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ROLE OF IDS IN PROMOTING INNOVATION AND GLOBAL R&D EFFORT IN DRYING TECHNOLOGIES

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ABSTRACT

Since the IDS series was initiated in 1978 at McGill University, Montreal, Canada in 1978, there has been a remarkable increase in the R&D effort devoted to understanding drying fundamentals and applying them to improving the performance of traditional drying techniques as well as developing innovative ones. This truly global .multi- as well as cross-disciplinary effort has grown nearly exponentially over the past two decades and now covers all continents. IDS has now spawned several other regional and national conference series as well as workshops which demonstrate the rising interest in this unit operation in almost all major industrial sectors and in developed as well emerging economies. This presentation will attempt to summarize my personal thoughts on the process of innovation and how it has been and will be applied to drying R&D after a brief introduction to the significance of drying itself drawing on some statistical data. The need for sustained R&D in drying in the face of severe competition for human and financial resources from the newer “extreme engineering” applications will be emphasized. Some areas for future development will be identified. The need for development of a new generation of highly qualified research personnel in drying and the importance of industry-academia interaction should be recognized to continue to enhance our knowledge of the complex field of solids drying. Significant progress has been made over the past two decades but a lot remains to be accomplished, which implies that IDS remains a comparatively youthful movement with a strong momentum to promote and synergize R&D in this very important field.

INTRODUCTION

Drying of solids is a complex operation involving transient transport phenomena coupled with physical/chemical/biochemical transformations, which, in turn, may lead to changes in heat and mass transfer mechanisms. Drying is amalgamation of material science and transport phenomena. Our understanding of drying at the microscopic level is still rudimentary while our knowledge base with regard to dryers has continued to expand over the years. Scale-up of most of the dryer types continues to be complex and empirical, and is often equipment and product-specific because of the highly non-linear nature of the governing conservation equations of transport processes. Following Albert Einstein's advice: *make them simple, but not simpler,"* most models and design procedures are simplified so that we can adequately scale-up drying hardware for industrial use. Precise modeling is still not possible for most product-equipment combinations. Even today empirical know-how plays a dominant role in the design of dryers.

Many commonly used drying technologies have matured and perhaps reached their respective inherent asymptotic limits of performance, at least for some products and in certain industries. New products, new processes, higher production rates, more stringent environmental regulations, increased safety concerns, etc. often demand better performance levels at lower costs than is possible with traditional dryers. This need has led to some innovation in drying technologies. Many of the innovative concepts are still at the pilot stage while several have reached successful commercialization. Due to the lower risk involved and their shorter gestation periods, many of the successful innovations are evolutionary in nature; revolutionary innovations involve greater risks, are more difficult to scale-up because of lack of experience, and hence are less readily embraced by industry. If energy costs are driven up due to global situations involving supply of oil and gas, then there will be greater pressure on development of more energy-efficient drying technologies and even on use of renewable energy sources in industrial drying operations.

A HISTORICAL OVERVIEW OF IDS SERIES

The First International Symposium on Drying, its official title at the time, was announced in the Spring of 1977 and held in August 1978 on the campus of McGill University in Montreal, Canada. Fortunately, despite the short induction time it turned out to be a success, thanks to sponsorships by several large companies and several professional societies. A formal proceedings volume was published, it contained only about 40 papers although about twice as many were presented at the meeting. A Forum was held on R&D Needs and Opportunities which reflected strong industrial interest and accentuated the need for a forum devoted to exchange of information on drying regardless of geographical, disciplinary and industrial sectoral boundaries. Thus, the food or textile industry could benefit from advances made by the paper industry in drying of continuous sheets, for example. It was recognized that drying is a truly inter- and multi-disciplinary field that can only advance by sharing the expertise in different disciplines and industries. Indeed, there is no major industry that does not utilize drying processes at some stage of their manufacturing sequences.

