A Capsule Summary of Current Research Projects of Professor Arun S. Mujumdar at the National University of Singapore

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Abstract

An attempt is made to summarize in capsule form the current research interests of Professor Mujumdar at NUS since mid-2000 as well as those with his many research collaborators around the world. It does not cover his earlier work which is covered in another paper in this book. For simplicity in presentation this summary is divided into following categories: A. Drying B. Heat and Mass Transfer. C. Other areas including his collaborative research with institutions in various parts of the world. Only the objectives and scope of the work are covered briefly along with references to selected publications if any. His website www.geocities.com/as_mujumdar provides up-to-date information on his research interests as well as publications in various areas.

Introduction

This paper is intended to provide a brief summary of the current research projects supervised by Professor Mujumdar in the mechanical Engineering Department at NUS since July 2000. It is not intended as a full account of the important results from these projects, many of which were initiated as

PhD student projects only about two years ago. It is noteworthy that Professor Mujumdar is trained as a chemical engineer and was on the chemical engineering faculty of McGill University until mid-2000 when he moved to NUS in the ME department. This reflects on his preference for inter-disciplinary research. Indeed, he currently collaborates with colleagues in civil and chemical engineering as well as food science at NUS alone.

This paper is organized to provide basic information on the following major thrust areas: Drying, Heat and Mass Transfer and Other areas such as sonochemical decontamination of wastewater streams, elctro-osmotic dewatering, vacuum frying; combined air and freeze drying etc.

Under each category a short write-up is provided on the title, objectives and scope of the project together with names of current researchers involved and any publications that maybe available for those interested in results from those projects so far. It is important to remember that most of these projects are recent and have been in progress for relatively short periods only. Information on Professor Mujumdar's earlier work is available form his website as well as from papers presenting this Mini-Symposium held to honor him.

In the following a list is made of current postgraduate student research projects. Details can be found on the website noted above.

A. Drying

1. Simulation of Spray drying using CFD

LiXin Huang

Recent rapid development in CFD and the ever-increasing power of computers make it possible to simulate and evaluate the new spray dryer chamber designs as well as air inlet and outlet arrangements to improve the spray drying process. The expensive pilot experiments or laboratory tests can thus be minimized.

a. Develop and validate a CFD-based model to predict flow patterns and overall drying performance of a conventional cylinder-on-cone spray dryer by comparing the results with published results as well as new data to be supplied by collaborating researchers in Norway and Australia

b. Evaluate novel spray dryer chamber geometries, i.e., cone-on-cone, purely conical, hour-glass shape and lantern shape changers. Axi-symmetric was considered. Prediction shows that Cone-on-cone or purely conical can also yield similar or even better volumetric effectiveness and higher heat/mass transfer performance than the conventional designs,

c. Evaluate a single stage and a new two-stage, two dimensional horizontal spray dryer concept proposed by Prof. Mujumdar. Prediction shows that a

two-stage HSD allows long drying times needed for heat-sensitive products and large droplet sizes. The geometry is also not designed occasionally if the better performance is expected.

d. A new special UDF program (New drying model) in FLUENT is developed to simulate the spray drying.

e. The rotary disc spray drying is simulated and validated with data from Brazil.

f. An experiment was carried out in a local industrial spray drying system. Parametric studies were also done. Model agreed well with data on a large scale spray dryer.

Some papers are written based on the earlier works. The summary of this project is shown in Figure 1.

