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A Brief Synopsis

Thermal Drying Research in Professor Arun S. Mujumdar's Research Group, Mechanical Engineering Department The National University of Singapore

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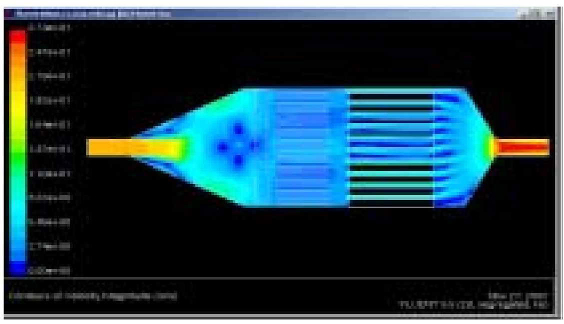
Thermal dehydration or drying is perhaps the oldest, most common and yet one of the least understood of industrial unit operations. Due to a misconception about need to understand the coupled transient heat, mass and momentum transfer phenomena involved, serious research in this area has only a rather short history dating back only about three decades. Some 50,000 substances need to be dried commercially at scales ranging from kg/h to tens of tones per hour. Almost all industrial sectors use this highly energy-intensive operation which has been variously estimated to be responsible for 8-20 per cent of national industrial energy consumption in developed countries. In the food, biotechnology, advanced ceramics and pharmaceutical sectors quality of the dried product is of decisive importance rather than energy. Drying effectively combines material science with transport phenomena in a uniquely multi- and cross-disciplinary manner. Indeed, it is not possible to do useful drying R&D without multi-disciplinary expertise and team effort.

The significance of thermal drying R&D can be appreciated by looking at some characteristics of the process. Over 500 types of dryers have been reported in the literature while some 100 are available commercially. The wide diversity and production scales required of wet feed materials and quality constraints on the dried products demand an incredible variety of dryers and operating regimes. Chemical, biochemical and physical transformations (e.g. glass transitions, shrinkage, puffing, crystallization etc) that can occur during drying make the process difficult to model at the microscopic level. The highly nonlinear nature of the governing equations makes scale-up of dryers from laboratory or pilot scales an especially complex and unreliable task even today. In view of the large number of parameters governing the drying process even in the simplest of dryers, mathematical modeling plays an ever-increasing important role in dryer design, operation and optimization. Unfortunately, prediction of quality of dried products remains an unresolved issue for most materials.

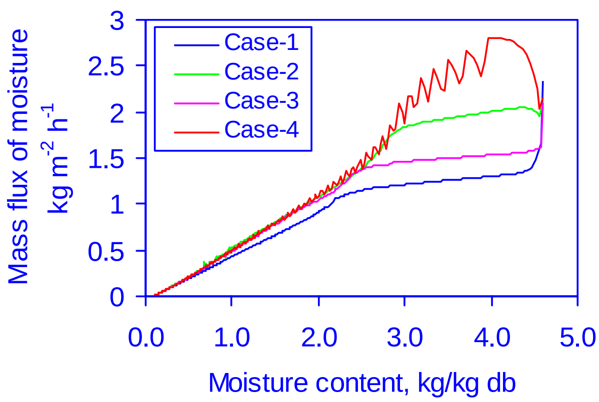
Research in Professor Arun Mujumdar's group in the Mechanical Engineering Department at NUS focuses on a number of generic problems encountered in industrial practice covering a wide range of materials. His drying effort started at McGill University in Canada in mid-1970's, and has been recognized all over the world. His contributions have covered practically all major industrial sectors (e.g. pulp and paper, forest products, foods, biotech products etc), and has been of a fundamental nature so that the results are applicable widely. His research at NUS, which started only about four years ago, focuses on drying of heat-sensitive materials. He has initiated a number of innovative drying concepts and validated them with mathematical models and experiments here as well as at a number of laboratories around the world with whom he has had sustained collaboration.

Following is a list of some of the active projects and summaries of key findings to date.

