THERMAL DRYING TECHNOLOGIES: NEW DEVELOPMENTS AND FUTURE R&D POTENTIAL

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Thermal dehydration processes are highly energy-intensive and are found in almost all industrial sectors, accounting for 10 to 20 per cent on national industrial energy consumption in developed countries. With escalating energy costs and need to mitigate environmental pollution due to emissions due to combustion of fossil fuels, it is increasingly important to develop innovative drying technologies. Furthermore, drying is also affects quality of the dried product due to physical and/or chemical transformations that may occur during the heat and mass transfer operation. With tens of thousands of products that are dried in hundreds of dryer types, it is a formidable task indeed to develop design and scale-up procedures of wide applicability. Attempts have been made over the past three decades to make fundamental and applied contributions to transport phenomena and material science aspects in drying of various forms of wet solids, pastes and liquids. This presentation will attempt to summarize the state-of-the-art as far as theoretical understanding of drying processes and provide examples of some new technologies being developed. Opportunities for challenging fundamental and modeling studies to enhance drying technologies will be identified. Illustrative results will be presented to show how mathematical modeling of spray, pulse combustion, spouted bed and heat pump dryers can be utilized to develop new innovative conceptual designs.

1. Introduction

With escalating energy costs, increased consumer demand for high quality products and the necessity to reduce greenhouse gas emissions contributing to serious climate change problems worldwide, it is unlikely the R&D interest in drying will wane in the foreseeable future. If anything, it should increase when countries like the U.K. have taken the initiative and mandated that CO_2 emissions from U.K. must decrease by 50% of the 1990 level by 2050- a very tall order indeed. Note that in U.K. drying operations consume 13-15% of industrial energy. Clearly, close forensic audits of the entire spectrum of dryers in diverse industries will come under scrutiny to shave off inefficiencies to bare bones.

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While there is a sustainable level of R&D already going on around the globe, as evidenced by the accelerating manuscript flow at the archival journal Drying Technology (Taylor & Francis) and the large number of global, international and regional conferences focused on drying issues, it is important to induct young blood with new ideas and deeper grounding in fundamentals, computational and analytical skills to inject new and innovative approaches to solving drying R&D problems and to come up with new designs without being biased by existing technologies- some have served well for decades or even centuries and are well past their prime. Our goal here is to provide some justification for his philosophy and provide a wish list of areas that are in need for further and deeper R&D. It is impossible to cite all the relevant references but in this age of "Digital Big Bang" the interested reader can readily locate the relevant references although they would be typically just a few in the newer emerging areas.

Also, the list and suggestions made here are by far incomplete. Interested readers should take this just as a starting point. This paper also contains special reference to two volumes of Drying Technology journal. This selection is arbitrary and intended only as an illustration of new ideas and new approaches being followed. Just two volumes of one journal already can lead to a number of innovative ideas in need of further R&D and eventually new applications. When possible it is strongly recommended that the young researcher engage an industry partner in whatever capacity possible. It is important to maintain a thread of relevance from the start.

It is well known that innovations may emerge by chance (serendipity) or by application of well known fundamental principles, or both. Sometimes watching how Nature solves similar problems gives a good clue; rarely can be duplicate the complexity and efficiency of Nature which has had hundreds of millions of years to evolve its techniques! Further, innovations may be evolutionary or revolutionary (or radical). The former are more common and more readily accepted in practice due to lower risk and costs involved. The latter are far fewer, not readily accepted as they are beyond the normal "comfort zone" of companies and people and involve great risk and costs. Market forces or legislations may enforce use of radical innovations causing "disruptive:" technologies to supplant conventional ones. Further discussion of these aspects is beyond the scope of this paper. The interested reader may refer to Mujumdar's books [1-3] for further discussion and additional references. Suffice it to say here that there are practically no truly disruptive drying technologies on the horizon at the time so the field is still open for new researchers!

2. Intensification of Innovations using Mathematical Models

The origin of innovation in drying technologies can be a result of application of the fundamental principles of heat, mass and momentum transfer as well as material science. 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.