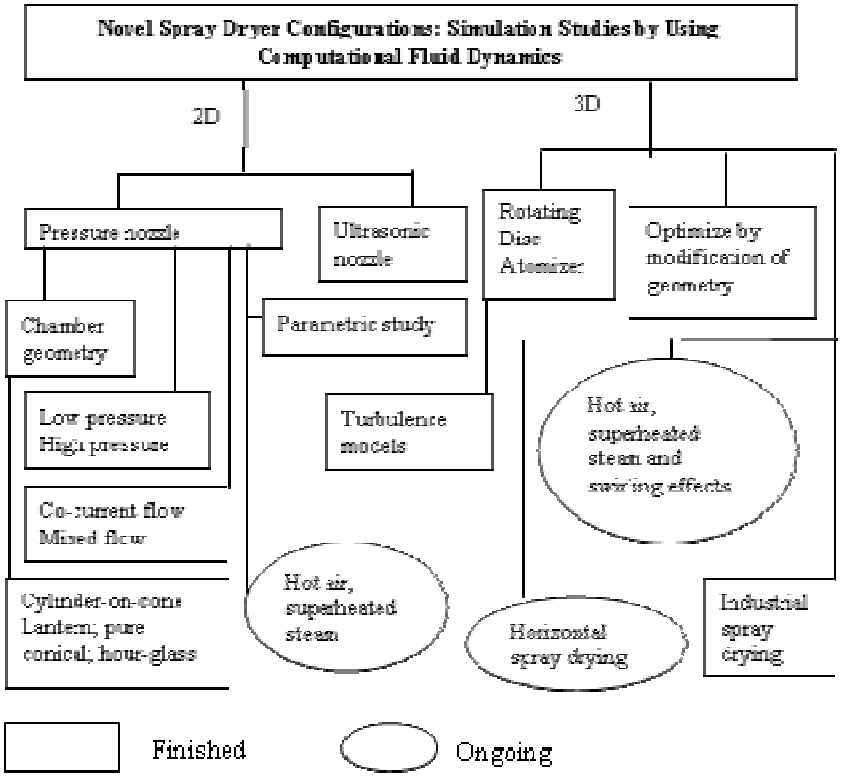

Figure 1: Plan and scope of the PhD thesis

Experimental studies on single droplet drying under conditions of time-varying drying conditions (e.g. temperature, velocity etc) are also underway. In a real spray dryer droplets undergo drying under rapidly changing drying conditions. This I s first attempt to evaluate the effect of transient drying conditions since it can so happen that no drying occurs in some parts of the spray dryer.

2. Multi-mode Heat pump Drying

Heat sensitive materials need to be dried at lower product temperatures to maintain their quality in terms of color, texture, nutritional value etc. In order to attain reasonable drying rates under such conditions to keep the capital costs of equipment low, heat pumps may be used. In order to make the heat pump drying process further cost-effective in terms of reduced energy costs and lower capital costs, this project aims at studying and modeling the drying process in which the material is subjected to time-varying heat inputs by convection, conduction, radiation etc. Microwave drying effects were also considered separately under low pressure conditions. Experimental results are compared favorably with simulations using a simple liquid diffusion model. Results are published in a series of paper in 2002-2004.

3. Other

A number of other drying projects have been and under way for a long time both at NUS and in collaborative research with institutions around the world. Among these are: effect of cyclic pressure swings between above and sub-atmospheric pressures on drying kinetics and product quality; use of a chemical heat pump instead of mechanical heat pump on energetic of drying (Japan); spray drying of milk (Brazil); atmospheric freeze drying (Norway)microwave-assisted fluid bed drying (Hong Kong, India); low pressure superheated steam drying of fruits and vegetables(Thailand); spouted bed drying (Canada, Thailand); impingement drying (Canada); vacuum frying (China); electro-osmotic dewatering (Canada, Norway); modeling of drying (USA); fluid bed drying (Malaysia) etc. Details can be found in publications listed on Prof. Mujumdar's websites.

B. Heat and Mass Transfer

1. Micro-impinging Jet Heat Transfer
Lou Zhengquan

This research project is on numerical and experimental investigation of micro-impinging jet with single and two-phase heat transfer. In this project, the dimension of micro-impinging jet refers to about 0.1 mm. This particular study will be applied to
electronic component cooling. Computational fluid dynamics model(CFD) using the commercial software Fluent and CFX is applied in the numerical simulation. Moreover, user defined functions (UDF) are inserted to their codes to make this particular simulation feasible. The key problem in the numerical simulation is how to simulate the boiling heat transfer properly, because it is really a changing topic and there are still no very satisfactory codes for this problem. Simultaneously, experimental investigation will be performed. The experimental results will be compared with numerical results to verify validation of the numerical simulation.

The previous work and the future plan are listed as follows:

a. Numerical investigation of geometric effect on the impinging jet heat transfer has been studied by CFD software FLUENT 6.
b. Numerical investigation of Biot number effect on the impinging jet heat transfer has been studied by CFD software FLUENT 6.
c. Effect of model roughness of the target on the impinging jet heat transfer will is simulated numerically at present.
d. The experimental set-up is been preparing on micro-impinging jet heat transfer.
e. Numerical simulation of two-phase impinging jet heat transfer is been trying by CFD software such as CFX 4 and Fluent 6.

