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Particle Transport, Deposition and Removal- A Research Based Curriculum Development

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Significant research progress in the areas of particle transport, deposition and removal has been made in the last two decades. Particle transport, deposition and removal occur in many natural and industrial processes. Microelectronic, imaging and pharmaceutical industries are a few examples for which particle transport, deposition and removal play key roles. Diverse areas from air pollution, sand storms land landslide to xerography and Chemical-Mechanical polishing in microelectronic fabrications involve particle transport, deposition and removal. A series of courses were developed to make the new important research findings available to seniors and first year graduate students in engineering departments through specialized curricula. This course series involved integration of numerical simulations and experiments in the curriculum and are composed of four modules:

- Fundamentals of particle transport, dispersion, deposition, and removal.
- Computational modeling of particle transport, deposition, and removal.
- Experimental study of particle transport, deposition, and removal, and aerosol instrumentation.
- Industrial applications of particle transport, deposition, and removal.

The materials for the course sequence were made available on the web and these full semester courses were taught six times each (over six years) and were taught twice at two campuses simultaneously. More recently, the course sequence was also offered simultaneously in house and on-line using lecture capture facilities. The purpose of this presentation is to provide information about the effectiveness of using web-based modules for enhanced learning of the in-class material and inform the audience about the availability of the course material for use at other institutions. (All course materials are posted on line and is available free of charge.) Assessment of usability of course web and of student learning through their projects and course grades was also presented and discussed.

INTRODUCTION

Understanding particle transport, deposition and removal is of crucial importance to many technologies that are critical for the competitiveness of the US microelectronic, imaging and pharmaceutical industries. In microelectronic fabrication, for example, the size of features of integrated circuits is in the range of 50 nm. During the fabrication process, if a particle of this size or larger deposits on the wafer it will short the circuits. In addition, solving a number of environmental problems requires a detail understanding of particle transport processes. Application of particle transport and deposition in human respiratory system was described in [1]. In fact, majority for air pollution and smug in cities are due to particulate maters. Particle resuspension form flooring has been identified as a health issue for indoor air pollution.

In the last decade, significant research progress in the areas of particle transport, deposition and removal has been made. The primary objective of this combined research and curriculum development project is to make the fruits of these new important research findings available to seniors and first year graduate students in engineering through the development and offering of a sequence of specialized courses. In these courses, the process of particle transport, deposition and removal and re-entrainment are described. The topic of particle transport deals with airflow in indoor and outdoor, work places, clean rooms, and how particulate matter in the size range of a few nm to 30 microns are transported in air, deposited on various surface from wafers, walls, carpets, to inside of human respiratory track [1]. Also how particles are detached from surfaces and are suspended in air. Each of the courses in the sequence is one full semester long, typically meeting three times a week for sixteen weeks including the final exams. There are also bi-weekly sessions for lab and computer projects. An extensive website for the course materials was developed and the courses were taught in-class at Clarkson University and simultaneously available via the web and video conferencing for students in Syracuse University. In 2012 and 2013 these courses were also offered on-line synchronously with the regular class. The total number students taking these courses for credits varied in the range of 15 to 30. Typically, there are also several students and postdoctoral fellows that are auditors in these courses.

PARTICLE TRANSPORT COURSE MODULES

These combined research and curriculum development (CRCD) courses are composed of four modules. The models are:

- Fundamental of particle transport, dispersion, deposition and removal.
- Computational modeling of particle transport, deposition and removal.
- Experimental study of particle transport, deposition and removal, and aerosol instrumentation.
- Industrial applications of particle transport, deposition and removal.

The front page of the course web is shown in Figure 1. The lecture notes and the calculations models are uploaded into the course web [2] and are available in both pdf form as well as html form.

Module I: Fundamental Concepts:

In Module I, the descriptions of fundamental theory of aerosols including hydrodynamic forces (drag, lift), and adhesion forces are described. The nature of particle adhesion and removal are also discussed. This module also contains the description of particle interaction with laminar flow, Brownian motion process, and particle deposition by diffusion, interception and impaction.

The interaction of particles with turbulence and turbulent deposition, normally taught as part of a second course, as also presented in this section. Details of computational modeling of turbulent flows are presented, and classical models of turbulent deposition are described. The process of aerosol charging and transport under the action of electrical forces and turbulence are also presented. The topics in Module I, thus provides a complete knowledge of fundamental particle forces that the students will use in later modules.

