days. Clearly, it makes a lot of sense and the world will be a better place if all development were truly sustainable. I believe that this concept is applicable to research and development effort as well, be it in academia or in industry.

We are concerned about the continually shrinking R&D funding pie almost all over the world. Granting bodies have tried to cut the pie in many different ways. Usually, areas that are currently popular or fashionable receive larger shares of the pie, thus reducing the funding for some other key or core areas—or worse, even eliminating funding for many of the so-called traditional areas of research. The implication is that enough R&D has already been conducted in areas that have existed for longer periods. New is automatically assumed to be innovative, creative and thus valuable for the future development of the economy. Larger portions of R&D funding have gone into energy technologies, environmental issues, bio-technology, IT, etc. over the past two decades, and more recently into nano-science and nano-technology. Clearly, all these areas are important and deserve funding. The issue is how much and at what cost to the other areas. Will it cause some core incompetencies in future?

This is where I think, we need to examine my idea of *sustainable research* level. Just for illustration, if all institutions around the world focus their effort on developing nano-technology, are there enough opportunities for so many to make original contributions? Also, is the market large enough for all the players to obtain adequate returns on their investments? Some institutions will lead and outpace most others as a result of their access to higher levels of human and financial resources. At the same time, areas that industry currently needs and technologies that form the lifeline of current businesses will be penalized as no new funding is made available for the new R&D areas. Overcrowding of pre-selected research areas is as risky as under-populating them with under-funding. Over-funding does not assure development of innovative ideas; it may even impede it as funding becomes easier to obtain and hence non-competitive. Also, projections of potential major windfall from new technologies are fraught with uncertainties.

I wish to postulate that for each research field at any given time and any given location, there is a sustainable level of R&D funding support beyond which the returns on investment will necessarily decline. The opportunity cost of not doing R&D is other areas will rise as well. Drying is considered a mature area: in many ways it is. However, there are still many unsolved, complex problems that deserve attention and offer challenges to researchers. The return on the modest levels of R&D funding needed to carry out drying research can be substantial since this operation is so energy-intensive and has a direct impact on product quality and the environment. What is needed is a focused effort with collaboration between industry and academia.

Aside from producing highly qualified researchers, such cooperation will also produce improved technologies that will benefit industry and the consumer at large. It is obviously unlikely that industries will be operating without the unit operation of drying, which means investment in drying R&D will have a useful pay-off at all times. One valuable effect of globalization and free flow of research results is that not all countries need to be involved in many areas of scientific R&D that can be best left to countries with needed resources.

3 Innovation

According to Howard and Guile (1992) innovation is defined as follows:

> *"A process that begins with an invention, proceeds with development of the invention, and results in the introduction of new product, process or service in the marketplace".*

To make it into a free marketplace, the innovation must be cost-effective. What are the motivating factors for innovation? For drying technologies, I offer the following checklist; one or more of the following attributes may call for an innovative replacement of existing products, operation or process:

- New product or process not made or invented heretofore;
- Higher capacities than current technology permits;
- Better quality and quality control than currently feasible;
- Reduced environmental impact;
- Safer operation;
- Better efficiency (resulting in lower cost);
- Lower cost (overall, i.e., lower investment and running costs).

Innovation is crucial to the survival of industries with short time scales (or life cycles) of products/processes, i.e., a short half-life (less than one year, as in the case of some electronic and computer products). For longer half-lives (e.g., 10–20 years typical of drying technologies) innovations come slowly and are less readily accepted. The need for replacement of current hardware with newer and better hardware is less frequent and the payback is less attractive. It is important to note that newness per se is not good enough justification for adoption of "innovative" technologies.

Innovations may be revolutionary or evolutionary. Evolutionary innovations, often based on adaptive designs, have shorter gestation periods, shorter times for market acceptance and are typically a result of "market-pull," something the marketplace demands, i.e., a need exists currently for the product or process. These usually result from a linear model of the innovation process (an intelligent modification of the dominant design is an example). Revolutionary innovations, on the other hand, are few and far between, have longer gestation periods, may have larger market resistance and are often a result of "technology-push," where development of a new technology elsewhere prompts design of a new product or process for which market demand may have to be created. They are riskier and often require larger R&D expenditures, as well as sustained marketing efforts. The time from concept to market can be very long for some new technologies. It is well known that the concept of a helicopter appeared some 500 years before the first helicopter took to the air. The idea of using superheated steam as the drying medium was well publicized over 100 years ago, yet its real commercial potential was first realized only about 50 years ago and that too not fully. In fact, it is not fully understood even today! The most recent example of this long-gestation period is the Condebelt drying process for high basis weight (thick grade) paperboard, proposed and developed by the late Dr. Jukka Lehtinen for Valmet Oy of Finland. It took a full 20 years of patience and high-quality R&D before the process was first deployed successfully.