2. Heat Transfer in Micro channels including phase change
Wang Xiangqi

Cyclic melting and freezing heat transfer in a rectangular container of infinite depth filled with two different phase change materials (PCMs) with different melting points is simulated using enthalpy-porosity model. Free convection in the melt phase as well as the heat conduction conjugated with metal wall is considered. Numerical results discovered that the 2-PCM slabs with different melting points could increase the performance of the system

obviously. The parameters such as melting/freezing time could affect the performance of the 2-PCM slabs. Future experimental and simulation studies are under way to examine multiple PCMs and effects of geometry of the container.

Another project was conducted on fractal-like micro-channel networks. In this project, conjugated fluid flow and heat transfer through fractal-like branching micro-channel networks which is embedded in a disc-shape heat sink is investigated using a three-dimensional computational fluid dynamics (CFD) approach. Results show the advantages of such networks compared with the conventional parallel channel networks compared with the conventional parallel channel networks. Their advantages include: low flow resistance, temperature uniformity and low danger of blockage. Various optimized designs are of the networks with parameters such as number of branches, number of branching levels and number of ducts that reach the center of the disc.

3. Pulse Combustion and its Applications to Drying
Wu zhonghua

This project addresses the fundamental understanding of the pulse combustion process and pulse combustion drying with focus on the design of a new small scale-pulse combustion system and heat/mass transfers in selected pulse combustion drying processes. A modified CFD model based on commercial software is being developed to minimize expensive pilot experimentation and laboratory tests. Some research works in this area are listed below.

a. To develop and validate computational fluid dynamics (CFD) combustion model to predict pressure oscillations, frequency and overall performance of a “Helmhotz” type pulse combustor. The influences of operating parameters and different layouts on the running of a pulse combustor will be studied.

b. A natural micro-pulse combustion (actually reaction) phenomenon, which happens in a kind of tiny creature –Bombardier Beetles, will be investigated through a CFD combustion model. The idea is to see if we can learn something new from nature.

c. To design a small-scale pulse combustor- limited several millimeters (micro PC)

d. To investigate pulse combustion spray drying process numerically and experimentally. An experimental pulse combustion spray dying rig in China Agricultural University (CAU), Beijing, may be used to obtain necessary data via collaborative research agreement.

e. To carry out experiments to verify above simulated results and to widen the knowledge of pulse combustion drying. Part of this work will be done in

cooperation with Chinese Agricultural University, Beijing. Figure 2 shows the research work plans.