Here we will give only a few examples that our group has looked at over the years. The novel concepts for dryer or dryer design/optimization were based on mathematical models of the governing equations. They included novel impinging jet and through dryers for paper, superheated steam dryers for paper, novel nozzle designs and patterns for impinging jets, intermittent and multi-mode batch drying of foodstuffs with heat pump assist, horizontal spray dryer design, a pulse combustor-based dryer for liquids and continuous sheets, multi-mode drum dryer, atmospheric freeze dryer using vortex tubes etc are some of the projects carried out at NUS in the past five years or so. They are all based on basics supported by small lab scale experiments. As experimentation is a slow and expensive process, we believe that mathematical models need to guide such development. Of course, experimental tests at lab and pilot scale are essential before full scale dryers can be designed. Advanced techniques of visualization of drying and dried products (e.g. SEM, TEM, NMR, MRI, ESEM etc) are increasingly used to assess quality. Non-invasive measurement of time-evolution of moisture profiles within a drying material can be obtained by X-ray computed micro-tomography (XCMT). X-ray tomography has been applied successfully to study of fluid bed granulation, for example.

Indeed, mathematical models also help with scale-up and optimization of operating conditions. Furthermore, model-based control is becoming increasingly popular to ensure good thermal efficiency, safe operation and product quality. Thus, out thesis is that mathematical models of dryers are a valuable prelude to arriving at innovative designs of dryers. Following are a couple of recent examples from our laboratory.

Figure 1 shows predicted particle trajectories inside various spray dryer chamber geometries, where Figure1 (A) shows a basic rectangular box design similar to a commercial horizontal spray dryer (HSD) [4]. From Figure 1, it can be seen that the chamber volume is not fully used in Cases A and B. The particle deposit on bottom wall is reduced and the chamber volume is fully utilized in Case C. However, a recirculation zone near the outlet will lead to backflow of ambient air. Condensation may occur and it may cause large deposit and poor product quality. Cases D and E can be considered as good conceptual designs: high chamber volume utilization ratio, reduced wall deposits, sufficient particle residence time, etc. If the evaporation rate per unit volume is considered, Case D gives better performance, about 25%, more than case E. Thus, Case D is the best one among the proposed geometric designs of spray dryer chambers.

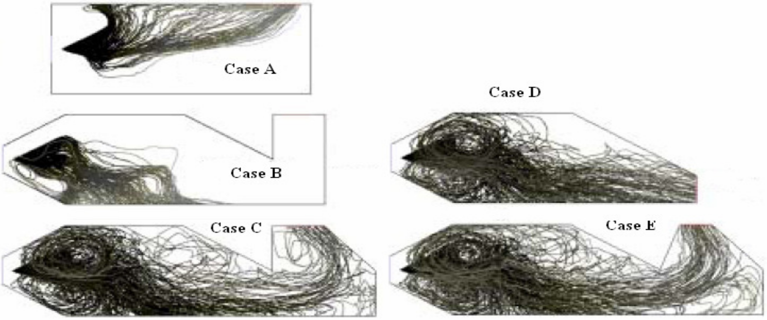

Figure 1 Particle trajectories for various HSD designs

The single-stage HSD dryer can be further improved by combining the spray dryer with a fluid bed dryer as second stage along the bottom wall. Two cases (I and J) were investigated; their geometry dimensions are similar to Case D; the main inlet air flow rate is equal to half that of Case D. The remaining half is used as supply to the fluid bed located at the bottom; the air passes through uniformly distributed holes at the bottom wall in Case I and enters uniformly the chamber through the entire length of the bottom wall in Case J. Figure 2 shows particle trajectories for Cases I and J. it is clearly seen the particle deposit on the bottom wall is reduced. A quantitative analysis show the percentage of droplets hitting bottom wall reduces 51.5% in Case D to 41% in Case I and 22.5% in Case J. Mean particle residence time to outlet increases 5.7s in Case D to 9 s in Case J, reduces to 3.7s in Case I. Compared with Case D, the energy consumption per unit evaporation and evaporation rate per unit volume in Case J changes from 2521 to 2470 kJ/kg, 7.9×10^{-3} to 8.1×10^{-3} $kg/m^3\cdot s$, respectively. Hence, Case J is a better conceptual design for two-stage HSD dyers.