The First International Symposium on Drying attracted 210 participants from 22 countries. About 90 papers were presented along with 6 Keynote lectures. Only about half of the papers presented appeared in the proceedings volume while most of the remainder appeared in Drying'80, volume 1. A Panel Discussion was organized on Needs and Opportunities in Drying to identify industrial needs and promote industry-university interaction on a global scale. One unique feature of the first symposium was the fact that it attracted a greater number of participants from industry rather than academia (112 from industry and government laboratories and 98 from academic institutions). It was clear that industry was well aware of its drying R&D needs while the academic world was not quite active in the field probably as a result of years of traditional isolation from the industrial environment. Without exception academic participation exceeded the industrial one in all later IDS meetings. I believe a balanced participation is the key to success in effective technology and knowledge transfer and IDS must endeavor to correct this anomaly in future.

Subsequent evolution of the IDS series, as indicated in Table 1, clearly shows the rising interest in drying R&D by both academia and industry on a truly global scale. Participation by industry demonstrated the need for better understanding of various drying processes and the numerous challenging problems in drying. The academic community benefited by being exposed to industry needs so that they could develop new viable research programs. Cross-fertilization of ideas occurred as participants from different disciplines, different countries and different industries inter-mingled and readily appreciated the commonality of several drying problems they had thought to be the exclusive domains of their discipline or industry. This awareness also helped develop research collaborations and avoid unnecessary duplication of research effort.

Table 1 IDS Events

Year	IDS Event
1977	International Drying Symposium announced in March
1978	First Symposium held at McGill University, Canada
1980	Second Symposium held also in Montreal
1982	Birmingham, U.K. - Symposium series goes global
1984	Kyoto, Japan - Term IDS used for first time
1986	Cambridge, U.S.A. - Major Awards initiated
1988	Versailles, France
1990	Prague, Czech Republic - First time IDS part of a major international conference (CHISA'90)
1992	Back to square one: Montreal, Canada
1994	Gold Coast, Australia
1996	Krakow, Poland
1998	Thessaloniki, Greece
2000	The Netherlands
2002	Beijing, China
2004	Sao Paulo, Brazil
2006	Budapest, Hungary

Without significant industry participation there is a danger that academic researchers will follow what I call a "closed-loop" approach to research (see editorial in Drying Technology-An International Journal, 16(1&2), 1998). Basically it leads to academic research by academics and for academics resulting in little technology transfer. In an applied field such as drying results of research are wasted if they are not used by industry in some fashion. In the closed loop approach one academic paper spawns another and this sequence continues indefinitely until, perhaps, research funds run out. Unfortunately, academic reward systems encourage citation by other academics rather than use of the research by industry for design or development. While this does lead to a larger citation frequency the results are typically wasted. What we really need to assess drying research (and indeed any other applied research) is a new "utilization index" and not a citation index since only another academic can typically cite a published paper. I believe that IDS provides an opportunity for the academic to interact with the industry counterpart and familiarize himself/herself with real world problems awaiting effective solutions.

As expected the geographic location of the meeting has a strong bearing on the number of local participants, industrial sectors of interest as well as the level of total attendance. IDS'98 attracted 430 abstracts from some 57 countries breaking all previous records. The final attendance figure approached 350 from 55 countries. The 3- volume set of Proceedings, Drying'98, contains over 250 papers. Subsequent IDS's in the Netherlands and China also matched these statistics.

It is difficult to make a sharp classification of the subject matter of papers presented at IDS's. Any classification scheme one might propose has to be somewhat arbitrary and overlapping since a given paper may be classified into several categories simultaneously. Coumans (1997) classified the IDS'96 papers into three major categories as follows:

1. Theoretical (fundamentals, simulation, modeling, etc.): 23%
2. Practical (equipment-oriented, technology, control, etc.): 25% and
3. Product-based (e.g., those dealing with foods, agriculture paper, wood, etc.): 52%

Of the product-based papers some 60% of the papers dealt with food and agriculture. Drying of paper and wood were major topics only at IDS meetings held in North America and Western Europe.

As far as industrial sectors are concerned, food and agriculture remain the most dominant sectors in view of the critical importance of drying to these industries; typically over 30 percent of the IDS content is devoted to this area. Drying of wood remains a major problem of great interest to the forest products industry. However, IDS has had to contend with biennial meetings which deal exclusively with wood drying which have in recent years been held at about the same time but in different parts of the world. Drying of coatings is another area of immense industrial interest that is inadequately represented at IDS meetings once again due to specialized meetings in the topical area. The same is true for drying of ceramics and advanced materials, which continue to remain weakly represented at IDS conferences.