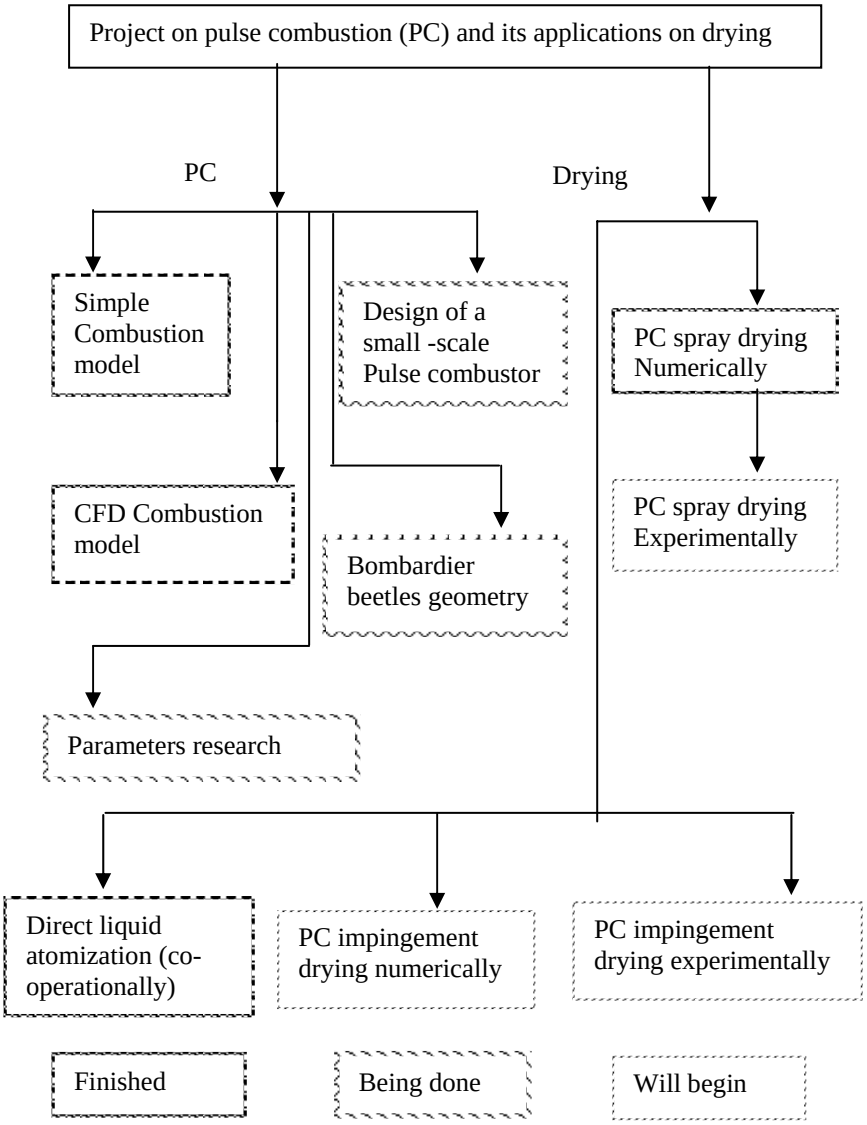

Figure 2: Research Work Plans for pulse combustion project.

4. Explosive Boiling
Prasanta Kumar Dey

Explosive (i.e. very rapid) boiling of a liquid at high degrees of superheats can generate large forces which can be successfully harnessed in developing novel thermal actuators with many potential engineering applications, e.g. displacement type micro-pump. Such devices have been shown to be suitable for specialized applications ranging from biology and medicine to space exploration and micro-electronic schooling, etc. Fluid volumes on the order of micro litres or less are figuring prominently in an increasing number of engineering applications. One well known successful application of this concept is the thermal inkjet printer head used in HP ink jet printers. The ink droplet ejection is actuated by cyclical explosive vaporization at very high frequency of the liquid ink and subsequent discharge through micro-nozzles. Nano-sized bubbles are produced by cyclic heating; the bubble produced displaces the liquid in the form of nano-litre sized droplets through the nozzle. Understand the properties of explosive vapor bubble are, therefore, important technically and scientifically. A research effort has been undertaken to extend the theoretical and experimental state-of-the art in the generation and control of explosive vapor bubbles in micro-systems. The objective is to develop criteria for surface and bulk explosive boiling. The research effort will also investigate the feasibility of a micro-device based on explosive generation of bubble in a micro-cavity.

5. Phase Change Material (PCM) based Hybrid Thermal Management of Electronic Components and Systems - Numerical and Experimental Study

Ravi Kandasamy

Technological enhancements at device, package, and system levels have resulted in increased functionality and decreased form factors. As a consequence, thermal management has become more critical and a thermal analysis must be included early in the design cycle for handheld electronics and communication products, such as cellular phones, digital cameras, personal digital assistants (PDA). The majority of integrated circuits operate best within a limited temperature range and their packages are expected to remove excessive heat. Furthermore, a high operational junction temperature decreases device reliability and reduces the operating lifetime of the device. In some specific applications, such as digital cameras, high

junction temperatures will also directly impact the component performance, like image quality. Several researchers have made an attempt to investigate the feasibility of using PCM for heat removal and thermal energy storage applications but to our knowledge not many active research solution is provided using PCMs for electronic cooling applications as of now.

A research attempt is being made by designing a several suitable experimental setup to investigate the feasibility of using phase change materials (PCM) for application in the thermal control of portable electronic devices. The heat transfer characteristics (freezing and melting) for various power levels and orientations will be determined experimentally for an electronic package and systems using PCM. A subsidiary objective is also to carry out several parametric numerical studies using CFD commercial tool to understand effect of orientations, various heat inputs and study the effect of odd shaped geometries which will be of industry interest in future electronics. Though the subject of melting of PCMs in the enclosure has received improved attention in recent years because of its wide-ranging applications and also interest in electronic industry. Studying the melting process of a PCM in square and rectangular enclosure may be a still promising alternative solution to natural convection air cooling for electronic components and systems in some special cases such as using PCM heat sinks, encapsulated PCMs. To our knowledge, no experimental work was done on melting PCMs with discrete heat sources has been reported for electronic cooling applications.