- **Multi-mode heat pump-assisted drying of heat-sensitive materials**. This project supported by a research grant from NUS, examines experimentally as well as via mathematical models the potential of utilizing multiple modes of heat input (e.g. convection, conduction, radiation, microwave energy, etc.) simultaneously or sequentially to minimize the drying time of heat-sensitive materials without compromising on quality. A heat pump provides an efficient means of providing dehumidified heated air at moderate temperatures. The model results are in reasonable compliance with experimental findings and hence can be used for optimization of such drying systems.

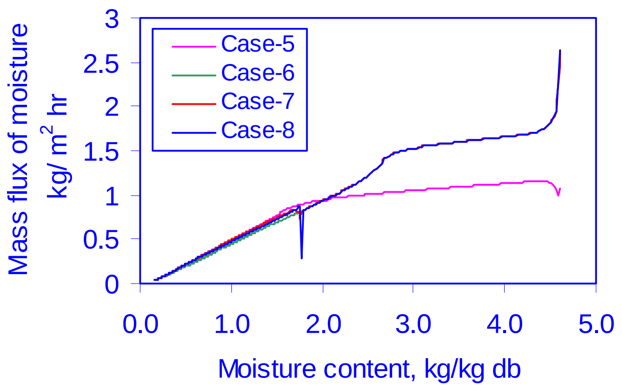


Flow distribution inside the drying chamber fitted with multiple trays which are stacked with spacing between them for dehumidified hot air to pass between them.



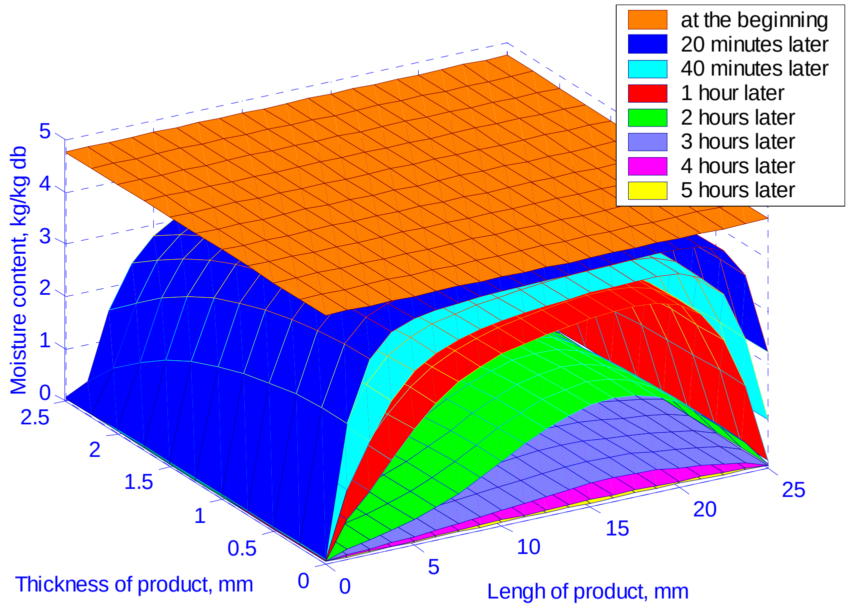
Effect of multiple modes of heat input: This figure presents diffusion model results for different heat input modes for drying. Here pure convection has the lowest and combined convection and volumetric heating with microwaves the highest drying rate. Results show that combination of different modes of heat input can increase moisture flux i.e. drying rate up to a moisture content of about 2.5 kg/kg db. In general drying time can be shortened by proper design and optimization of the operating conditions depending on the material being dried. In drying heat-sensitive materials the product temperature must necessarily be low and so it is reasonable to assume that no vaporization occurs within the material. Results given here cannot be applied in high temperature drying or highly porous materials for this reason.