The format of IDS conferences has remained largely unchanged since its inception. It consists of several Keynote lectures, several parallel sessions in lecture format and poster sessions to accommodate the increasing number of technical contributions. I believe that each IDS has had the critical mass required for a fruitful interaction and yet has been small enough to allow development of personal contacts which could later flourish into valuable joint R&D projects.

The number of participants, number of countries represented as well as the number of papers presented have all shown a steady rise over time with occasional dips related mainly to the geographical location of the specific IDS. Each meeting has had a good distribution of attendees from industry and academia although for more effective technology transfer we ought to seek greater industrial participation. IDS is grateful to the companies that have supported IDS either directly or indirectly through the Major Awards program. Such sponsorship gives the right signal to those from industry who need to justify their participation in a meeting such as the IDS.

Some countries have traditionally been more active in drying R&D relative to others, e.g., Brazil, France, Poland, Finland, Norway, Canada, etc. The drying activities in the U.S.A. have traditionally been at a level one would expect on the basis of papers presented at IDS's and published in Drying Technology-An International Journal. In general there is a rise in interest in drying R&D in Latin America, Asia and Australia while it appears to be steady in other continents. In fact, IDS has spawned other major meetings of a regional nature, e.g., the Inter-American Drying Conference (IADC), the Asia-Pacific Drying Conference (ADC), the Nordic Drying Conference (NDC), etc. As many as three separate drying conferences are held biennially in P.R. China reflecting the high level of interest and activity in drying in that country.

A careful reading of the technical programs of all the IDS events held so far clearly demonstrates a change in the themes and the relative significance of various topics. While in early years energy savings and scale-up procedures for dryer design were prominent topics in recent years it is quality aspects, optimization via mathematical models and development of novel drying techniques. It seems that modeling drying at the microscopic level has remained a formidable task over the past decade with only a handful of research groups around the world devoting serious attention to the subject.

It was in 1985 that I suggested to Dr. C.W. Hall, the then-Editor of Drying Technology and Deputy Director for Engineering at the National Science Foundation, Washington D.C., that since IDS had matured and developed its own momentum and recognition around the world, it was time to recognize those who make outstanding contributions to the field. Much to my delight Dr. Hall accepted the idea and went ahead to seek successfully sponsors for four major awards that were initiated at IDS86 held on the campus of M.I.T., Cambridge, MA. This program has now evolved into a major event with the support of large multinational companies. I believe that this program in its own right has helped promote drying as a viable research area worthy of serious investigation. It has also helped bring "new blood" into drying R&D - an extremely important and desirable by-product of the success of IDS. This is important for the future of IDS and to sustain its goals.

The rising number of participants in IDS events is particularly spectacular in view of the fact that numerous regional and national conferences solely devoted to drying are being held each year in different parts of the world. Indeed, 2003 was a particularly bumper year for drying-related events. For instance, two major regional drying conferences viz. the 2nd Nordic Drying Conference, Copenhagen, Denmark, and the 3rd Asia-Pacific Drying Conference, Bangkok, Thailand, were held successfully with over 70 papers presented at each meeting. Additionally, drying-focused conferences were held in Moscow (Russia), Crete (Greece), Lodz (Poland), Hangzhou (China), Lagos (Nigeria), Durgapur (India) etc.. This is aside from the large number of drying workshops held for the benefit of industry and commercial establishments. I was personally involved in lecturing at drying workshops in Thailand, Viet Nam, Indonesia, Singapore, India etc. in just 2003!

This year will see one more major drying event – viz. IWSID2004 (International Workshop and Symposium on Industrial Drying) to be held in Mumbai in December 2004. As a rapidly growing economy, the Indian sub-continent is expected to require access to modern drying technologies to enhance industrial as well as agricultural productivity. Indeed, India is the last major country to initiate activity in drying R&D and provide a forum for academics and industry to interact and become familiar with the latest developments in the field of drying. Other major developing countries of the world e.g. China and Brazil initiated such activities nearly two decades earlier.