Module II: Computer Simulations

We have developed and added a number of computational modules to make the course presentations of the materials more interactive. These calculation modules help the student develop a better understanding of physical meaning of the complex concepts. One class of examples concerned with exploring the flow and particle transport in a variety of obstructed ducts. JAVA based simulation programs were developed and these programs were incorporated in the modules dealing with the motion of aerosol particles in the obstructed duct flows. The students will be able to interactively use the programs to explore the effects of various forces (gravity, drag, lift, Brownian), materials properties (particle density), and the flow geometry on the motion and deposition of particles. A module was developed for illustrating Brownian particle motion in cross flows. The flow field in this module is a parabolic velocity profile between two parallel plates. The particle equation of motion includes Brownian motion, drag, lift, and gravity. Figure 2 shows the user interface for this module. Here, particles are injected from a nozzle in the middle of the channel and the Brownian dispersion of particles can be visualized. The module can also be used to illustrate the effects of the lift force on larger particles. Student can select values of the particle diameter and density, the number of particles, and the centerline fluid velocity and understand the relative magnitudes of the different forces.

Figure 1. Front webpage of CRCD and the related courses.

There are more than thirty computation model covering drag and lift on particles to diffusion to cylinder and particle collisions. More details may be found at the course web site [2].

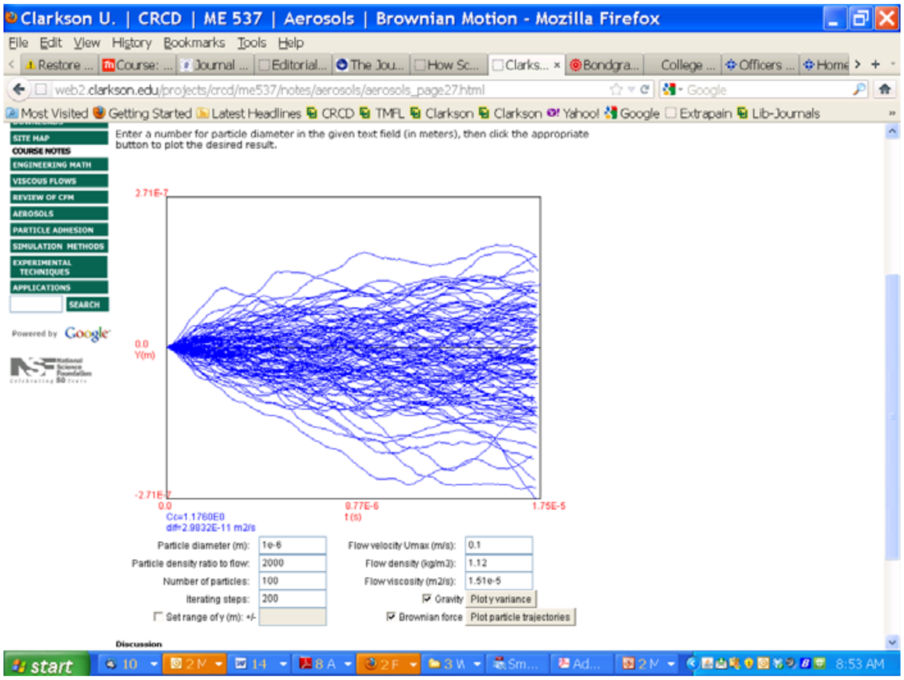

Figure 2. User interface for the module for Brownian particle motions in cross flows.

Module III: Experimental

The course sequence includes two experimental modules. One main experiment is the measurement in the aerosol wind tunnel with the use of Particle Image Velocimeter (PIV). The goal of the experiment was familiarize the students with optical measure of fluid flow. Groups of student work with the lab instructor to measure the velocity vector field in back-step flow using PIV. The aerosol wind tunnel is located in the Turbulence and Multiphase Flow Laboratory at Clarkson University. The laser used was a 120mJ Nd:YaG laser with a 20° adjustable width sheet generator. In this experiment, the sheet width was 0.5 mm. The digital camera that was used was a Kodak ES1.0 MegaPlus camera. The camera had a pixel range of 1008x1008. The pixel size was 25 micrometers and the interframe delay between pictures was 12 microseconds. A picture of the experimental setup is show in Figure 3. A sample PIV measurement of the velocity field behind a step is shown in Figure 4. The formation of a recirculation zone in the separated flow can be seen from this figure.

The other experimental study is to perform is the particle resuspension experiment. In this particles are fist deposited on a test section and placed in the resuspension wind tunnel. A microscope is used to take pictures of the particles on the test section. The air velocity in the wind tunnel is gradually increased from 1 m/s to about 15m/s in steps. After each increase of the airflow velocity, some particles are removed, and a picture of the particles still on the test section is taken. By counting the number of particles of different sizes remaining on the test section, the critical shear velocity for detachment of different size particles are measured. Additional experimental studies, originally intended for the course sequence were enhanced and incorporated in a companion course on aerosol instrumentation that is offered on alternate years.