Case-1: Pure convection; (T_{air} = 45°C, RH_{air} = 15 %, V_{air} = 2 m/s)
Case-2: Convection and Conduction; (Conduction heat flux: 0.5 kW/m^2)
Case-3: Convection and Radiation; (Temperature of radiation heater: 110°C)
Case-4: Convection and volumetric heating using Microwave; (MW power: 0.6 W/g of initial wet material)

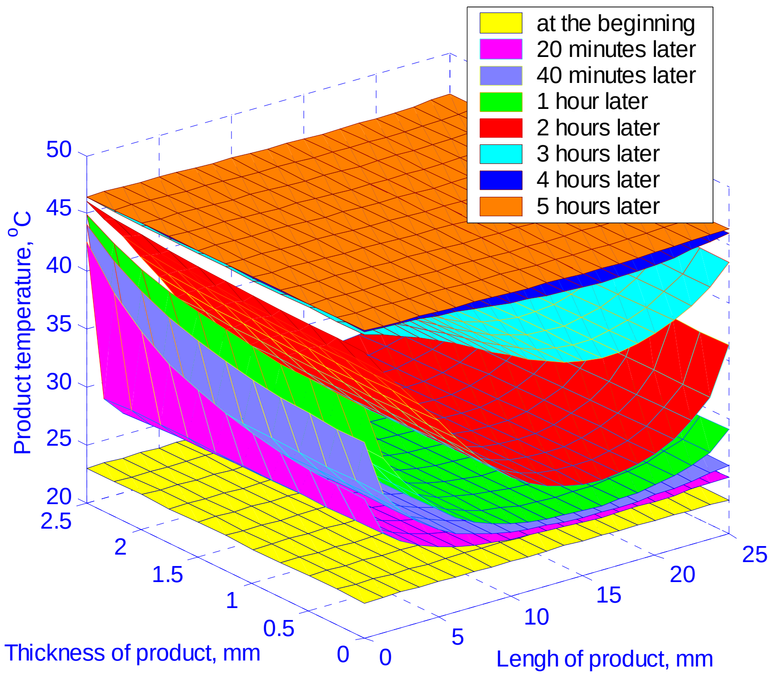


Effect of relative humidity of drying air: It is seen that dehumidified air using heat pump can improve drying rate at lower operating temperatures- a benefit for heat-sensitive materials. Results also show that heat pump is needed only in the initial drying period.

T_{air} = 45°C, V_{air} = 2 m/s, Drying time: 8 hrs
Case-6: RH=30% from 0 to 8 hrs of drying
Case-7: RH=7% from 0 to 8 hrs of drying
Case-8: RH=7% from 0 to 2 hrs; RH=15% from 2 to 4 hrs; RH=30% from 4 to 8 hrs
Case-9: RH=7% from 0 to 2 hrs; RH=30% from 2 to 8 hrs of drying



Predicted evolution of the moisture distribution inside a slab-like drying object using a 2D liquid diffusion model



Predicted evolution of the temperature distribution inside a slab-like drying product using a 2D liquid diffusion model

- **Development of novel spray dryer concepts for drying of suspensions and solutions** This project has employed computational fluid dynamic models along with experimental data on pilot and full-scale spray dryers from various parts of the world to evaluate the effects of numerous design parameters on spray dryer performance. Among the new concepts evaluated are various spray chamber geometries, a horizontal spray dryer (conventional spray dryers are vertical), low pressure operation for highly heat-sensitive materials, potential for use of an ultrasonic atomizer, use of superheated steam as drying medium, two-stage horizontal spray-fluid bed dryer, etc. Currently an industrial scale spray dryer for coffee is being modeled. This work is carried out in cooperation with Dr. K. Kumar of the Institute of High Performance Computing.