NEED 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 in 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 generation of new knowledge as well then they are very effective in enhancing the rate of innovation, which drives 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 was truly sustainable. I believe that this concept is also 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 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 already enough R&D has 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 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 noncompetitive.

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 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 which can be best left to countries with needed resources.

INNOVATION

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

"A process that begins with an invention, *precedes 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.

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 one hundred years ago, yet its real commercial potential was first realized only about fifty years ago and that too not fully. In fact it is not fully understood even today! Most recent example of this long gestation period is the Condebelt drying process for high basis weight (thick grades) paperboard proposed and developed by the late Dr. Jukka Lehtinen for Valmet Oy of Finland. It took a full twenty years of patience and high quality R&D before the process was first deployed successfully. The vision required by the management teams of such organizations must be truly far-sighted!

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), time is right 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 2 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.

Table 2 – Examples of new drying technologies developed through technology-push and market-pull

Technology Push*	Market-Pull**
Microwave/RF/induction/ultrasonic drying Heat pump dryers Pulse combustion drying – PC developed for propulsion and later for combustion applications Vibrating bed dryers – originally developed for solids conveying Impinging streams (opposing jets) – originally developed for mixing, combustion applications	Superheated steam dryers– enhanced energy efficiency, better quality product, reduced environmental impact, safety, etc. Impulse drying/ Condebelt drying of paper (also needed technology-push to succeed) Combined spray-fluid bed dryers – to improve economics of spray drying Intermittent drying – enhance efficiency by reducing energy consumption and/or allowing use for multi-chamber, multi-product designs

*Technology originally developed for other applications applied to drying; also may be "science-push" type
**Developed to meet current or future market demand

Innovation has become a buzz word 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 journal. However, 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.

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 in 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 per second. 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, study of natural engineering marvels can help us with arriving 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.

Revolutionary innovations in any technology are always met with skepticism and even disdain by industry. Everyone wishes to work within one's comfort zone. Most industries are risk-averse. Hence true innovations are hard to market and get 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 conventional technology of the day.

Innovations can thrive only under appropriate conditions of incubation. 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 nonlinear 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 nonlinear 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!

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 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. Boeing 777 was designed primarily by computer-aided simulation and design unlike its predecessor models.

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:

- 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 defer from the conventional ones in a significant manner, 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, 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 to 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 market with 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 the society at large. On the other hand, potential industrial interest is dampened by the fact that the innovation is in 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 for intensifying 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 inherent also in the word drying itself! Without R the field itself cannot survive!*
- Drying, contrary to popular belief, is a knowledge-based technology. Manufacturing technologies needed are often very straightforward and found readily in most 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 have 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.

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 3 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 4 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.

Table 3. Conventional versus innovative drying techniques

Feed Type	Dryer Type	New Techniques*
Liquid suspension	Drum Spray	Fluid/spouted beds of inert particles Spray/fluid bed combination Vacuum belt dryers Pulse combustion dryers
Paste/sludge	Spray Drum Paddle	Spouted bed of inert particles Fluid bed (FB) (with solids back-mixing) Superheated steam dryers
Particles	Rotary Flash Fluidised bed (hot air or combustion gas) Conveyor dryer	Superheated steam FBD Vibrated bed, Ring dryer, Pulsated fluid bed, Jet-zone dryer Impinging streams Yamato rotary dryer
Continuous sheets (coated paper, paper, textiles)	Multi-cylinder contact dryers; Impingement dryers	Combined impingement/ radiation Combined impingement and through dryers Impingement and MW or RF or Radiation dryers

MW, microwave; RF, radio frequency
* New dryers do not necessarily offer better techno-economic performance for all products. Many require future R&D and market acceptance to succeed.

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 product “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 the help of computer simulations, better designs of the dryer chamber and air flows within the dryer have led to reduced wall deposit problems in spray dryers. A new spray dryer concept even uses a flexible canvas cone instead of the usual metallic one. Multi-stage spray dryers in which the surface water is removed while the droplets are airborne and the internal moisture (which takes longer dwell time to be removed is dried in a smaller fluid bed dryer at the bottom of the spray chamber), are now common technology for large scale spray drying applications. Both the capital and operating costs of such dryers are much lower than those for spray dryer alone for same duty.