It is natural to inquire if it is possible to "guesstimate" the best time when the marketplace requires an innovative technology or the mature technology of the day is ripe for replacement. Foster's well-known "S" curve (Foster 1986), which gives a sigmoid relationship between product or process performance indicators and resources devoted to develop the corresponding technology, is a valuable tool for such tasks. Every technology has its asymptotic limit of performance. When this happens (or even sooner), the time is ripe to look for alternate technologies, which should not be incremental improvements on the dominant design but truly new concepts, which once developed to their full potential, will yield a performance level well above that of the current one.

Table 1 lists examples of some new drying technologies that were developed via technology-push versus market-pull. In some cases, a sharp distribution or grouping in just two types is not possible since a "market-pulled" development may require a "technology-push" to succeed. For example, development of new materials was key to successful implementation of the Condebelt or impulse drying process for paper.

Innovation has become a buzzword in academia and industry alike. Drying R&D and technology is no exception. We have been promoting innovation in drying for over two decades via the IDS series as well as Drying Technology journal. However, the quantitative measurement of innovative performance remains an elusive task. There are no widely accepted indicators of innovative performance or a common set of indicators to assess the returns on investment. Such an indicator or set of indicators is crucial to managing innovation. Some literature studies have used R&D inputs, number of patents, number of patent citations, counts of new product launches, etc., as indicators of innovative performance in industry. The task is harder for academic institutions, however, which often remain fixated on the impact of the "printed matter" generated rather than industrial significance, which is hard to measure.

Table 1 Examples of new drying technologies developed through technology-push and market-pull

Technology push[a]	Market-Pull[b]
Microwave/RF/induction/ultrasonic drying	Superheated steam dryers— enhanced energy efficiency, better quality product, reduced envi ronmental impact, safety, etc.
Heatpump dryers	
Pulse combustion drying—PC developed for propulsion and later for combustion applications	Impulse drying/Condebelt drying of paper (also needed technology-push to succeed)
Vibrating bed dryers—originally developed for solids conveying	Combined spray-fluid bed dryers—to improve economics of spray drying
Impinging streams (opposing jets)—originally developed for mixing, combustion applications	Intermittent drying—enhance

[a] Technology originally developed for other applications applied to drying; also may be "science-push" type

[b] Developed to meet current or future market demand

It is always interesting to look at Nature for truly creative ways of solving complex problems. A recent article in Mechanical Engineering Design (2004) discussed a species of beetle, called the Bombardier beetle, which squirts its predators with a high-pressure pulsed spray of a boiling hot toxic liquid. The chemistry of the liquid and the mechanism of the pulsed spray have been studied in depth by biologists and biochemists for over two decades. Research by Professor G. Eisner of Cornell University discovered that the Bombardier beetle produces hydrogen peroxidase and hydroquinone, and when attacked by a predator, it can mix the two in a tiny heart-shaped combustion chamber to produce benzoquinone and steam; the mixture is then emitted as a pulsed jet at temperatures of the order of 100°C. Recent research at the University of Leeds by Professor McIntosh has already found that the unique shape of the beetle's reaction chamber is critically important in maximizing the mass of ejected spray for each "explosion", which can occur about 300 times/ s. The shape of the nozzle, which can swivel in any direction, is also important. An in-depth study of this unique creature is expected to yield a solution to the occasional but serious problem of re-igniting a gas turbine aircraft engine, which has cut out at high altitudes and extremely low temperatures. Clearly, the study of natural engineering marvels can help us arrive at novel engineering solutions to complex problems.

Copying such natural mechanisms is a feature of the field of biomimetics in which scientists and engineers learn from the intricate design ideas that nature uses. Indeed, the pulsed combustion-based self-defense mechanism of the Bombardier beetle is an extremely complex design. Such a study will require sophisticated research techniques and multi-disciplinary teams involving biologists, biochemists, chemists as well as engineers. I believe that improved design of the pulsed combustion process could also lead to improved design of novel pulsed combustion dryers to produce powders from liquids. The jury is still out on the viability of this concept.

Revolutionary innovations in any technology are always met with skepticism and even disdain by industry. Everyone wishes to work within their comfort zone. Most industries are risk-averse. Hence, true innovations are hard to market and gain acceptance by industry. However, when they do cross the barrier, they can be truly disruptive in that they have the potential to displace or even supplant the conventional technology of the day. It is noteworthy that in the business world most want to be "second" and not the "first with innovation".