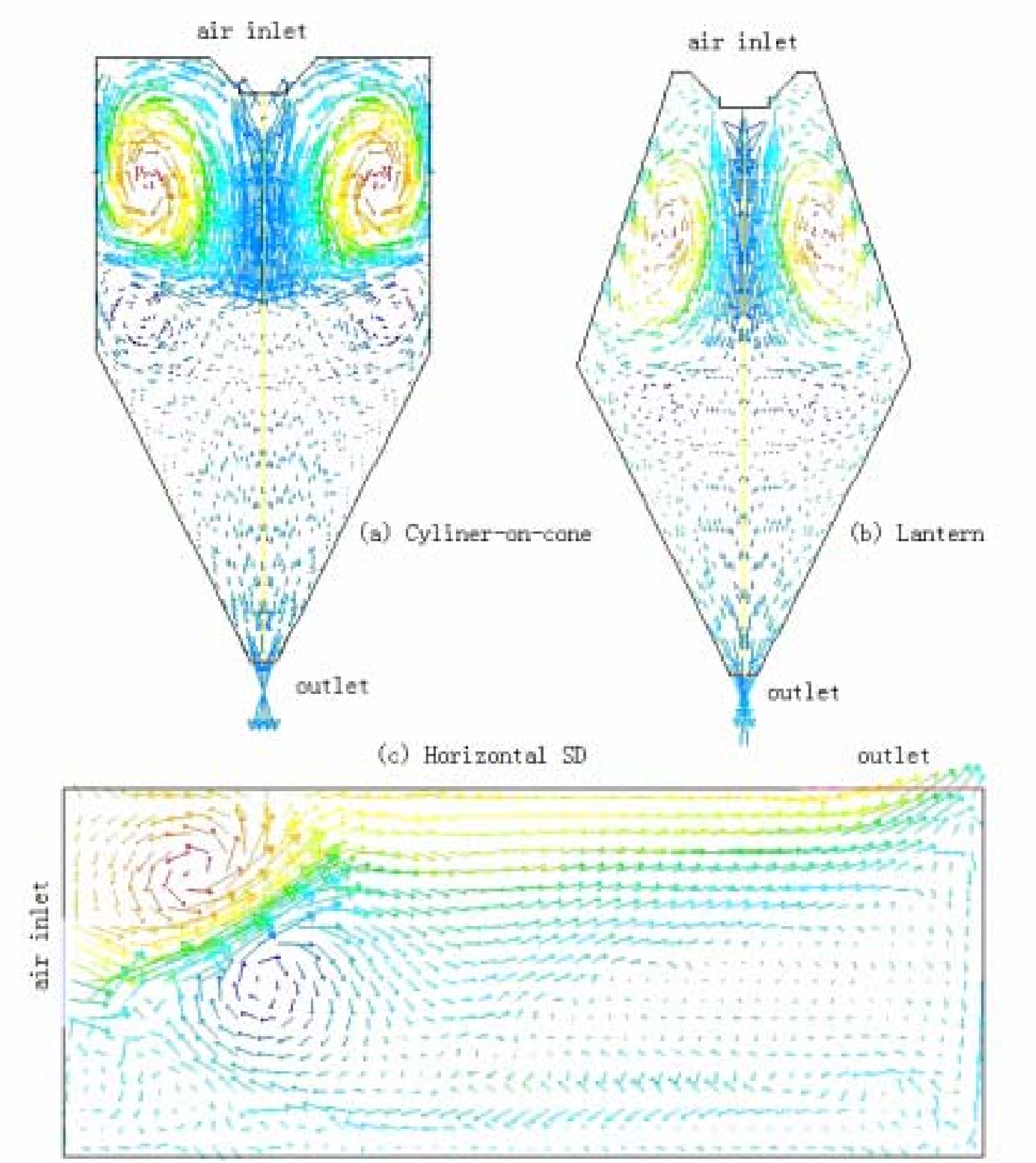


Figure 2-1 Air flow pattern in different geometries

Figure 2-1 provides the air flow pattern in different spray dryer geometries. It was seen that air flow patterns are similar in cylinder-on-cone and lantern geometries (Figure 2-1a and 2-1b). This proves that the geometry for spray dryer can be modified in order to obtain the similar drying performance. The horizontal geometry gives a total different air flow pattern due to different layout for air inlet and outlet (Figure 2-1c). Since it is still a new design, it may give a good drying performance after some modifications are made.