More recently horizontal spray dryers are also being considered and at least two companies market such units which require more floor space but more head space. Operation at reduced pressure for drying of heat sensitive materials, use of ultrasonic atomizers for a less poly-disperse spray, and use of superheated steam with its many advantages are some of the newer spray drying technologies over the horizon.

Table 4. Comparison of conventional versus emerging drying technologies

	Conventional	**Emerging Trends**
Energy (heat source)	Natural gas, Oil Biomass, Solar/wind Electricity (MW/RF) Waste heat	No change yet. Renewal energy sources when fossil fuel becomes very expensive
Fossil fuel combustion	Conventional	Pulse combustion
Mode of heat transfer	Convection (>85%) Conduction Radiation (<1%) Microwave/ radio frequency	Hybrid modes Non-adiabatic dryers Periodic or on/off heat input
Drying medium (convective dryers)	Hot air Flue gases	Superheated steam Hot air + superheated steam mixture or two-stage
Number of stages	One – most common Two or three – same dryer type	Multi-staging with different dryer types
Dryer control	Manual Automatic	Fuzzy logic, Model based control, Artificial neural nets

The development of in-place cleanable bag filters makes it possible to retain the particulates within the dryer chamber; this is achieved by mounting the filter elements in the roof of the spray dryer chamber. No external cyclones are needed in this case. This technology, coupled with the popular fluidized-spray dryer featuring a fluid bed dryer integrated into the base of the spray dryer chamber, allows efficient production of dust-free agglomerated or granulated products at substantially lower product temperatures than those found in conventional spray dryers.

For drying granular or particulate solids, the most common dryers in use today are cascading rotary dryers with or without internal steam tubes, conveyor dryers, and continuous tray dryers (e.g., turbo or plate dryers), which must compete with fluidized-bed dryers (with or without internal exchangers) and vibrated bed dryers, among others. At least 20 variants exist of the fluidized-bed dryer alone. For larger particles, a spouted bed dryer is preferable to the conventional fluidized-bed-dryer. For difficult-to-fluidize, sticky particles or feed stocks with a wide particle size distribution, the vibrated bed dryer offers advantages over the conventional fluid bed because it allows use of low drying air velocities while mechanical vibration assists in pseudo-fluidizing the solids. Recently the pulsed fluidization technique has found some interesting applications similar to those for vibrated fluid beds.

Fluidized-bed dryers have been operated successfully using superheated steam as the drying medium both at near atmospheric pressures (e.g., drying of pulverized lignite) and at elevated pressures (3-5 bars for drying of beet pulp). In addition to eliminating potential fire and explosion hazards, use of superheated steam permits utilization of the exhaust steam by condensation, reheating, or compression. Of course, such steam is often contaminated and must be cleaned before re-utilization depending on the application. Net energy consumption in superheated steam dryers may be as low as 700 to 1000 kJ/kg water evaporated, which is five to ten times lower than many conventional convective air drying systems consume. Mujumdar 1990 has discussed the principles, practice and potential of the rapidly emerging superheated steam drying technologies in various industrial sectors, principally for drying paper, wood, some processed foods, sludge, etc. Numerous relevant references are cited as well. It is commonly recognized as the drying technology of the future. It is known that low-temperature superheated steam dryers are feasible for drying very heat-sensitive materials like fruits and vegetables, silk cocoons, etc. SEM pictures of steam-dried products show clearly the quality advantages such products can offer. Easy to re-hydrate dried fruits such as strawberries, pears, apple, have been produced by low-temperature steam drying in Argentina. Vacuum steam drying of wood is probably the best technology for drying of wood. It is more commonly found in the developing countries (e.g., Malaysia, India, Thailand, etc.) rather than in developed countries of North America who have invested heavily in the hot air kiln dryers for wood, which cannot be easily switched to steam operation.