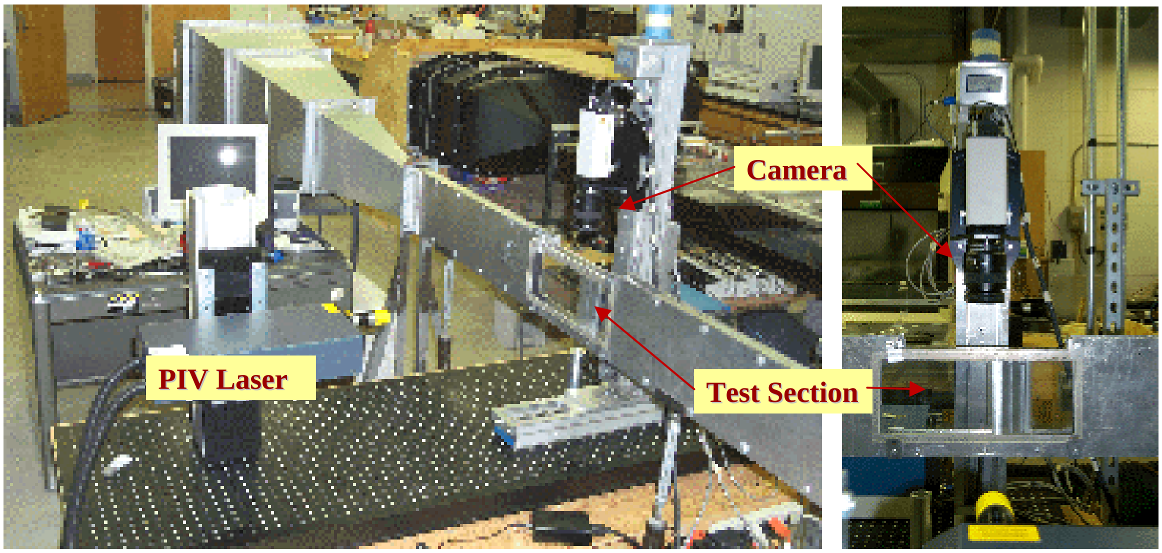

Figure 3. A picture of the aerosol wind tunnel.

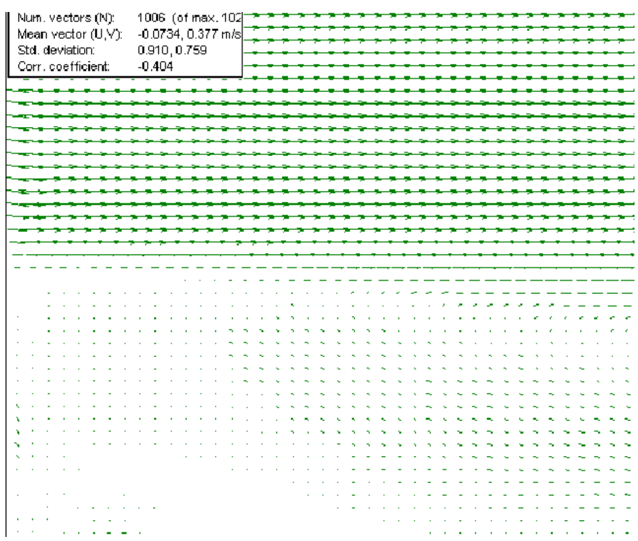

Figure 4. Sample PIV measurement behind a step in the aerosol wind tunnel.

Module IV: Applications

The applications module includes a number of examples from air pollution to xerography. Students are asked to use the material learned in Modules 1-3 to solve complex air pollution problems. There are typically two projects. Here are sample course projects:

First Course Project

Part 1: Brownian Diffusion in Micro-Channel

a) Point Source: Consider a laminar flow between two parallel plates. Assume that a point source located at different locations emit particles in the size range of 0.01 to 10 micron. Simulate the motion of particles under the action of Brownian force in the presence and absence of gravity. Assume that the mean air velocity is V= 0.01 m/s, the channel is width is h=1 mm, with a length of about 10 mm, and particle-to-air density ratio is S=2000. Use an ensemble of N=50 to 200 trajectories and evaluate the mean, variance and other statistics for particle position. Verify your results for dispersion for the source near the duct centerline by comparison with the exact solution. Discuss the importance of gravity and Brownian forces for different size particles. Also evaluate the deposition rate of panicles for point sources, which are very near the wall (about a=1 mm). (Use FLUENT as well as your own program and compare the results.)