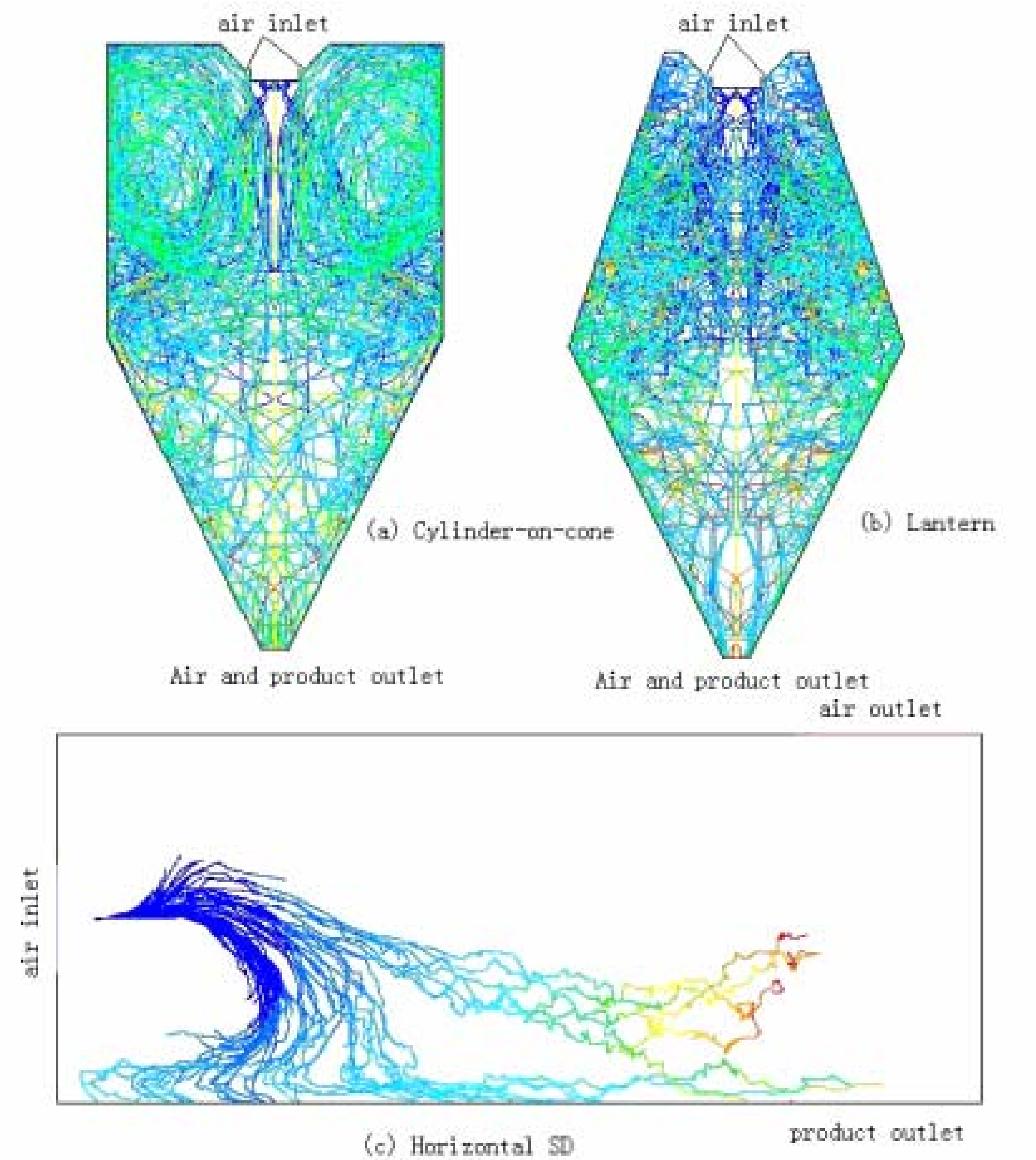


Figure 2-2 Particle trajectories in different geometries

Figure 2-2 presents the particle trajectories in three different geometries. Pure water is used as the feed only in horizontal spray drying (Figure2-2c). It was found that the droplets will fall down to the bottom wall of the horizontal spray dryer due to gravity. So if a fluid bed drying is applied at the bottom of the horizontal spray dryer, it will improve the drying performance in horizontal spray dryer. The particle trajectories in Figure 2-2a and 2-2b show that the particle have occupied all volume of the geometries. On the other hand, it can be found that lantern geometry may replace the conventional cylinder-on-cone geometry in somewhere since it also can give a good drying performance.