Use of volumetric heating by microwave (MW) and radio frequency (RF) fields has yet to make major inroads in the chemical industry. It is well established that MW/RF-assisted drying is faster, but the energy costs are also significantly higher and scale-up for large production capacities is much more difficult. Such dryers are expected to find some niche applications. RF drying under vacuum has been applied successfully on a commercial scale by a Canadian company for drying of timber and thick veneer with future applications anticipated for drying of chemicals, polymers, and foods. An RF dryer, in conjunction with impingement with hot air jets, is already a commercial process for drying of coated paper. The efficiency of conversion of line power into electromagnetic energy and the cost of electricity are major impediments in commercializing this technology.

Some of the newer drying technologies utilize newly developed gas-solid contactors as dryers for particulates e.g., impinging streams, rotating spouted beds, pulsed-fluid beds, etc. In batch drying one can take advantage of multi-mode heat input in an intermittent manner to optimize both the energy consumption and product quality. Intermittencies may be in the form of changes in flow regimes (packed vs. fluidized), drying air conditions (air velocity, temperature, humidity, etc), operating pressure (atmospheric, above or below atmospheric), and/or changes in modes of heat input (convection, conduction, radiation or microwave/RF applied sequentially or jointly). It has been shown by many investigators that intermittent operation enhances energy efficiency as well as product quality for heat-sensitive materials. When several parameters of the process are altered with time then we have multiple intermittencies. This is a filed that has not been explored in depth yet although this can be done quite easily. Many of the traditional dryers, which we assume to be operating under continuous heat input in fact operate intermittently, e.g., multi-cylinder paper machine. On the other hand, all batch dryers requiring very long dwell times in the dryer are often dried under time-varying drying schedules, e.g., freeze dryers, wood drying kilns, etc.

The list in Table 5 is very short and included only for illustrative purposes. The proceedings volumes of IDS series and several other drying conferences (e.g. ADC, NDC, IADC etc) and the archival journal Drying Technology (www.dekker.com) provide rich sources for new ideas for further R&D. Searches on the internet are also invaluable in identifying new technologies and new research challenges. The whole field is far from maturity; it is still in a state of rapid flux.

SOME R&D NEEDS IN DRYING

It is impossible to summarize R&D needs for all types of industrial dryers. The problems are as diverse as the equipment and often the wet materials processed. Since the prospects for a universally applicable theory of drying is not on the horizon any time soon, scale up of dryers will continue to rely heavily on carefully planned experiments with phenomenological models of limited applicability. Most models are applicable for specific product-equipment combinations (with notable exceptions, of course). Some 60,000 products need to be dried at different scales in over 100 dryer types. The need for R&D is therefore enormous. What is included here covers just a few basic ideas and the interested reader can readily extend them into some innovative designs for improved drying technologies.

Table 5. Some R&D Problems in Selected Drying Equipment

Dryer Type	Nature of R&D Problems
Rotary (direct/indirect)	Prediction of particle motion/residence time distribution for poly-disperse solids including effect of cohesion, heat/mass transfer rates; effect of flight design, internal heat exchangers; effect of hold-up; effect of hot air injection into particle bed, noncircular shape of dryer shell, etc.
Fluid bed (direct/indirect) dryers	Effect of particle wetness/poly-dispersity on hydrodynamics, agglomeration, heat /mass transfer rates etc. Design of internal heat exchangers. Effects of agitation, vibration etc. Classification of particle types according to fluidization regime including effect of particle wetness/stickiness. Math models. Effect of agitation, vibration, pulsation, acoustic radiation etc
Flash Dryers	Detailed discrete particle modeling including effects of agglomeration and attrition, effects of geometry, use of pulse combustion exhaust, superheated steam, internal heat exchanger surfaces, variable cross section ducts, hot air injection at various axial locations, CFD models
Drum Dryers	Heat transfer to thin films of suspensions including effects of crystallization, boiling etc.; enhancement of drying rate by radiant heat or jet impingement
Batch Dryers	Effects of intermittent heat input using different modes of heat transfer; cyclic pressure swings; variable gas flow; use of heat pumps (including chemical heat pumps) etc
Spray Dryers	Effects of various types of atomizers on flow patterns, product properties, agglomeration, size distribution; chamber geometry effects; injection of supplementary air; superheated steam operation; CFD models to investigate novel dryer designs e.g. horizontal spray dryers; multi-stage horizontal spray/fluid bed dryers
Impingement Dryers	Effects of high temperatures (tissue drying); noncircular multiple jets; variable spacing arrays of round or noncircular jets.
Batch Dryers	Time-varying heat input, multiple modes of heat input, time-dependent operating pressure, etc.