Additionally research will also be focused on heat spreader design improvement, enhancing thermal conductivity of PCMs, attempting multi-PCMs with single and discrete heat sources will be studied. More added attention and focus will be on PCMs selection to meet not only lower cost and lighter but also will be on chemically stable, non-toxic and non-flammable PCM would be of great interest during the selection process. The influence of solid liquid interface during melting, its size and shapes, melt fraction and variation of the surface temperature and nusselt number estimation in natural convection will be presented. Experiments will focus on measuring transient temperature profiles at multiple points, infrared imaging, flow visualization will be of interest and will be planned at different stages. The effects of various factors from time to time will be varied depending on thermal management with a PCM system in which convection heat transfer in an enclosure plays an important role during melting.

6. Mass transport phenomena in two and three dimensional confined opposing jets

S.J. Wang

The basic opposing jet configuration that includes two oppositely and closely spaced entering jets provides high heat and/or mass transfer rates through normal collision creating a relatively narrow zone of high shear and intense turbulence. It has found a number of industrial applications such as thermal drying of solids, combustion of gases, reaction injection molding, mixing, extraction, absorption and deabsorption, dust collection and liquid-liquid chemical reactions. Although a number of experimental works have been performed for different applications of opposing jets, fundamental studies of heat and/or mass transfer transport in confined turbulent opposing jets are still limited. Opposing jet flows have only recently attracted research attention. Studies on the fluid flow and heat/mass transfer behavior of turbulent opposing jets remain incomplete although a few fundamental studies have been published.

The first objective of the current project is to experimentally and numerically study the fluid flow and mixing characteristics of two/three dimensional confined laminar and turbulent opposing jets in an in-line static mixer. Secondly, some relatively new approaches are numerically explored to investigate the potential to improve the mixing effectives in this new kind of IS mixer. Thirdly, the development of enhanced turbulence models are used to improve the prediction of the complicated impinging flow characterized by strong streamline and recirculation zones. Finally, new data on flow, heat and mass transfer in selected opposing jet flows are experimentally generated to validate turbulence models and to permit computer-aided optimization of such flow configurations.