- **Modeling of a pulsed combustion spray dryer (PCSD)**. Although pulsed combustion is an old technology its use as a spray dryer for highly heat-sensitive materials is new and yet to be explored fully. A PCSD does not require a separate atomizer (since liquid stream injected in the highly turbulent pulsating tail pipe flow atomizes the liquid into a spray) or a blower for the drying medium unlike the conventional spray dryer. Drying times are in the order of milliseconds because of the small droplet size and high temperature drying medium. Current research is aimed at developing CFD-based models to examine the drying kinetics, energy efficiency as well as acoustic emissions from such a dryer. Concurrently we are also examining the feasibility of designing and testing micro-scale pulsed combustors of unique combustion chamber design. Furthermore, via CFD modeling we are examining the potential for use of PC tailpipe exhaust jet for drying of paper- a concept that has recently been proposed in the literature.

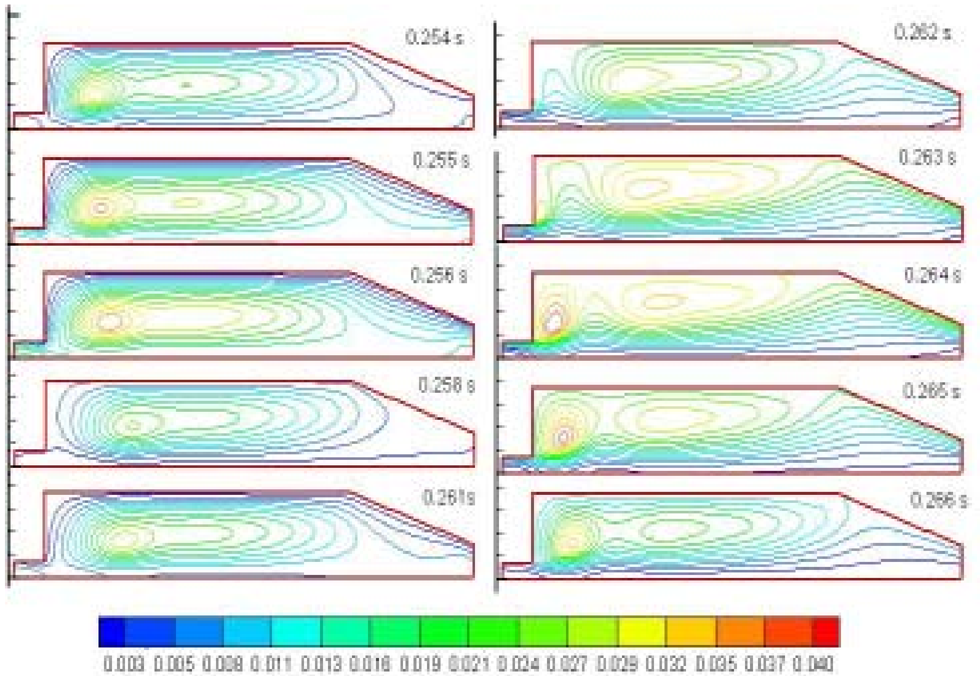


Figure 1 Gas flow pattern within drying chamber oscillate during a pulse combustion cycle (0.254-0.266 s, 81Hz)

Oscillations of the flow that reflect the natural frequency of the pulse combustor operating frequency (81 Hz) promote intensive mixing and augmented heat and mass transfer between the disperse and continuous phases.