Innovations can thrive only under appropriate incubation conditions. For example, the USA is well recognized as the greatest engine of innovation. It is hard to duplicate it elsewhere with equal success since it is a product of numerous factors, ranging from freedom of thought and expression, stress on independent thinking, ready acceptance of diverse ideas and cultures, immigration of new minds and mindsets, developed financial markets, and risk-taking culture. It is not surprising that the US system is unmatched in recent decades when it comes to bringing innovative ideas and concepts to the world markets. Although there is much hue and cry in the USA about job losses due to outsourcing to the developing world—another innovation from corporate America—it is unlikely it will have a long-term undesirable effect on the US economy since this change will soon precipitate another innovation in business models.

Meteorologist Edward Lorenz in 1972 published a paper entitled "Predictability: Does the flap of a butterfly's wings in Brazil set off a Tornado in Texas", which essentially sums up the Chaos Theory. In complex non-linear systems small perturbations can lead to major disturbances; apparently random events (like flapping of wings and tornado) may actually follow some underlying rules. True innovations follow a non-linear pathway. Thus, there is high likelihood that even minor modifications in dryer designs may eventually lead to major improvements in drying technologies, which we cannot anticipate today. At least, we hope developments in drying are chaotic at least for this reason!

Finally, innovation is not necessarily based on new ideas. Some old ideas will re-emerge, e.g., use of superheated steam drying. It is important to re-visit some old ideas to see if they are viable at the present time. Novel ideas ahead of their time sometimes fizzle out but re-emerge when the time is right.

4 Intensification of innovation

Dodgson et al. (2002) have argued that the innovation process can be enhanced by applying digital technologies, which can simulate, model, integrate and intensify the innovation process via a cost-effective effort. They propose that automation of innovation is feasible. In fact, this is called "Rothwell's concept of the fifth generation" innovation process. Basically, the digital computing power provides a new "*electronic tool kit*" that facilitates transfer, transformation and control of various kinds of information that is required for the successful introduction of innovative products and/or processes in the market place.

The origin of innovation in drying technologies could be a result of: (a) serendipity (chance); (b) fundamental principles of heat and mass transfer, or (c) empiricism. Empirically generated innovations are evolutionary in nature; they are based on incremental improvements of prior technology. Innovations arising from serendipity or fundamentals can be evolutionary or radical. Digital enhancement of innovation is clearly possible primarily with the help of fundamental principles, which can be modeled either deterministically or stochastically with reliable mathematical relationships. As examples, we can cite innovations in spray dryers, flash dryers, high-temperature impinging jet dryers for tissue paper, etc., which allow computer-aided design and modeling. New spray dryer chamber designs can be evaluated with minimal expense and risk using computational fluid dynamic simulations. Both the time from concept to product in the market as well as the cost of the design process can be reduced very significantly via computer simulations. This is not very different from what is already being done in the aircraft industry, e.g., the Boeing 777 was designed primarily by computer-aided simulation and design, unlike its predecessor models. However, transport phenomena occurring in the spray dryer chamber are far more complex than the aerodynamics of flow over the airplane.

Without going into the details of the types and nature of innovation, we can make the following general observations about innovation in the field of drying of solids and liquids:

- Most new dryer design improvements are incremental in nature, e.g., two or three-stage spray drying.
- They are based on intelligent combinations of established technologies, e.g., two-stage spray and fluid bed dryers, steam-tube rotary dryers, ultrasonic spray dryers, etc.
- No disruptive drying technologies (i.e., ones which have supplanted traditional technologies) have appeared on the horizon as yet.