b) Uniform Inlet Concentration: For a uniform inlet concentration of particles in size range of 0.01 to 10 micron, evaluated the deposition rate for laminar flows between two parallel plates. Plot the results in term of Schmidt number. (Use FLUENT as well as your own program and compare the results with those obtained from the diffusion analysis.)

c) Electromagnetic Forces: For the cases studied in parts a) and b) assume that the particles carry the average of the Boltzmann charge distribution. When an electric field is acting perpendicular to the flow direction, evaluate the dispersion and deposition of particles that are emitted from the point sources and/or enter the duct with a uniform concentration. Repeat the simulation when a magnetic field in the flow direction is present.

Part 2: Particle Detachment

Develop a computer program for evaluating the critical velocity needed to remove particles in the size range of 0.1 to 100 micron from a flat surface in a laminar duct flow. Assume that the duct is two mm wide and use JKR, DMT and Maguis-Pollock models for two materials of your choice.

Part 3: Applications

Solve the attached projects, or alternatively, select three industrial/environmental examples and perform two and three-dimensional analysis of the flow and particle transport.

As an example of Part 3, the particle pollution near Peace Bridge area in the south west Buffalo, NY because of traffic emissions was studied a few years ago. Figures 5 shows the area that was modelled. Figure 6 shows the trajectories of particulate pollutant pass line emitted from vehicle on the Peace Bridge. It is seen that the bridge emission is carried to the residential areas near the bridge.

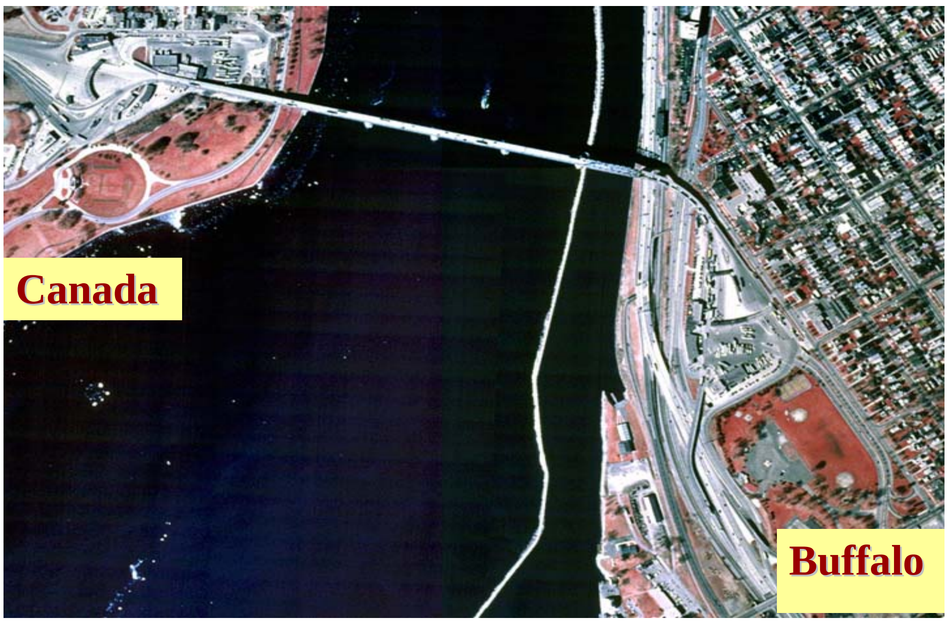

Figure 5. A picture of Peace Bridge area and city of Buffalo.

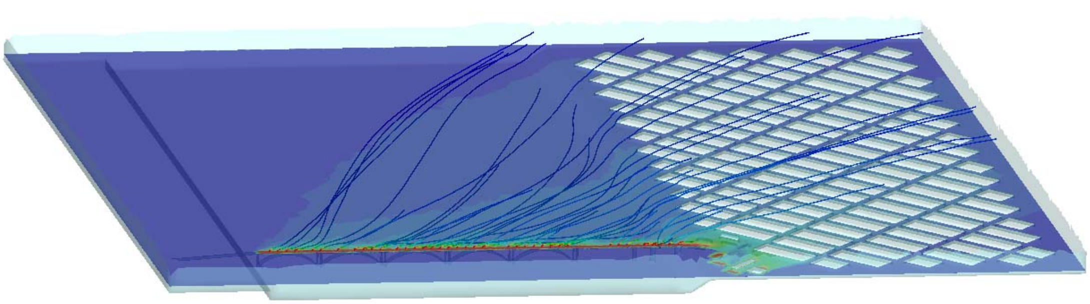

Figure 6. Sample computational results for pollutant dispersion from Peace Bridge traffic.