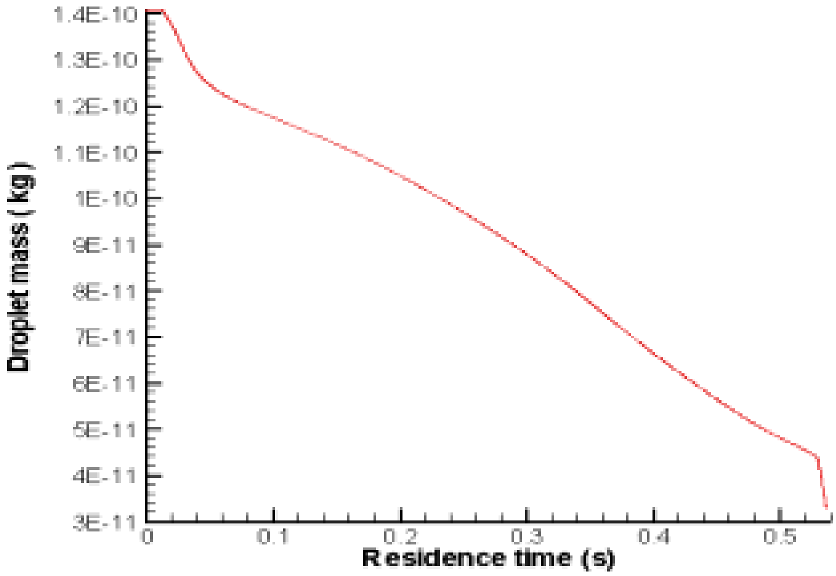


Figure 2 Droplet mass during the residence time after injected at t= 0.254s (droplet diameter D=63.1×10^{-6} m, 10% mass fraction NaCl solution)

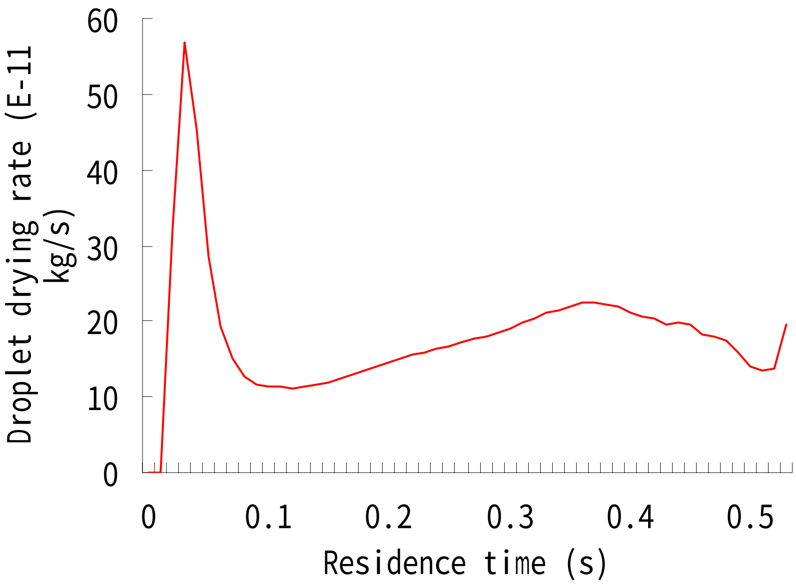


Figure 3. 13 Droplet drying rate during the residence time after injected at t= 0.254 s (D=63.1×10^{-6} m, 10% mass fraction NaCl solution)

Figure 2 and 3 show that in a short time of about 0.5 s, the droplet loses about 85 % of its moisture, which means intensification of drying rate and a fast way of dehydration that may suitable for drying some heat –sensitive materials. This results from the high driving force (~ 380^{o}C), small droplet diameter and intensive mixing and increase of heat and mass transfer coefficient.

- **Impingement Heat Transfer**

Impinging jets are used in diverse industrial applications from large scale drying of paper, textiles, films etc to cooling of high power density electronic components. Despite the large body of research literature on the subject there are still some gaps in the knowledge about heat transfer characteristics of such jets e.g. pulsed jets, noncircular jets, arrays of noncircular jets, effects of large temperature differences between the jet and the target surface, presence of solid particles in the jet fluid, roughness of the target surface etc. The turbulent flow field under such jets is complex and provides major challenges in predicting them reasonably well for practical applications. A number of projects ranging from undergraduate research projects to doctoral studies are currently under way to make contributions to this area.

Readers interested in this area should contact Prof. Mujumdar or visit his websites for list of publications and current research projects.

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