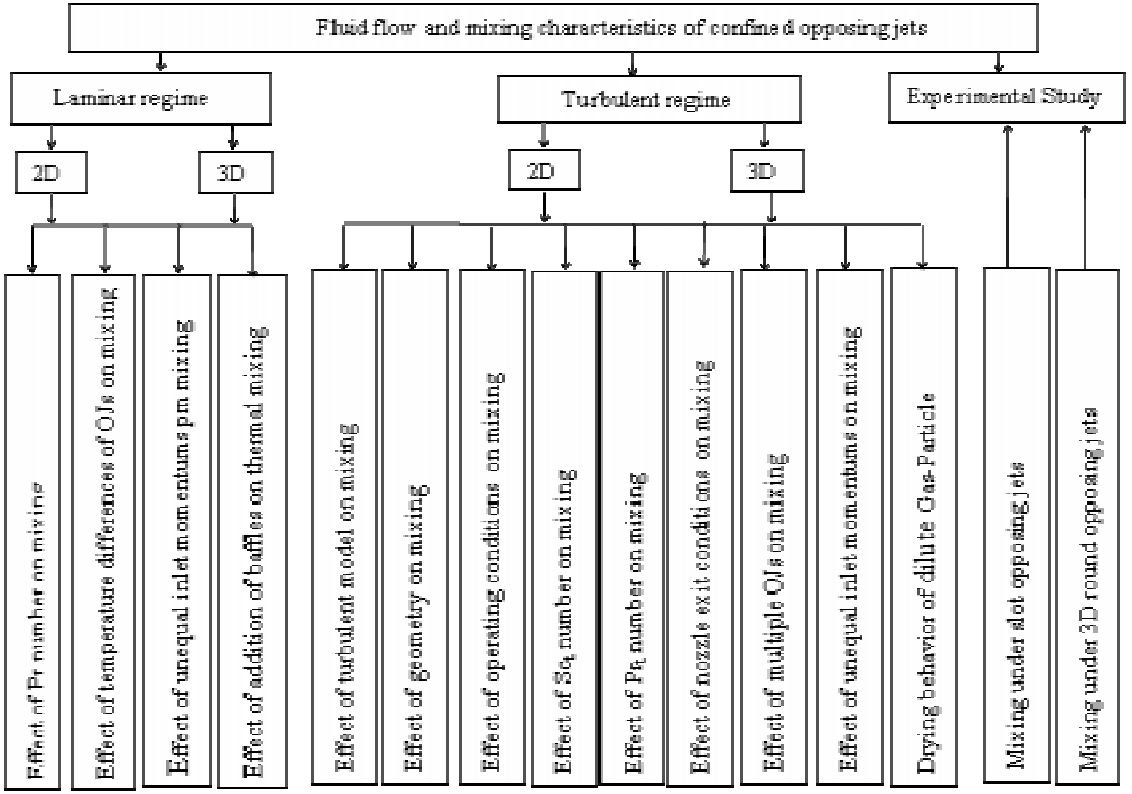

Figure 3: Plan for PhD work

7. Characterization of unsteady transport phenomena with moving boundary using Large Eddy Simulation
Poh Hee Joo

LES is compromise between DNS (Direct Numerical Simulation) and RANS (Reynolds Average Navier Stokes). LES is often regarded as a prediction method that will eventually replace RANS modeling in a practical environment. Pursuing LES gain insight into complex turbulence physics and create data bases for turbulence-model improvement and validation. Instantaneous information on the flow structure obtained from LES can be coupled with other internal flow field such as sound generation, scalar transport (temperature or sediment), chemical reactions or external physical processes such as dynamical response of solid structure for studying the aero-acoustic, fluid-structure coupling and control of turbulence by appropriate unsteady forcing.
This research project is aimed at unsteady fluid flow and/or heat transfer phenomena using the current state-of-art Large Eddy Simulation (LES) technique. Industrial processes applications such as self-sustained oscillating jet or whistle nozzle, multiple impinging jets and modeling of fish aerodynamic had been identified as the potential topics. High Performance Computing resources (IBM Regatta P690, 7 x 32 CPUs) as well as commercial CFD software (FLUENT, CFX) available through collaboration with Institute of High Performance Computing would facilitate the modeling processes greatly. Code development and parallezation for LES modeling and experimental investigation of the transport phenomena would be pursued. This is a new project at the stage of initialization.

C. Other areas

1. International Research Collaborations

Drying is an interdisciplinary and transdisciplinary field requiring expertise in diverse areas. It must combine transport phenomena with material science at the simplest level of interaction. It also needs expertise on mathematics, mechanics, computer science, analytical techniques, biology, botany etc. depending on materials being dried. Professor Mujumdar recognized the need for such collaboration and developed them locally within NUS and McGill but even many more with overseas universities and industry. As early as mid 1980 he had a highly successful PhD joint project with University of Tokyo. The student, who worked on this initiative-Dr. Karun Malhotra, went on to make major contributions to his research field but also to the Japanese company he works for. Similar overseas stays for his

students were arranged in Finland, Hungary etc. His active projects leading to sizable publications have included universities in Brazil, Japan, Czechoslavakia, Hungary, Russia, Finland, Norway, Hong Kong, Thailand, China, India, Israel, Mexico, Malaysia, Poland etc. His website lists his current collaborative projects which reflect the long term impact and success of this program. His students benefit a great deal from such interactions. Interestingly, his collaborators come of academia as well as industry and government research centers giving his students three-pronged overall exposure to the field of their interest.

It should be noted that currently Professor Mujumdar's research portfolio includes numerous non-drying projects as well. So, some of the collaborations are in non-drying fields too.

Concluding Remarks

This summary is provided to provide the reader a convenient overview of current activities of the research group led by Prof. Mujumdar at NUS. It is noteworthy that a very large number of active research collaborations- some active for over 10 years since his McGill days- have borne fruit and resulted in numerous valuable archival publications. His websites are a valuable source for current information on drying and related areas. Extensive list of publications can be found there. Also, there are several power point presentations available for free download on his sites that Prof.. Mujumdar has made, that are of general value to students as well as academics and industry personnel.

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