EXPERIMENTAL/AEROSOL INSTRUMENTATION COURSE

As noted before, a separate companion experimental aerosol and instrumentation course was developed by Dr. Suresh Dhaniyala at the Department of Mechanical and Aeronautical Engineering at Clarkson University. The course includes both lecture-based instruction on the theory related to aerosol measurements and laboratory experiments for a hands-on experience. During the lectures, a wide-range of aerosol topics, as related to aerosol measurements and instrumentation, were covered, including: a review of fundamental aerosol mechanics, particle statistics, size distributions, aerosol electrical properties, and aerosol sampling. The lectures helped provide students with a theoretical understanding of the basics of popular aerosol measurement techniques, such as electrical mobility instruments, inertial samplers, mass measurement devices, and diffusion-based instruments. The experimental aspect of the course included four extended experiments where a wide range of aerosol instruments and analysis techniques popular in aerosol science were used.

COURSE WEB EFFECTIVENESS:

The effectiveness of the course website was assessed in two ways:

1. Usability tests were conducted on an early version of the site and conducted again on the revised version of the site. In both tests, participants were given tasks to find course material and use the calculation model available on the site. The purpose of these tests was to determine how efficiently the participants could complete each task.

2. A survey questionnaire was administered to students enrolled in the courses designed to assess the students' satisfaction with the website.

USABILITY TESTS

The Usability Testing Lab in the Eastman Kodak Center for Excellence in Communication at Clarkson University was set up to record users testing out the website. Participating in the first test on the early version of the website were twelve student volunteers: six Mechanical Engineering majors and six Information Technology majors. Information from these tests was communicated to the website designers. A year later after the website had been redesigned a second usability test was conducted with two Mechanical Engineering majors and three Information Technology majors

For both test sessions a list of twelve tasks was devised that would cover a variety of possible uses of the website. All tasks required the students to search the site for course-related information. One task asked the students to do a calculation using the calculation model currently embedded into the site.

The results indicate that the participants using the revised site completed the tasks more efficiently.

Original Site
Average number of clicks, searches, scrolls to complete each task per user: **3.70**
Revised Site
Average number of clicks, searches, scrolls to complete each task per user: **2.56**

Original Site
Average number of failed or incomplete completions of the task per user: **1.41**
Revised Site
Average number of failed or incomplete completions of the task per user: **0.60**

Survey Questionnaire
Twenty-two students filled out a questionnaire upon completing the course, using the website to assist their learning. Overall, these students found the website useful for their needs: The specific results of the survey are:

1. The website was used to access information and employ calculation models:
- 77% used the website to read the course syllabus
- 86% used the website to read homework assignments
- 77% used the website to download course notes
- 54% used one or more of the calculation models

2. Students found the availability of course notes to be useful:
- 86% found the course notes to be easy to moderately easy to find.
- 96% found the course notes helpful to moderately helpful to their coursework.
- 86% found the course notes to be easy to moderately easy to understand.

3. Students found the calculation models to be useful:
- 81% found the calculation models to be helpful to moderately helpful.
- 81% found the calculation models to be easy to moderately easy to use.

4. Overall, 86% found the website to be very to moderately helpful to their coursework.

STUDENT LEARNING ASSESSMENT

Course grade and student projects were used for assessing the student learning by the development of the new web based materials. The student course final exam grades and course projects for five years before the new web-based course development were compared with the recent five years after the availability of the web based courses. It was found the average final exam grades improved from 81.5 to 86.7, which showed about 6% increase. The averaged course project grades also showed a 4.7% increase. In addition, the student comments on their course evaluation were generally positive.

CONCLUSIONS

The development of a sequence of web-based courses on particle transport, deposition and removal was described. Different modules of the course are outlined and the integration of simulations and experiments into the curriculum are described. The student learning and the suitability of the course website in helping the student learning were assessed. The results showed that the availability of the course material and computational modules on the website were very helpful to student learning, and students at multiple campuses could take the course simultaneously. The student evaluations of the experimental course suggested that the hands-on component was very well received by the students. The associated experience of technical writing for the lab reports was also noted as being very valuable by the students.

Acknowledgements:

The support of the National Science Foundation for this CRCD Project is gratefully acknowledged.

References:

1. J. Y. Tu, K. Inthavong, and G. Ahmadi, "Computational Fluid and Particle Dynamics in the Human Respiratory System," Springer, New York (2013). ISBN 978-94-007-4487-5,

2. http://web2.clarkson.edu/projects/crcd/