It is hard to make an all-inclusive wish list of R&D projects that would be highly worthwhile in my opinion. The list I made in 1990 for a similar presentation still stands as is and has grown enormously as I became increasingly aware of the industrial needs and intricacies of drying. With advances in digital computing capabilities and innovative analytical instruments we can now search deeper and examine moisture movement at the microscopic level. Advances in new materials and nanotechnology have made new demands on drying research. In the old days we were interested only in scale-up- going from smaller to larger scale. Now there is new need to also go from small to smaller scale! Spray drying of minute quantities of drugs or advanced materials is a case in point.

Control of dryers based on quality measurement in real time is a challenge. For example, an artificial nose can sense flavor quantitatively and trigger appropriate control action. One can think of smart dryers that automatically adjust drying conditions to optimize quality, for example. Miniaturization of dryers has the advantages of reducing both capital and operating costs. Dryer control using artificial neural nets, fuzzy logic, and model-based control has already become mainstream technologies. With deeper understanding of drying processes the operation can be made more reliable and cost-effective. If energy costs sky-rocket, drying will be an expensive operation in need of serious R&D!

LOOKING AHEAD

Despite the explosive growth of technical or technological literature on drying, the scientific literature has lagged behind consistently. In recent years one can discern a new trend; one now can see a number of scientific papers dealing with specific quality attributes of specific products, particularly in the emerging areas of biotechnology and nanotechnology as well as the so-called mature fields of food, agriculture, paper and wood drying. The list and citation of specific literature is arbitrary and for the purpose of illustration only. Interested readers can find numerous similar examples with an in-depth review of the current literature. It is most important to develop multi-disciplinary research teams for effective R&D in drying.

Techniques such as TRIZ may be useful in utilizing prior experience to develop new solutions to new problems. This technique basically says “borrow ideas from the past and reduce excessive number of features”. This Russian-origin technique requires that the user specify the goals rigorously and correctly, focus on key features desired and trim away unnecessary ones, and borrow successful ideas found workable in the past to achieve similar requirements. Any search engine will give interested reader access to many excellent sites that can get one started quickly.

Innovation in drying technologies is continuing over the past two decades although it has not accelerated because of the long life cycles of dryers and relatively unchanged fuel costs over the past decade. No truly disruptive radical drying technologies have emerged, nor are they expected to emerge over the near term. Many innovations are based on existing knowledge viz. use of heat pumps to dry heat sensitive materials using various modes of heat input concurrently. Indeed, the capital and running costs of heat pumps can be reduced by using heat pumps only over the initial drying period beyond which the dehumidified drying air does not enhance the drying rate any longer. Intensification of innovation can occur only when we are able to use a reliable electronic kit to simulate and test new designs without heavy investment of time, manpower and funds. This implies that strong base in fundamentals in a pre-requisite to rapid innovation. Finally, some emerging drying technologies that will slowly replace traditional ones are identified, but most of them still require significant R&D effort to be marketable. Interested readers may visit http://www.geocities.com/AS_Mujumdar for information on the latest resources that can assist in their R&D or marketing activity in drying systems.

CLOSING REMARKS

Finally, I look forward to IDS continuing its momentum and discover new challenging areas for R&D that will benefit society at large. IDS is also unique in that there is equal participation of developed and developing countries. It permits cross-fertilization of ideas. One industry can benefit from advances made by another industry in solving a similar problem. It allows transfer of knowledge across geopolitical boundaries and across language barriers. Only current weakness I see is the lower level of industry participation, especially since industry will be the primary beneficiary of successful developments in drying technologies. A SWOT (strengths, weaknesses, opportunities and threats) analysis is needed to identify areas of future relevance and make IDS a continuing success. It is obvious that there are emerging threats to funding situation by fashionable R&D areas. We need to be innovative in attracting new blood with truly innovative ideas to cruise successfully and effectively over the next few decades for the problems are enormous and far from being fully solved!

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