- Truly novel technologies, which significantly from the conventional ones, are not readily accepted by industry, e.g., superheated steam impinging jet drying of paper, Condebelt drying of liner board, pulse combustion dryers, use of a bath of liquid metal to dry paper, the Remaflam process for textile drying, impinging stream drying for sludge, etc.
- The need for new drying hardware is typically limited due to the long life-cycle of drying equipment; for example, most dryers have a life span of 20–40 years. Hence, the need for replacement with new equipment is limited.
- Often, firms which are first to commercialize a new product or process in the market, do not necessarily benefit from being the true innovators. This phenomenon hinders the introduction of new technologies. A fast second or even a slow third might outperform the innovator. According to Teece (1986), this observation is particularly pertinent to science and engineering-based companies that have the illusion that development of new products that meet customer needs will ensure success. A classical example of this phenomenon is RC Cola, which was first to introduce Cola in a can; however, it was Coca Cola and Pepsi Cola that dominated the market. There are numerous such examples, e.g., pocket calculator (Bowmar was outperformed by Texas Instruments, HP and others); personal computer (Xerox outperformed by Apple); jet aircraft (de Havilland Comet outperformed by Boeing 707), etc. In all these cases, the innovator was first to the market but could not sustain or even attain prominence in the market. Hence, the reluctance to be first in the market with a new process or product.
- Often, innovative concepts are initiated by academic researchers and published without filing for intellectual rights protection in the open literature. Although this is really impactful R&D, little credit accrues to the academic since no archival papers result from industrial use and hence no "citations"! This is a double-edged sword from this author's experience. It is good in that the ideas are widely and freely disseminated for wider economic benefits to society at large. On the other hand, potential industrial interest is dampened by the fact that the innovation is in the public domain so that further R&D investment by industry may not have a payback. The problem of IP (intellectual rights) must be properly addressed to encourage innovation by academia and its transfer to industry and to value it appropriately.
- Since there is potential to innovate via the route of fundamentals and simulations, close industry-academia interaction is another attractive and cost-effective way to intensify innovation. It represents a true win–win situation. A close inspection of the relevant technical literature shows that many new concepts for dryers originate in academia but are rarely utilized in industry since the necessary development work is beyond the scope of academic research. Without the D in R&D no technology transfer occurs. Without the R, there is no potential for D in the R&D combination. *The importance of R is also inherent in the word drying itself! Without R the field itself cannot survive!*
- Drying, contrary to popular belief, is a knowledge-based technology. The manufacturing technologies needed are often very straightforward and found readily in most of the developing world. What is needed for a cost-effective drying system to be made is "knowledge" and "know-how" to counteract deficiencies of knowledge. Knowledge knows no geopolitical boundaries, as is evidenced by the rapid spread of IT technologies in the developing world. Indeed, the latter in some cases has assumed the world-leading role despite capital shortages. This drying

knowledge/ know-how has the potential to be assimilated readily as was done with IT by the developing countries with strongly educated and motivated human capital. Note that the total US market for capital expenditure on dryers was estimated to be only about $500 million by a contractor for the DOE. It is likely an underestimate but perhaps not a far cry from the real figure. Thus design, operation, and optimization of dryers are the key business needs in this field. Clearly, this requires both basic and applied research.

- Drying R&D to be effective must be cross-disciplinary. Typically, product knowledge and techno-economic aspects are best provided by industry collaborators.
- International collaboration, cooperation, and competition is conducive to intensifying innovation in general. Aside from savings in the use of human and financial resources for R&D it can lead to synergy.

5 Conventional versus new drying technologies

It is difficult to make a sharp distinction between what is conventional and what is really new in drying technologies since most of the newer developments are evolutionary, i.e., based on traditional ones; often the transition is seamless and it is not possible to identify where and when it occurred. The following discussion must therefore be taken within this vagueness inherent to the field itself.

Kudra and Mujumdar (1995) have classified and discussed various novel dryers, ranging from laboratory-scale curiosities (e.g., acoustic drying, drying of slurries by impinging sprays over a hot surface) to pilot-scale demonstrations (e.g., pulse combustion dryers, ultrasonic spray dryers, impinging stream dryers) to full-scale commercial dryers (e.g., pulsed fluid beds, superheated steam fluid bed/flash dryers, rotary dryers with drying air injected into the rolling bed). A full discussion of the truly bewildering variety of non-conventional dryers is beyond the scope of this presentation. The interested reader may refer to the book by Kudra and Mujumdar (2002) for a comprehensive coverage of the numerous new drying concepts and technologies. The Handbook of Industrial Drying (Mujumdar 1995) is also a source of relevant information.

Table 2 summarizes the key features of the newer dryers as compared to those of conventional ones for drying of various physical forms of the wet feed material. Note that the new designs are not necessarily better than the traditional ones for all products, but they do offer some advantages that may make them a better choice in some applications. Some of them are simply intelligent combinations of conventional dryers.

Table 3 compares some key features of the newer or emerging drying technologies with those of the more commonly used conventional techniques. In terms of the sources of energy there is no difference. However, in terms of how this energy is delivered and transferred to the wet solid there are some significant differences.

In the chemical industry, the most common drying application involves production of dry particulates from pumpable liquids (solutions, suspensions, or slurries), thin or thick pastes (including sludge), or granular solids. Spray and drum dryers are used most commonly for such applications. Spray dryers today no longer just convert a pumpable liquid to a powder but can be used to produce "engineered" powders with specific particulate size, as well as structure (e.g., agglomerates, granules, or large mono-sized spherical particles). Personnel safety on and around dryers, prevention of environmental pollution, and emphasis on production of a high-quality product at minimum cost are paramount considerations in the design of spray dryers today. With