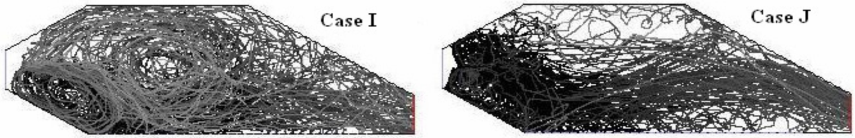

Figure 2 Particle trajectories for two-stage HSD designs.

Another example we can cite for innovations developed via modeling is the use of pulse combustors. In this investigation, mathematical models play an important role due to the cost experimental work to be carried out without knowing the right parameter effects. Wu developed a numerical model of a mechanically-valved pulse combustor to understand the basic dynamics of flame structure, flow-chemistry interaction and the resulting pulsation [17]. Parametric studies are carried out for different operating conditions and flapper settings to manifest the cause-effect scenario between the dynamics of the flapper and pulsating combustion. Numerical results were found to be in broad agreement with experimental observations and provide useful guidelines for design of this type of pulse combustors. Hence, this model can be used as a design, analysis, and optimization tool for a flapper valve coupled pulse combustor. Also, we have examined via simulation the suitability of utilizing a novel pulse combustor chamber based on Nature's design of the Bombardier Beatle. It was found that the natural "heart "shape combustion (actually reaction) chamber can reduce efficiently the required tailpipe length, resulting in a very efficient compact design. A recent project was carried out to examine numerically pulse combustion using different fuels including fuel oils, ethane, propane, and renewable fuels such as bio-gas in a pulse combustor. We also have carried out acoustic simulations to try and reduce the noise problem of such devices.

3. Some Recent Ideas Published in Drying Technology (2005, 2006)

Just for illustrative purposes, the following two tables provide a list of papers that, in our judgment, provide some new approaches to dryer design or analysis. The selection is not complete. Interested readers will be able to identify additional topics and approaches they can follow up on. For lack of space we do not discuss the merits of each case; that is left to the reader. Drying Technology (now in 25th year of publication), IDS proceedings (started in 1978) and the proceedings of a host of other high quality drying conferences (ADC, IADC, NDC, CDC, IWSID, WFCFD etc) provide a rich source of ideas. Other engineering and science journals also contain numerous relevant articles on drying that deserve careful attention. In this digital age it is relatively easy to access such diverse and scattered literature but even easier to be inundated by it. Hence occasional expert reviews in journals and book series or handbooks can save much time and effort.

We believe the potential for R&D in drying is vast and covers all scales, from nano to mega. In fact multi-scale modeling is very important for many drying problems e.g. wood drying. It is also important to couple modeling quality parameters with transport phenomena in drying. Prediction of nutrition loss, color loss, shrinkage and even deformation of dried product in advance is

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http://www.worldscibooks.com/engineering/6614.html

Table 1 Selected innovative concepts which appeared in Drying Technology (2005)

Topics	Innovative concepts in Drying Technology Vol.23, 2005	Remarks/comments
Process control	Optical control of the secondary drying stage of freeze drying of solutions in vials using variational calculus [5]	Drying time cut by half. More uniform temperature and moisture distributions
Microwave drying	Effect of scattering by fluidization of electrically conductive beads on electrical field intensity profile in microwave dryers [6]	Uniformly improved electrical field intensity.
Superheated steam drying	Enhancement of properties of diverse grades of paper by superheated steam drying [7]	23%-37% increase in strength and toughness. Same brightness but23% higher tensile index (Compared with hot air).
EHD drying	Electrohydrodynamic (EHD) drying characteristic of Okara cake [8]	1.7-3.2 times higher initial drying rate with EHD. Energy efficiency ratio decreased with moisture
Drying model	Pore-level modeling of isothermal drying of pore networks accounting for evaporation, viscous flow, and shrinking [9]	Pore-leveling, comprehensive modeling
Combination drying	Drying of Diced carrot in a combined microwave-fluidized bed dryer [10]	2-5 times shorter drying time of MFB than FB dryer. Higher drying efficiency.

Table 2 Selected innovative concepts which appeared in Drying Technology (2006)

Topic	Innovative concepts in Drying Technology Vol.24, 2006	Remarks/Comments
Heat pump drying	Comparison of retention of 6-Gingerol in drying of ginger under modified atmosphere heat pump drying and other drying methods [11]	Better retention of flavor. Suitable for sensitive and volatile products
Superheated steam drying	A comparative study of pork drying using superheated steam and hot air [12]	Higher initial drying rate of pork. Retardation in rehydration. More uniform color and glossier.
Combination drying	A superheated-steam fluidized bed dryer for parboiled rice: testing of pilot-scale and mathematical model development [13]	Hybrid of superheated-steam and fluid bed drying. Over 60% head rice yield.
Infrared drying	Optimal control of continuous infrared dryers [14]	A robust optimal control method based on genetic algorithms.
Multi-stages drying	Dehydration of concentrated *Ganoderma Lucidum* extraction by combined micro-vacuum and conventional vacuum drying [15]	Microwave-vacuum followed by vacuum drying. Same product quality as freeze drying Much shorter drying time
Biodrying	Emerging biodrying technology for the drying of pulp and paper mixed sludge [16]	Biological heat from aerobic degradation of organic matter. Techno-economically feasible. 2 years or less payback period

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very important for many products e.g. wood, foods etc. Even now reliable modeling of commonly used dryers such as rotary, fluid bed, flash, spray etc is difficult. We rely on empiricism and know-how a lot. It is necessary to increase the component of scientific knowledge in these models. CFD models of fluid bed or spouted bed hydrodynamics have met with some success. This is not the case with drying yet. Furthermore, these models are still computationally too demanding to serve as useful design tools. Of course, in the longer term we may be able to look at molecular dynamic models, fractal analysis etc but their usefulness in practice will have to wait.

Creativity is the spark that ignites innovation. It can lead to big, small or no change at all- a high entropy process, thermodynamically speaking. Truly radical innovations have been accidental. However, we cannot depend on accidents to happen for progress. Hence we emphasize the need for a systematic fundamentals-based approach as suggested in this paper.

Closing Remarks

This paper has attempted to stress the need for new R&D in drying and made some suggestions as to the kind of research that is needed utilizing a combined approach e.g. mathematical modeling, careful experimentation using advanced analytical and computational tools to obtain deeper insight into the microscopic as well as macroscopic issues involved. Since this is a truly multi- and inter-disciplinary area of academic as well as industrial interest, it is suggested that a collaborative project has the best chance of making a true impact.

New technology areas are evolving all the time. Drying problems occur in production of nanoparticles and advanced materials. New biotech products are being produced all the time that need to preserve activity even after drying. Formation of polymorphs during drying a pharmacy product is a challenge. Often vacuum drying of pharmacy products involves multiple solvents posing even greater challenges.

Drying plays a role in the energy sector as well. As low rank wet coal will need to be used in coming decades new drying processes are needed. Even treatment of nuclear waste by vitrification requires sophisticated drying processes due to safety issues involved. Waste sludge treatment also involves complex drying problems due to the need to be highly cost-effective, safe and emission-free.

The semiconductor industry faces challenges in handling photo-resist stripping solvents. Supercritical CO_2 is being used in this application. In fact, SC

CO_2 has been widely used for drying aerogels and hydrogels for production of catalysts and advanced materials. Although not strictly a drying process SC extraction serves a similar purpose in highly specialized cases. Thus drying operations cover the whole gambit from below the triple point to the supercritical range of temperatures and pressure. Literally the sky is the limit for those eager to make a real lasting contribution – of course the goal is to keep the emissions from reaching the sky!

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